# Ground-Source Heat Pumps – Whence the Energy?

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## 1. The Question

Domestic ground source heat pump installations are increasingly common as a means of both saving money on fuel bills and reducing your carbon footprint. They work like a buried fridge. They use electrical power to pump heat from the ground, which is thus cooled. But unlike a fridge, the heat is not rejected but used – usually as the first stage in raising the temperature of feed water further and hence providing space heating. There are two common types of ground installation: shallow trenches which are only ~2.0m deep, and bore holes which are typically between 50 and 100 meters deep.

The question is: from where does this energy originate? Is it geothermal in origin, or is it solar? Some people refer to ground source heat pumps as "geothermal heat pumps". Is this name justified?

The question is more subtle that it first appears.

## 2. False Start

My initial reaction to this question was, "I just have to work out the direction of the heat flow through the earth at the position of the buried heat exchanger. If it is upwards, then the energy must be geothermal. But if the heat is flowing downwards, then it must be coming from the sun". Of course, this is nonsense. The heat flow through the earth is upwards everywhere except sometimes in the first few metres below the surface. Seasonal temperature variations can drive heat downwards in the first few metres during hot summer weather. But ground source heat exchangers are deliberately placed below the depth in which seasonal temperature variations are significant. At the location of ground source heat exchangers, whether 2m or 100m, the heat flux is upwards. Does this mean that they really are geothermal heat sources?

## 3. The Correct Analysis (I Think)

The answer is "no". Ground source heat pumps are actually tapping solar energy not geothermal energy – and this applies whether they are 2m deep or 100m deep. In fact the harvested heat would remain predominantly solar in origin even if the bore hole were  up to ~9km deep. Only at depths greater than ~9km does the ground heat start to become predominantly geothermal in origin.

The way to see this most clearly is to consider what the temperature near the Earth's surface would be if only one heat source were present: the sun or the Earth's own hot geothermal centre.

### Solar Heating Only

For our purposes we forget about complicating factors like the atmosphere. Consider the Earth to be a sphere receiving radiant heat energy from the sun and re-radiating heat into space. The total power radiated by the sun is,

$$P_{sun} = 4\pi R_{sun}^2 \sigma T_{sun}^4 = 4\pi \times \left(7\times 10^8\right)^2 \times 5.67\times 10^{-8} \times 5900^4 = 4.2\times 10^{26} W$$

The fraction of the sun's radiation impinging upon the Earth is,

$$f = \frac{\pi R_{earth}^2}{4\pi d^2} = \left(\frac{6.36\times10^6}{2\times1.496\times10^{11}}\right)^2 = 4.52\times10^{-10}$$

where $d$ is the Earth-sun distance, the astronomical unit. Hence, the power incident on the Earth from the sun is,

$$P_{sun}^{\text{at earth}} = fP_{sun} = \pi\sigma T_{sun}^4\left(\frac{R_{earth}R_{sun}}{d}\right)^2 = 1.91\times10^{17}\,W$$

The power actually absorbed by the Earth will be this figure times some absorptivity factor, $\varepsilon$ (i.e., one minus the albedo).

In the absence of any other heat source, the surface of the Earth would come into equilibrium with this incident energy by re-radiating energy at the same rate at some temperature $T_{earth}$. The rate of radiating energy is the emissivity times the black body radiation rate. But the emissivity and absorptivity are equal so that,

$$\varepsilon\sigma T_{earth}^4\, 4\pi R_{earth}^2 = \pi\varepsilon\sigma T_{sun}^4\left(\frac{R_{earth}R_{sun}}{d}\right)^2$$ , which reduces to,

$$T_{earth} = T_{sun}\sqrt{\frac{R_{sun}}{2d}} = 5900\times\sqrt{\frac{7\times10^8}{2\times1.496\times10^{11}}} = 285K = 12^o C$$

This is a very decent estimate of the average temperature of the Earth's surface, especially if we define this a few metres down so as to be just below the seasonally affected region. Note the Earth's temperature depends only upon parameters for the sun, i.e., the temperature of the surface of the sun, the sun's radius, and the sun-Earth distance.

In the absence of any other heat source, the whole of the Earth's volume would eventually come into equilibrium at this temperature, $12^o$C. The length of time required to achieve this equilibrium temperature even at the Earth's centre would be truly prodigious. However, achieving this $12^o$C over the whole length of (say) a 100m bore hole would only take the order of centuries. This is shown below.

It is already clear, then, that ground source heating would work just as well if the earth had no geothermal heating in its core. So ground source heat is actually solar energy. To drive this message home, let's see what the temperature near the surface of the Earth would be if there were no sun and geothermal heat were the only heat source.

**Geothermal Heating Only**

The temperature variation through the Earth is quite complicated. The gradient is by no means uniform. I'm not expert in these matters but I think the reason is as follows. On a large scale, the Earth consists of three regions: the core, the mantle and the crust. The core is largely iron, much of it is molten. Consequently the thermal conductivity is high (and, I presume, is enhanced by convection). The mantle is mostly molten silicate materials. The heat transfer will again be quite high due to convection currents. The existence of these convection currents is manifest in the form of tectonic activity. In comparison, the heat transfer through the cooler, solid material of the crust is quite poor, depending entirely upon conduction through non-metallic materials. As a consequence the temperature gradient in the crust is much higher.

In the few km near the Earth's surface, the temperature gradient can easily be measured and is, on average, 30$^o$C/km. If this steep gradient were sustained over the whole of the Earth's 6,360 km radius, the temperature at the centre would be a massive 191,000K. The true temperature of the core is not known with great accuracy, but lies in the range 4000K-7000K.

Fortunately, to calculate the total geothermal power output it suffices to know the temperature gradient in the crust, together with the crust's thermal conductivity[1]. I have seen sources quoting the average crust thermal conductivity as 3 to 5 W/mK. I have also seen sources quoting the thermal conductivity of dry earth as 1.5 W/mK, which seems consistent. Values for moist clay range from ~0.2 to ~2.5 W/mK, which are again consistent. In contrast, dry chalk has a conductivity of a mere 0.1 W/mK, whilst that of water is 0.58 W/mK. (Note that, when trapped in small pores, it is the conductivity of water which indicates its contribution to heat transfer, since convection is suppressed). For sake of argument the range 0.5 to 5 W/mK will be assumed for the crust. The heat flux due to the 30$^o$C/km gradient is thus,

Geothermal Power = 0.5 to 5 W/mK x 0.03 K/m = 0.015 to 0.15 W/m$^2$

Multiplying by the Earth's surface, $4\pi R_{earth}^2 = 5.08 \times 10^{14} m^2$, gives the total geothermal power production by the earth as,

Geothermal Power = 8 x 10$^{12}$ to 8 x 10$^{13}$ W

This compares to the 1.91ε x 10$^{17}$ W absorbed by the earth from the sun. Hence, the energy entering the Earth due to the sun exceeds that due to the geothermal source by a factor of 2,500 to 25,000. From this alone it seems likely that the ground source heat must really originate from the sun.

To clinch the matter, let's now calculate the temperature of the Earth's surface if there were no sun. Radiation into space would still be the means of achieving thermal equilibrium. So the heat balance is,

$$\varepsilon\sigma T_{earth}^4 4\pi R_{earth}^2 = 8 \text{ x } 10^{12} \text{ to } 8 \text{ x } 10^{13} \text{ W}$$

Using $\varepsilon = 0.7$ (for an average albedo of 0.3) therefore gives,

No Sun implies:- $T_{earth} =$ 25K to 45K

So, without the sun the surface of the Earth would be extremely cold. The oxygen and nitrogen of the atmosphere would be liquid (or possibly solid?).

In view of this observation it would seem perverse to claim that the heat we harvest at a temperature of ~12$^o$C (285K) could be of geothermal origin. It is not. It is solar.

Since the temperature in the Earth's core is 4000K-7000K, the lower surface temperature will not change the average gradient very much. Consequently, the gradient through the crust would still be roughly 30$^o$C/km. Consequently, a temperature of 285K would occur at a depth of ~9km. This is a very crude estimate, but this implies that at a depth of ~9km the geothermal energy source is roughly as significant as the solar source.

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[1] This suffices only on the assumption that the temperature throughout the whole volume of the Earth has achieved its steady equilibrium distribution.

**Timescales**

The thermal diffusivity of the crust, κ, is ~1 mm$^2$/s. The heat penetration time over a distance *w* is $\tau \approx \frac{w^2}{3\kappa}$. How long does it take heat to penetrate to the bottom of a 100m bore hole? It is $100^2 / 3\times10^{-6} \approx 3\times10^9 s = 100$ years. So, in a manner of speaking, when using a 100m deep ground source heat exchanger, part of the heat being harvested originated from the sun 100 years ago. More accurately, it will take 100 years to reheat this region and to recover all the required energy from the sun.

How deep is the seasonally affected region? If we allow 6 months, how far can heat penetrate? The answer is $\sqrt{3\kappa\tau} = \sqrt{3\times10^{-6}\times1.58\times10^7} = 7m$. In truth, attenuated sinusoidal temperature waves can penetrate further than this, but we would expect temperature variations to be small at depths greater than ~7m.

How far down might the ground be frozen? Obviously this depends upon location. In the UK, let's assume a severe month long freeze with (say) -12$^o$C atmospheric temperature. The penetration depth for 1 month is $\sqrt{3\kappa\tau} = \sqrt{3\times10^{-6}\times2.6\times10^6} = 2.8m$. But at this depth the temperature will be unaffected (at, say, the average temperature of 12$^o$C). The temperature change varies with depth roughly as $(1 - x/d)^2$. Hence, 0$^o$C is reached when $24(1 - x/d)^2 = 12$, i.e., for $x/d = 0.3$, that is a depth of ~0.8m. This seems rather deep to me – perhaps because, (i)I have assumed a ground surface temperature equal to the atmospheric temperature, and, (ii)we never really get a persistent -12$^o$C for a whole month in the UK (though Jan/Feb 2010 tried hard), and, (iii)perhaps a thermal diffusivity of ~1 mm$^2$/s is too large for top soil? However, as an order of magnitude estimate it is not too bad. A better value might be ~0.4m perhaps.

Conclusion

Ground source heat pumps are a means of tapping solar energy using the ground as a solar heat reservoir. The source of heat would become predominantly geothermal only at depths greater than ~10 km.