Geothermal energy: a significant source of energy?

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The heat contained in aquifers for which the temperature is between 50 and 120°C can be used for district heating provided that the point of heat production is fairly close to the point of consumption (about ten kilometres). When the aquifer temperature exceeds 200°C, this heat can be converted into electricity, allowing operation at much greater distances from the point of production. The French reserves allowing such exploitation are currently limited to natural aquifers only. But recent research results suggest that the heat from hot, low-permeability rocks may be exploited. The contribution of geothermal energy exploitation to national energy production could then become quite significant.

1. Heat and its transfers within our planet
La notion de géothermie fait référence à la température présente dans le formidable moteur thermique que nous appelons la Terre. Nous utilisons le terme gradient géothermale pour décrire la variation de température en fonction de la profondeur. Dans la croûte terrestre, ce gradient varie généralement de 20 à 40°C/km en fonction de la localisation, mais il peut localement dépasser 100°C/km et même atteindre plus de 300°C/km dans certains endroits (voir Figure 1).

La notion de température est liée à celle de chaleur, une forme d'énergie dont les transferts affectent localement la température (lire Pressure, temperature and heat). Une distinction est faite entre les transferts de chaleur par conduction, les transferts de chaleur par convection, et les transferts de chaleur par radiation".

Les transferts de radiation sont associés aux mouvements de photons et sont seulement significatifs sur la surface du globe. Ils sont négligeables pour comprendre les variations de température dans la Terre. Les transferts de conduction, décrits par la loi de Fourier [1], se produisent lorsque une roche chaude est en contact avec une roche froide. Certaines des chaleurs contenues dans la roche chaude sont transmises à la roche froide par conduction à travers l'interface qui sépare les deux corps. En outre, les roches sont plus ou moins poruses et plus ou moins permeables et le volume poreux généralement contient un liquide qui se déplace et transporte la chaleur.

Un exemple de transferts de chaleur impliquant à la fois des transferts de conduction et de convection est fourni par une éruption volcanique (voir The issues of industrial hydraulic fracturing). Le transport de chaleur associé au flux de lave correspond à un transfert de convection : l'éruption volcanique évacue dans la chambre magmatique une quantité de chaleur proportionnelle à la masse de lave émise pendant l'éruption. Une partie de cette chaleur est transmise aux parois de tuyaux volcaniques et est diffusée aux alentours, dans la masse rocheuse, par conduction.

Deux concepts liés à ces transferts de chaleur sont particulièrement importants : la capacité thermique et la conductivité thermique. Le premier est utilisé pour estimer la quantité de chaleur associée à un certain volume de matériau. Le second décrit comment la chaleur est transférée d'un volume chaud à un volume plus froid sans mouvement de matière. Par exemple, dans un liquide à l'état stable, la chaleur est transférée du plus chaud au plus froid grâce à la conductivité thermique du liquide seul. Cependant, la densité et la viscosité d'un liquide dépendent de sa température. En conséquence, les variations de température peuvent générer des mouvements de convection dont la vitesse dépend de la viscosité, qui à son tour dépend de la température.

Par conséquent, pour comprendre pleinement les variations de température avec la profondeur, il est nécessaire de se pencher sur les diverses mouvements fluides et de déterminer les sources de chaleur présentes dans notre planète. Le sujet associé à cet article introduit quelques notions fondamentales sur la structure du globe. En particulier, la définition de la lithosphère avec des comportements mécaniques solides et celle de l'asthénosphère avec des comportements mécaniques fluides sont rappelées.

Une grande partie de la source de chaleur provient de la radioactivité naturelle des éléments de la croûte terrestre. En outre, une source importante de chaleur vient de la formation initiale de la Terre et est associée au noyau. En conséquence, la température à la base de la lithosphère dépend des transferts de chaleur associés à la circulation de convection affectant la manteau supérieur, c'est-à-dire l'asthénosphère.

Dans la partie profonde de la croûte terrestre, le gradient géothermale dépend principalement de trois éléments. Il dépend d'abord de la flux de chaleur à l'état asthénosphérique, i.e. la quantité de chaleur par unité d'aire (exprimée en watts par mètre carré dans le Système International des Unités). Il dépend ensuite de la conductivité thermique et de la quantité de chaleur produite par la radioactivité naturelle des éléments de la manteau supérieur. Enfin, il dépend de la conductivité thermique et de la radioactivité naturelle dans la croûte. Pour la majeure partie superficielle de la croûte, la présence de fluides dans le poros des roches peut engendrer des mouvements de convection. Ces derniers directement affectent la région de la température. Il est question de zones de convection qui peuvent être le site de très hautes températures à des profondeurs superficielles (par exemple 300°C à 900 m de profondeur sur l'île de Leyte aux Philippines, voir Figure 1). Il est dû à noter que lorsque la pression dans le fluide est suffisamment faible, il peut exister simultanément dans son phase liquide.
and in its gaseous phase (e.g. presence of water vapour bubbles in liquid water). In addition to the mass heat already mentioned, latent heat associated with changes in the liquid-vapour phase transition must then be taken into account.

2. Temperature variations near the ground surface

![Figure 2. Heat balance controlling the temperature at the ground surface. [Source: according to G. Vasseur[3]]](image)

The temperature at the ground surface depends on the different heat exchanges that occur locally, as illustrated by figure 2 (Figure 2, [3]).

These mechanisms are as follows:

- **Evapotranspiration (term Et)**
- **Absorbed solar radiation (term Ri)**
- **Atmospheric radiation (term Wa)**
- **Radiation of the ground (term Ws)**
- **Convective exchange term (h[θs-θa])**
- **Deep heat flux term of geothermal origin**

In practice, observations have shown that the heat flux of deep origin is generally negligible as compared to the other sources of heat, except on volcanoes. Therefore, the surface ground temperature differs little (a few degrees) from the air temperature. Variations in solar radiation impose temperature variations on the surface of the ground, related to daylight or seasonal variations.

These temperature variations are propagated in the underlying soils, in particular due to their thermal conduction. Hence, diurnal variations (within a day) affect the first 15 cm of soil. The annual variations imply temperature variations over the first three metres, while secular variations can reach the first 30 metres. At a scale of 10,000 years, variations of exchange temperature (h[θs-θa]) between the ground at θs temperature and the atmosphere at θa temperature (about 20,000 years ago) can be found in thermal profiles (variations in the geothermal gradient with depth) up to about 400 to 500 metres deep from the surface of the ground. It is remarkable that temperature variations over periods of less than a year are only in the order of a few tenths of a degree as soon as one reaches a few metres below the surface of the ground. For example, annual measurements, repeated over a few years and carried out in a granite outcropping at an altitude of about 500 m in the Vichy region, revealed seasonal temperature variations of just one-tenth of a degree at a depth of 15 m below the ground surface. It is this stability of the shallow temperature that allowed the installation of geothermal heat pumps, as discussed below.

3. Conventional methods of exploiting geothermal energy

An aquifer is a highly permeable geological level with high porosity and pores filled with water. It should be remembered that permeability characterizes the ease with which fluids flow through rocks. It relates the flow rate observed between two given sections to the pressure difference between them. For the same flow rate, the more permeable the rock, the smaller the pressure difference required to ensure this flow rate.

**Heat flux with deep origin.**

**Conventional** geothermal energy exploitation only concerns natural aquifers and consists in extracting the heat contained in the aquifer by bringing its water to the surface of the ground at a temperature close to that of the aquifer.

There are traditionally three types of geothermal energy exploitation: exploitation by heat pump, direct exploitation of the heat contained in aquifers, and finally, when the temperature allows it, electricity production after conversion of heat from geothermal sources.

In France, for the year 2012, the energy production associated with geothermal heat pumps installed for individual heating was equivalent to just under 300 ktoe (kilotonnes of oil equivalent), or about 3.4 GWh (Giga Watt hour). The energy production...
linked to the direct exploitation of geothermal heat amounted to 140 ktoe (about 1.6 GWh) for the same year 2012. In 2016, the geothermal electrical power installed in France amounted to 17 MW (Megawatt), representing an annual production of approximately 149 GWh if we assume full-time operation of the installations over that year. To better appreciate the current contribution of geothermal energy exploitation to national energy production, it should be recalled that the quantity of electrical energy produced in 2013 by French nuclear power plants alone amounted to 391,000 GWh.

3.1. Heat pump operation

A heat pump is a device for transferring a certain amount of heat from a first medium, called an emitter, to another medium, called a receiver. The system thus makes it possible to lower the temperature of the emitting medium and increase the temperature of the receiving medium.

For example, a heat pump is used to lower the temperature in a refrigerator (emitting medium), but it can also be used to heat a room (receiving medium). Moreover, the same heat pump principle can be used to cool a room if it is used as a emitting medium, and no longer as a receiving medium. In the case of the refrigerator, heat extraction is carried out by the expansion of a fluid, known as refrigeration, which changes from liquid to vapour by pumping the heat into the refrigerator, resulting in a decrease in the local temperature. This vapour is then compressed back to the liquid phase outside the refrigerator where the operation emits heat, raising the local ambient temperature.

The coefficient of performance (COP) of a heat pump (PAC) is defined by the ratio between the thermal power of the machine and the electrical power consumed. For example, a heat pump with a COP of 3 provides 3 kWh (kiloWatt hour) of heat for every 1 kWh of electricity consumed. The coefficient of performance of a heat pump decreases as the difference between the temperatures at the cold and hot source increases. Thus, if the temperature of the cold source is constant, the efficiency of the heat pump decreases with the temperature of the hot source. As a result, so-called geothermal heat pumps, i.e. heat pumps with a cold source located in the basement, are more efficient when used to ensure a constant temperature in a floor, for example. In this case they provide a minimum basic heating, the complement being provided, depending on the needs, by electric convectors.

Geothermal heat pumps use three types of heat capture in the basement:

**Horizontal capture.** The heat is captured by a network of parallel horizontal tubes through which a heat transfer fluid flows. These tubes are buried between 60 cm and 1.2 m deep, depending on the climate. They are placed under a lawn, but away from trees whose roots could disturb the installation.

**Vertical capture.** Vertical capture involves a series of parallel tubes distributed in a vertical borehole that can reach a depth of up to 100 metres. This borehole, itself being solidly tubed (read Some characteristics of drilling techniques), can be placed near trees.

**Vertical collection on groundwater.** In this case, the water from the local groundwater is used directly as a heat transfer fluid. It is pumped through a so-called suction borehole. A groundwater temperature of 10°C or more is targeted. The water from the groundwater circulates in the heat pump emitting enclosure located in the house. It is discharged into a borehole downstream of the suction borehole so as not to disturb the temperature.

3.2. Direct use of heat

![Figure 3. Producing wellhead in the Melun area. Note the thermal insulation required to limit heat loss during flows in the surface piping. [Source: photo ADEME]](image-url)
Direct heat exploitation concerns aquifers whose temperature ranges between 50°C and 120°C. Water from the aquifer is extracted through a producing borehole (Figure 3). On the floor surface, it passes through a heat exchanger in which it heats the heat transfer fluid used for heating. Once cooled, it is re-injected into the aquifer, at a certain distance from the extraction point (about one kilometre) so as not to disturb the temperature there. Such a system is called a geothermal dipole.

Reinjection is necessary for two reasons. The first is that water in aquifers of economic interest (more than 500 m deep) is very generally loaded with various mineral salts (at concentrations of 6 to 35 g/l or more). It should therefore be purified before its release if it were to occur in the hydrographic system at the surface of the ground. In addition, the reinjection ensures that the tank is maintained under pressure, which ensures a constant flow rate during production.

Geothermal energy is therefore not strictly speaking a renewable energy, because the amount of heat extracted from the geothermal reservoir is much greater than the amount of heat provided by the regional heat flow from the deepest depths.

The dipoles must therefore be properly dimensionned (production rate, sufficient distance between injector and producer wells) to avoid their premature cooling. Another dimensioning element has long been corrosion, which affects the various elements of the geothermal loop. But after having caused a problem when this type of operation started in the 1970s, this corrosion problem was well solved and no longer affects the service life of the doublets. Today, the oldest dipoles have not experienced premature cooling for most of them and are therefore still effective. However, their inevitable ageing requires that solutions be found for their renewal when the cooling becomes too significant. Current research is therefore focused on obtaining a good characterization of the extension of the areas cooled by the operation, in order to define the areas where future replacement doublets will be installed.

This type of exploitation has developed particularly well in the Paris Basin, where the Jurassic limestone geological layer of the Dogger has proved to be a very interesting aquifer. It has also been somewhat successful in the Aquitaine basin. But to be profitable, these geothermal operations must be located at short distances from heat use points (usually district heating) due to energy losses during the transport from the production well to the heating point. Their field of application thus remains essentially limited to urban areas in which there are enough consumers at an acceptable distance from the doublet, as for example in the Paris region.

### 3.3. Electricity production by converting heat into electrical energy

When the aquifer temperature is high enough, the heat produced can be efficiently converted into electricity through a converter located next to the producing well (see cover image). A geothermal reservoir is a volume of rock large enough to allow for the exploitation of its geothermal energy for a period of time of real economic interest. This typically reaches a few decades, even more so in Larderello in Italy where the field was first exploited in 1904. Today, such geothermal reservoirs for electricity production involve aquifers generally at temperatures above 250°C. Production can vary, depending on the reservoir, from a few tens of MW to several hundred MW, or even exceed the GW as in the Geysers reservoir in northern California.

The profitability of a geothermal reservoir depends, of course, on its temperature field, but also significantly on the volumes of water that can be produced in a stable way over time. The higher the temperature of the reservoir, the lower the flow rate required to be economically viable. In reservoirs that have been in operation for some time, there is a local drop in pressure that can lead to the appearance of a vapour phase in the produced water, which affects the ageing of the system. This notion of aging is one of the important factors to consider when determining the profitability of a geothermal operation.
Zealand produce most of their electricity from geothermal energy. In France, the only region where this type of geothermal energy is used is Guadeloupe (West Indies): the Bouillante field (Figure 4) currently produces 16 MW of electricity, which covers 6% of the island's electricity needs.

4. Exploiting the heat from warm, low-permeability rocks

Figure 5. Map of the heat flux of France at the surface of the ground corrected for paleoclimatic and topographical effects. [Source: Figure F. Lucazeau[5]]

The temperature increase near the ground surface is related to the presence of a geothermal flux that includes the effects of conduction and convection in the environment under consideration, but also other effects such as past climatic variations or the effects of topography (the average annual temperature at the summit of Mont Blanc is much lower than the value measured in Geneva for example). Figure 5 [5] presents a map of the heat flux of France derived from geothermal gradient measurements observed near the ground surface, after correction for topographical and paleoclimatic effects.

We note a strong heat flux anomaly in the northern Rhine graben, as well as a fairly high heat flux zone (over 110 mW/m²) over a large portion of the territory extending from the centre of the Massif Central to the Vosges.

For example, the temperature reaches 140°C at the base of the sedimentary series encountered at a depth of 1500 m in Soultz-sous-Forêts, a village in the northern Rhine graben. It reaches 160°C at the basement-sediment boundary encountered at a depth of 2300 m at Rittershoffen located about fifteen kilometres east of Soultz. However, while drilling in Rittershoffen has reached aquifers with satisfactory water production characteristics for direct economic exploitation of heat, the same has not been the case in Soultz. For this site, which is hot but too low in permeability for conventional operation, a new operating method called EGS (based on the initials of the English words Enhanced Geothermal Systems) has been developed to enable small electricity production (1.5 MW).

The EGS method is based on the idea that it is possible to considerably increase the permeability of a rock mass by appropriate hydraulic and chemical stimulation. The objective is to circulate, after stimulation, water flows compatible with the planned economic exploitation, and this at local flow rates slow enough so that the temperature of the water produced at the surface is close to that of the stimulated area. For this type of application, it is not possible to use the conventional hydraulic fracturing process (read The challenges of industrial hydraulic fracturing) because granular products, set up to keep a hydraulic fracture open at the end of the fracturing operation, tend to be dissolved by circulating water. It is also necessary that there are enough flow channels in the rock to avoid premature cooling of the system.

The method adopted at Soultz consists in gradually increasing the pressure in the deep rocky massif, in order to induce shear movements along the pre-existing fractures used by water flows. Similarly, acid injections have made it possible to dissolve calcite locally and thus reduce the hydraulic impedance of the system (the hydraulic impedance, inversely proportional to permeability, makes it possible to characterize the pressures required to reach given flow rates). In addition, the efficiency of the process of converting heat into electricity has been improved by using a liquid at a much lower boiling point than water. This experimental system has been operating satisfactorily in its current configuration since summer 2016. It will allow us to test, in real life, the ageing of the system.
Once these ageing studies are completed, the EGS process should make it possible to consider exploiting the huge geothermal reservoir that could be constituted by the heat flow zones above 110 mW/m$^2$ shown in Figure 5. The contribution of geothermal energy exploitation to national energy production could then become quite significant.

References and notes

**Cover photo.** Electricity production in Soultz-sous-Forêts (Bas-Rhin) from geothermal energy extracted at a depth of nearly 4500 m. In red, the head of the water-producing well at 150°C; in the background on the right of the wellhead, the binary converter producing 1.5 MW of electricity (photo, Électricité de Strasbourg)


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