# Optimal and sustainable use of the Dogger aquifer geothermal resource: long-term management and new technologies

S. Lopez[1*], V. Hamm[1], O. Goyeneche[1]

1: BRGM, 3, avenue C. Guillemin, 45060 Orléans CEDEX 2.

*presenter: s.lopez@brgm.fr, +33.(0)2.38.64.39.38

## Abstract

Geothermal energy has been supplying heat to district networks in the Paris Basin for more than 40 years. In this densely urbanized area, the main target of all exploration and exploitation projects has been the Dogger aquifer (1500-2000 m deep). Initial difficulties, due to corrosion and scaling related problems, have been overcome in the mid-1980s and, since then, operations have been providing heat daily to more than 150,000 dwellings. Operating facilities use the “doublet” technology which consists of a loop with one production well and one injection well. Consequently, injection of the cooled brines leads to the progressive exhaustion of the resource at the local doublet scale. Most of the research effort has been focused on quantifying the temporal evolution of the cooling, and to forecast the lifetimes of doublets and the occurrence of the “thermal breakthrough”.

Yet, with the need for carbon free energy sources there has been a revival of geothermal energy development in France: many projects are presently being considered and new operations have already been carried out. In this context, it appears that the aquifer geothermal resource has to be managed and modeled as a whole. For this purpose, BRGM maintains an up-to-date hydraulic and thermal model of the aquifer which can help policy makers to improve regulatory framework and which can support stake holders to carry out new operations. Moreover, because of potential conflicts of use which are emerging in densely exploited areas, a fine understanding of reservoir behavior is needed and new technological solutions must be developed: exploration and exploitation of underlying or overlying aquifers, seasonal heat storage...

# Historical perspective

## 40 years of geothermal exploitation of The Dogger aquifer

The Paris basin is the largest onshore sedimentary basin in France. It occupies a vast part of Northern France (110,000km$^2$) and extends northward to Belgium and below the English Channel. Its origin is linked to a period of rifting in Permo-Triassic times. The central part of the Basin, where the subsidence was the greatest, is filled with about 3000 m of sediments (Guillocheau *et al.*, 2000; Delmas *et al.*, 2002).

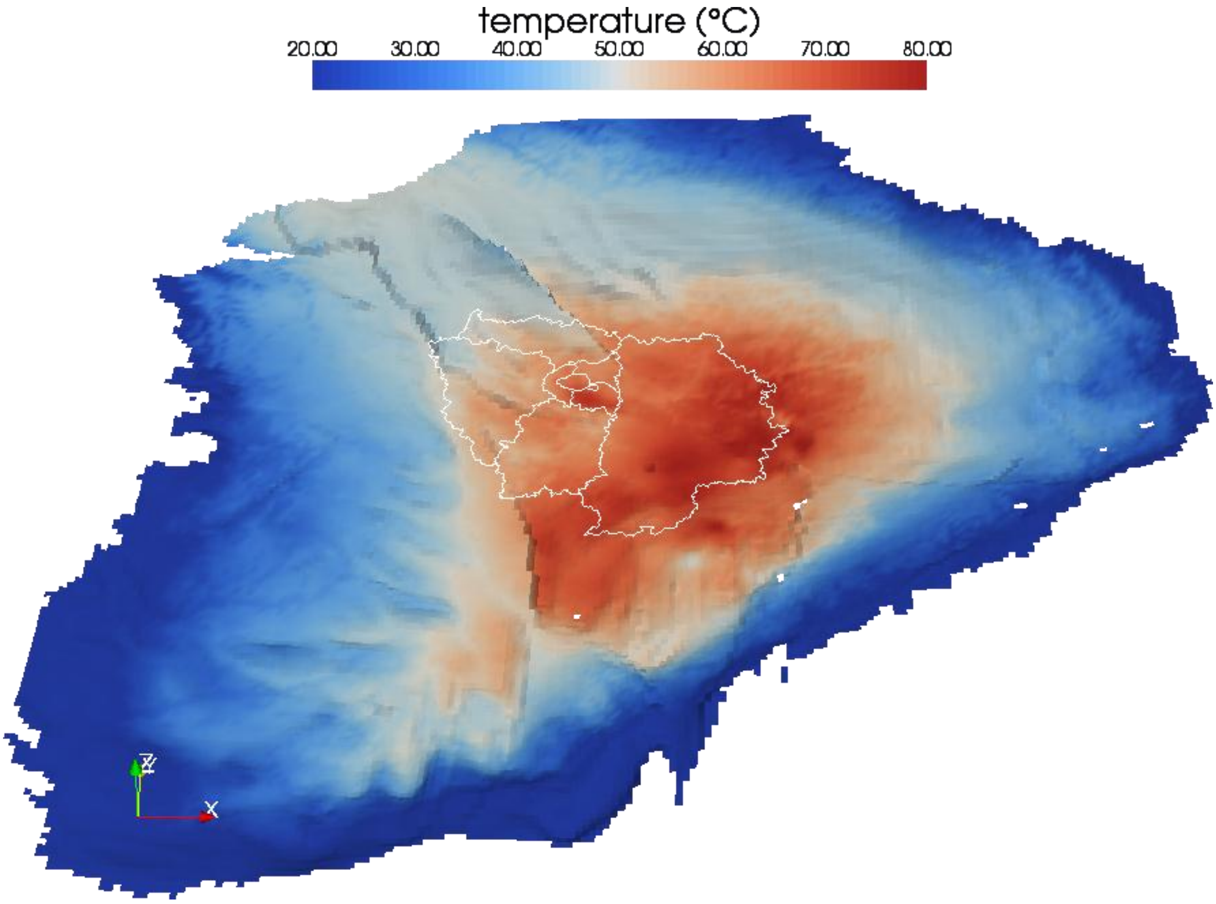


**Figure 1 : 3D view of the top of the Dogger aquifer and associated temperatures (white wirelines highlight the Ile de France region with Paris at its center)**

Among the four main lithostratigraphic units exhibiting aquifer properties in the basin, the mid-Jurassic (Dogger) carbonate rocks were identified as the most promising geothermal development target below the urbanized Paris area (Ungemach *et al.*, 2005). Several oil-bearing reservoirs were also identified in this geological unit some of which correspond to the target layers for geothermal exploitation. In its slow circulation through the basin, the fluid reaches depths of 2000m where it acquires its geothermal potential with good transmissivities and temperature that can reach 80°C in the deepest areas.

The geothermal development of French sedimentary basins started in the early-1970s (Lemale and Pivin, 1987; Demange *et al.*, 1995; Laplaige *et al.*, 2005; Lopez *et al.*, 2010). In the Paris basin, the main target has been the Dogger aquifer whose development was favored by three main technical and economic factors:

- The presence of a productive hot reservoir, located at a reasonable depth, whose characteristics (temperature and transmissivities) were suitable for the supply of district heating networks (cf. temperature map on figure 1).
- The existence of an important potential heat market, with densely populated areas, suitable for low-temperature energy production: the Paris area with more than 10 million inhabitants.
- Availability of public policy incentives and insurance policies that favored the development of new energy sources.

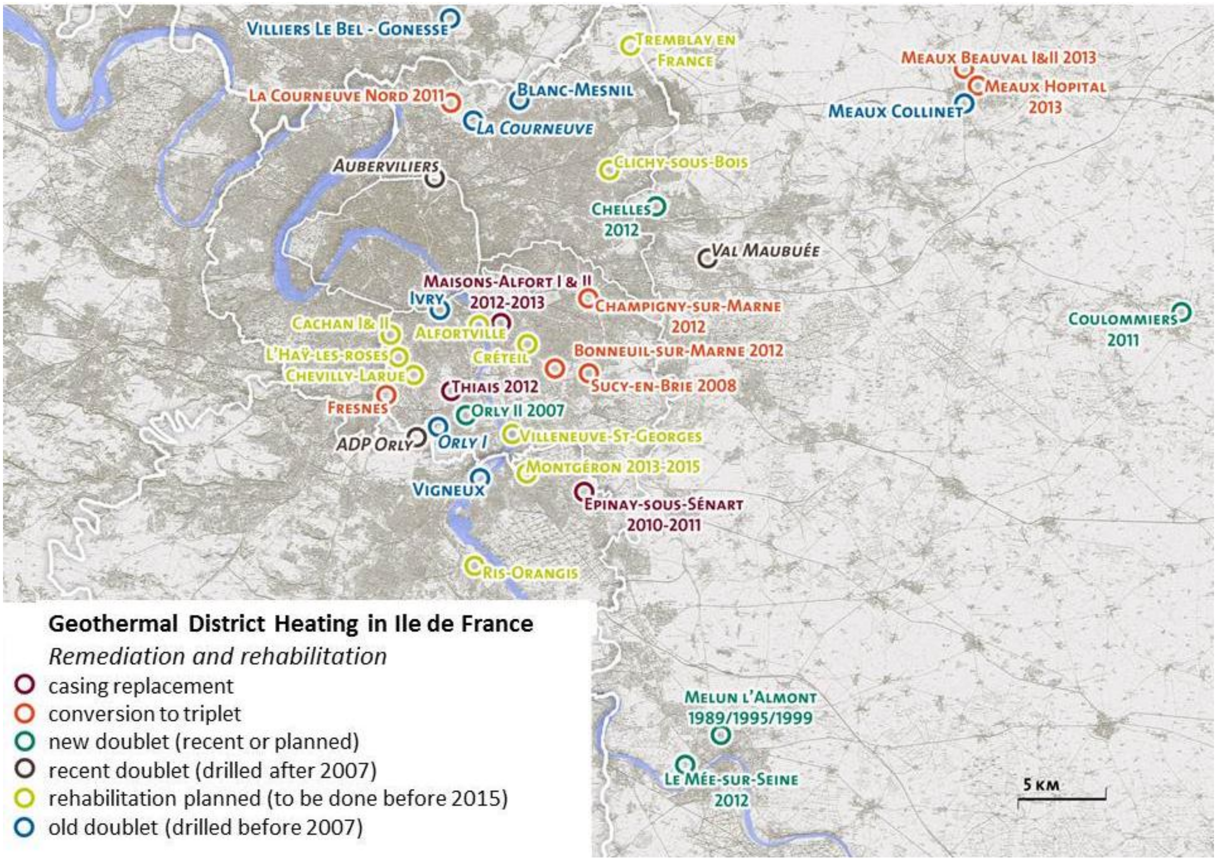


**Figure 2 : Remediation and/or rehabilitation of deep geothermal wells in the Paris area (Ile de France region) (map by C. Chery/BRGM)**

The first successful operation targeting the Dogger aquifer was drilled at Melun l'Almont in 1969, more than 40 years ago (cf. location map on figure 2). It is still active today, providing space heating for 5000 houses, after the replacement of the first two wells. Nevertheless, the growth in exploitation of the Dogger geothermal potential has not been steady instead and has rather been reflecting the French technical and economic context. A large number of operations were planned and completed in the aftermath of the 1973 and 1979 oil crises, when governmental policies supported energy conservation and the development of alternative sources of energy. The drilling of new doublets was especially favored by the development of an insurance policy that covered geological hazard (e.g., poor flow rate), as well as long term behavior and exploitation of the doublet (i.e., decrease in the temperature of the produced brine).

The 1986 drop in fossil energy prices impeded new operations and initiated a period marked by very little activity. Forty-two wells were abandoned for technical (corrosion or scaling) or economic reasons (low profitability of geothermal operations compared with fossil energies, drop in interest rates that penalized older loans used to finance geothermal operations). The vast majority of abandoned operations lie in the northwest part of the Basin, which is the area of lowest geothermal fluid temperature ranging from 55 to 65°C (figure 1).

Then, during the 90s and until the middle of the years 2000, drilling activities in the Paris basin were reduced to the replacement of damaged wells or the development of existing facilities (Laplaige *et al.*, 2005). Tough there has been a boost in geothermal activity at the turn of the century, over half of the existing district heating networks with a geothermal supply in the Paris region (17 out of 29) were equipped with gas cogeneration plants. This choice had significant impacts on existing geothermal loops. The resulting reduction of the average exploitation flow rate induced an increase of corrosion and scaling related problems. These damaged several well casings that had to be replaced. In 2005, the average rate of geothermal energy use for the group of 29 heat networks was around 60%, compared to 72% for the previous situation when there were no cogeneration facilities (Laplaige *et al.*, 2005).

As a consequence of the growing needs for producing heat in a less polluting way and with a lower carbon footprint, it's been a few years now that old wells are progressively being replaced, several new geothermal doublets have been drilled and many other operations are planned (figure 2). By the beginning of 2012, there were more than 120 deep geothermal wells exploiting the Dogger aquifer in the Paris basin. Moreover, some areas are becoming so densely exploited that potential resource exploitation conflicts are emerging and new challenges concern mainly the sustainable exploitation of the aquifer as a whole.

## Exploitation characteristics

Nearly all geothermal operations exploiting the Dogger aquifer use the "doublet" technology consisting of a closed loop with one production well and one injection well. The wells target productive layers which lie between 1500 and 2000 m deep. They are usually completed with an open hole through a reservoir thickness ranging from 100 to 150m of carbonate deposits. By the end of the 1970s, the routine acquisition of well logs, especially flowmeter logs, revealed the high vertical and lateral variability in the hydrological characteristics of the aquifer. There can be from 3 to 20 individual productive layers in the formation with a cumulative thickness (*net pay*) of only 10% of the total aquifer thickness. On average, this net total productive thickness is of the order of 20 m, with 10–15 high permeability (2–20 Darcy) layers. A single productive layer may represent as much as 80% of the total flow rate (Lemale, 2009).

Formation temperatures at the top of the productive layers are generally between 55°C and 80°C (figure 1). The mean temperature gradient between the surface and the formation is 3.5 ◦C/100 m. Minimum temperatures are found at 1650m below surface, northeast of Paris, where average thermal gradients are as low as 2.75 ◦C/100 m. This zone corresponds to a cold anomaly area that can be explained by regional cold water flows coming from the upper parts of the aquifer. Some authors proposed that this cold area could be linked to circulations induced by the historical intensive exploitation of overlying aquifers for drinkable water, since the middle of the 19$^{th}$ century (Burrus, 1997). Maximum gradients of 4.1°C/100m are recorded southeast of Paris.

The salinity of exploited brines ranges from 6.4 mg/l to 35 mg/l. At basin scale, salinity increases from the southeast, where the reservoir outcrops (0.5 g/l), to the deepest area where it reaches 35 g/l.

These salinity variations influence the brine density and viscosity and hence the aquifer-scale fluid flow (Menjoz and Lambert, 1991), but these variations have a negligible effect at the scale of geothermal doublet exploitation.

Facies and diagenetic porosity reduction patterns are complex. The original porosity and permeability properties are strongly influenced by contemporaneous dissolution events related to high frequency sea level fluctuations. Fracture porosity is often present (Delmas *et al.*, 2002). Investigations showed a direct relation between the porosity and the sedimentary environment, particularly where the sandy sediments with matrix porosity were deposited (Rojas.J. *et al.*, 1989).

The doublet technology has several advantages:

- There are no environmental impacts as the cooled geothermal brine is fully reinjected, and prohibitive costs of chemical processing of geothermal brines for surface disposal are avoided.
- Production flow rate is maintained whereas a single well exploitation would have progressively reduced the reservoir pressure, eventually affecting pumping conditions.
- Thanks to the pressure interference the exploitation pressures are stabilized and the area impacted by pressure variation is limited: an exploitation domain can be legally defined by the authorities, thus allowing the setup of an efficient strategy for the optimal management of the aquifer.

## From the doublet scale to regional scale management

Cold water breakthrough is an inevitable consequence of the doublet approach. The practical lifetime of a geothermal project can be defined as the time for the produced fluid temperature to decline to a level that exploitation is no longer beneficial. During the 1980s, when most of the doublets were drilled, numerical modeling studies based on rather pessimistic assumptions estimated the average lifetime of geothermal doublets to be 20–25 years. Most of the doublets have now been exploited for more than 20 years, and, so far, no thermal decline has been observed in any but one of the geothermal loops and one more may be suspected on another operation.

Although the practical lifetime is longer than had been expected, uncertainty still remains about when and how much the temperature will decline. Since the beginning of geothermal exploitation in the Paris Basin, the resource has been exploited without any real attempt to optimally manage the Dogger resource. Now, as the predicted thermal breakthrough time of some doublets is approaching, the non-sustainable character of individual geothermal projects has become a matter of concern for many stakeholders. Consequently, there is a urgent need to define guidelines to be followed for the development of new doublets in order to properly manage and optimize the exploitation of the resource. This is especially true in districts where the doublet density is already high or where the density of surface heating networks would make future intense exploitation probable.

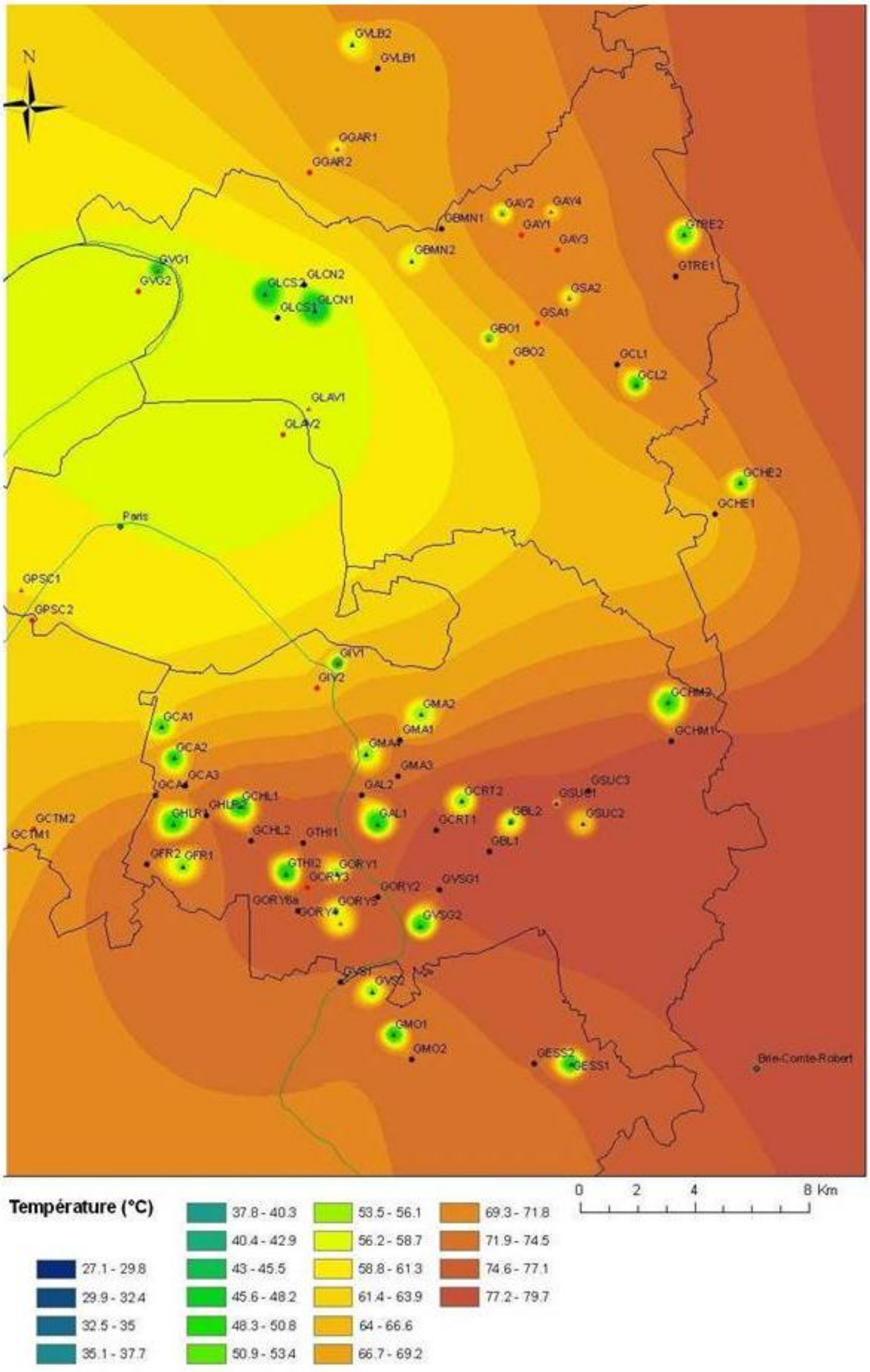


**Figure 3: Temperature of the resource in densely exploited areas**
**(Hamm *et al.*, 2010)**

A long term project devoted to Dogger aquifer management has been started in 2007. This project is run cooperatively by ADEME (French Environment and Energy Management Agency), BRGM, and the Ile de- France Regional Council. As of today, out of the 35 pairs currently operating in the Paris region, 27 are located in Val-de-Marne and Seine-Saint-Denis areas. Since 2009, a regional model of the geothermal resource and of the impact of its exploitation has been developed with the objectives (figure 3) :

- to better understand the extension of the cooled zones and to optimize the forthcoming operations (rehabilitation or location of new wells, doublets or any other technology),
- to be able to predict the production temperature evolution of existing producing wells.

Modeling works have been constrained using the “Dogger database” which was created in 2001. For all operations, this database contains all historical data since 1969 concerning drilling, workovers, plant equipment, aquifer characteristics, operating histories (flow rate, injection temperature and pressure, etc.) and monitoring data. The regional model is regularly updated and new data from the Dogger exploitation are integrated via the database.

Finally, in very densely exploited areas, sophisticated completion schemes and well architectures such as horizontal or multi-lateral wells may be an interesting option if they become economically affordable (Ungemach *et al.*, 2011; Hamm and Lopez, 2012).

## Sensitivity analysis of reservoir models

Until today, only one case of temperature decline has been observed among all the exploited geothermal doublet of the Paris basin. This very slight decline has been very satisfactorily reproduced by several modeling teams (figure 4). Nevertheless, the temperature of the produced brine temperature is far from being stable and the amplitude of the observed fluctuations is still greater than the amplitude of the temperature decline. First, the reliability of the measurements introduces uncertainties. Measurements are performed on the geothermal loop at the surface, and therefore depend on the working conditions of the loops (mainly flow rate) and heat losses through the casing between the reservoir and the well head. Besides, the precision of the instruments does not permit systematic measurement of small variations. Finally, the numerical forecasts are often made assuming periods of constant production rate with constant injection temperatures, whereas production flow rates may also fluctuate as well as injection temperatures which depend on weather conditions.

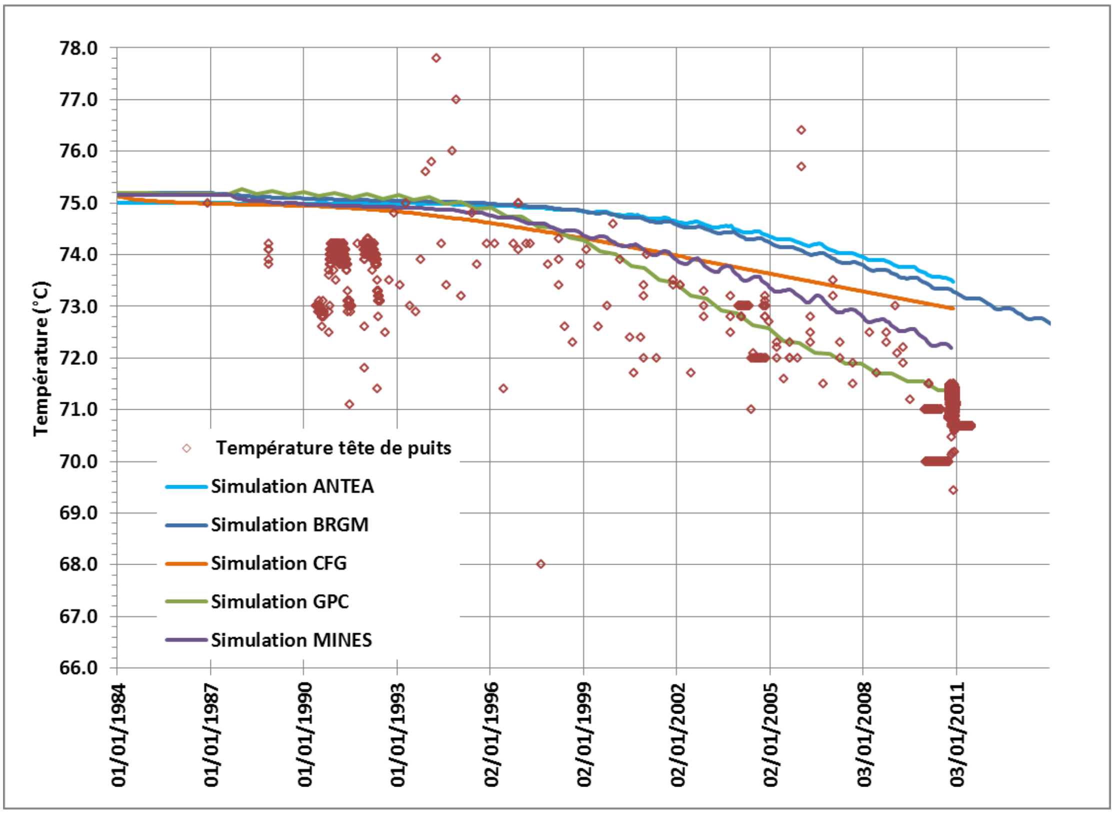


**Figure 4: Downhole reservoir temperature (color lines) compared with the observed well head brine temperature (red circles) on the Alfortville operation.**
**Simulation results were obtained by different modeling teams (Hamm et al., 2011)**
**There is a 1 to 2 °C difference between reservoir and well head temperature which is due to heat losses along the casing.**

Nevertheless, it is worth noting that regional modeling predicts thermal decline on another operation though it is not observed yet. It is very likely that such discrepancies between model predictions and observations are linked to the very scarce data available for reservoir characterization. This scarcity introduces a great deal of uncertainty in the modeling results. Indeed, data points are separated by the distance between the production and the injection wells inside the reservoir which is often greater than 1km. Consequently, accurate identification and correlation of productive layers or estimation of the true productive thickness remain very difficult tasks. This is all the more important because these parameters are among the most important in controlling the time of the thermal breakthrough, and hence the overall lifetime of the doublet (Menjoz, 1990).

As only the beginning of a single temperature decline has been observed among the nearly 40 operating doublets of the Paris basin, numerical modeling remains the best way to forecast the thermal breakthrough, and to provide a basis for devising a sustainable strategy for the development of the Dogger aquifer (see also see also:Ungemach *et al.*, 2007; Ungemach, 2008). Modeling studies can be performed at different scales, ranging from the full regional scale, i.e., the entire Paris Basin, to the smaller scale of a pair of neighboring doublets or even a single doublet. Accurate numerical modeling of heat or chemical transport requires spatial and temporal discretization designed to avoid numerical dispersion or instabilities. Thus, horizontal mesh must be fine around wells, as must be vertical mesh near the boundaries between the reservoir and adjacent layers to correctly reproduce heat exchanges. Selection of the modeling scale and of the physical processes to be investigated is often the result of a trade-off between the accuracy required to answer a particular question and the available computing power.

The conceptual model of the aquifer will have a great influence on the modeling results. As the productive levels of the aquifer cannot be individually correlated, they are generally grouped into distinctive facies units whose lateral continuity is assumed according to geological knowledge. It is often considered that the Dogger aquifer is correctly represented with three productive layers, each corresponding to one of the geological units : Comblanchian, Oolitic, and Cyclical (Rojas.J. *et al.*, 1989; Lopez *et al.*, 2010). Yet, it has also been proved very efficient to divide the total productive thickness (net pay) into two identical layers with the same properties and an impervious inter-strata layer between them that accounts for the thermal capacitive effects (heat store) of all impervious layers (Antics *et al.*, 2005; Hamm *et al.*, 2011).

In the early 80s, modeling predictions of the thermal breakthrough that were made were rather pessimistic. The reason of this was that they were only considering the total productive thickness as one productive layer and were neglecting impervious interstrata. Figure 5 shows the difference between such an *old-fashioned* conceptual models and a three productive layer model with impervious confining layers. If the doublet's practical lifetime is defined on the assumption that a 3°C temperature drop is economically acceptable, simulation S1, which is the *old-fashioned* one*,* predicts a practical lifetime of 17 years, whereas simulation S3, the simulation with three productive layers yield a practical lifetime of 62 years.

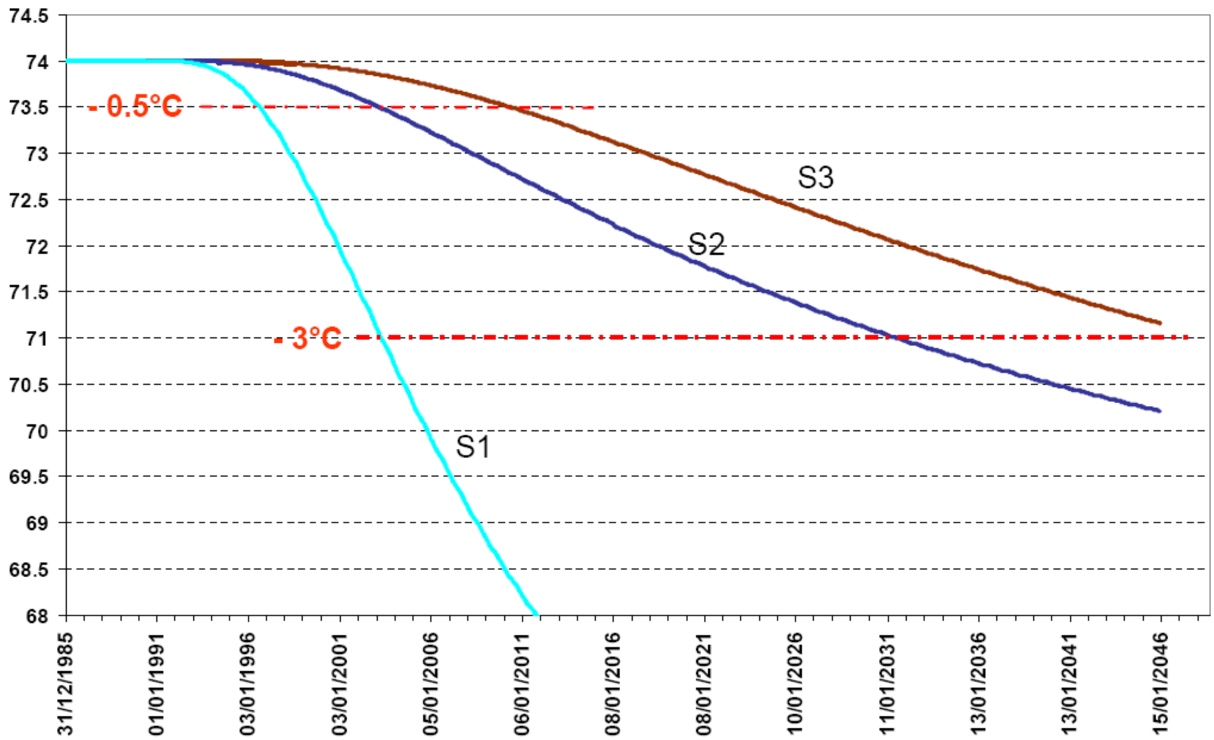


Figure 5: Production temperature decline at the production well of an isolated geothermal doublet for different conceptual model of the Dogger aquifer. (Lopez *et al.*, 2010)
S1 – one productive layer only, S2 – one productive layer and impervious but conductive confining layers, S3 – three productive layers and impervious but conductive confining layers and inter-strata. Initial reservoir temperature is 74°C.

To perform a sensitivity analysis of parameters influencing the thermal breakthrough, a reference case was defined for a geothermal doublet in the Dogger aquifer. Then several simulations were run varying these parameters inside realistic ranges. Parameters that were considered were the thicknesses of the impervious strata layer, the vertical structure of the reservoir (number of productive layers), difference in transmissivity of the productive layers, thermal properties rock (thermal conductivity, heat capacity, dispersivity), operating parameters (flow rate, injection temperature) and the distance between the production and the injection wells inside the reservoir. The histogram in figure 6 summarizes the results of the sensitivity analysis and shows the impact of the several parameters on the thermal breakthrough time and the amplitude of the temperature decline.

The most important parameters, controlling both the thermal breakthrough time (early recycling of cooled brine) and the amplitude of the thermal decline are: flow rate, injection temperatre, the distance between wells and the thickness of the impervious inter-strata (conductive heat store). Consequently, these parameters must be introduced into the simulation models as accurately as possible : any uncertainty on these input parameters will induce a significant uncertainty on the final results. Whereas the distance between wells can be estimated from the drilling reports with a reasonable degree of confidence, the correct reproduction of the history of exploitation flow rates and injection temperatures is much less guaranteed. Indeed, it depends greatly on the efficiency and correctness of the Dogger database and the careful and repeated recollection of all operational data which represents a large amount of data. Thus, in order to achieve a sustainable management of the aquifer geothermal resource, improving models needs a precise monitoring of geothermal operations and a rigorous and full storage of all corresponding data. This point is especially important because of the gradual nature of the temperature decline and the very small amplitude of the changes that are to be modeled, in comparison with background noises (figure 6).

Less influent parameters are the thermal properties of the rock, the distribution of transmissivities between productive layers and, to an even lesser extent, the vertical structure of the conceptual model. The impact of the vertical structure of the reservoir is indeed limited to the immediate vicinity of the injection well, where convective effects are predominant. Away from this zone of relatively high velocities, diffusion processes tend to homogenize the reservoir temperatures and smooth the temperature front corresponding to the cooled brine injection. Consequently, a two layers structure of the "sandwich" type is then largely enough to correctly predict the thermal behavior of the producing well.

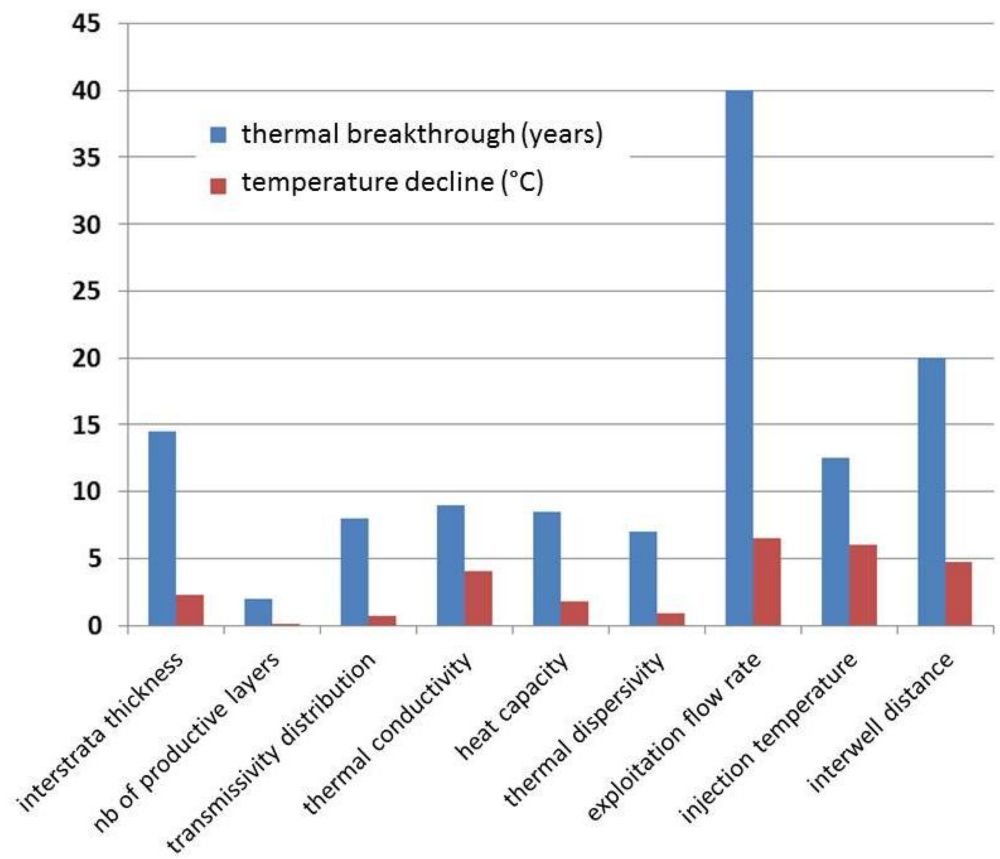


Figure 6 : Maximum impact on breakthrough time and production temperature decline for nine key parameters of numerical models. (Hamm *et al.*, 2011)

It is also worth noting that an inter-comparison study involving 5 French modeling teams coming from different organizations has been organized to benchmark their modeling tools and compare their modeling practices (figure 4 and Hamm *et al.*, 2011).

# New developments

## Rehabilitation of old operations

As the geothermal wells are getting older, and as many of them suffered corrosion and scaling related problems, the need for their rehabilitation is becoming more and more important. The most frequent rehabilitation scheme is the conversion of a doublet into a triplet by drilling a new well from the old doublet platform which becomes the producer and the two old wells that are used for injection. In terms of determining the new well location, each case is site specific and depends on neighboring installations, aquifer properties, well diameters, and the like. Nevertheless, several theoretical studies were performed on an isolated doublet to quantify the impact of the possible rehabilitation schemes on the practical lifetime of the operation.

Figure 7 shows the production temperatures corresponding to different rehabilitation schemes of a 30 years old isolated geothermal doublet. The "usual" triplet conversion is compared with the drilling of a brand new doublet from the old platform and a two steps operation consisting in first drilling a new production well to operate a triplet for ten years and then drilling another well to have a new doublet. According to simulation results, this second approach does not seem to be too prejudicial in terms of temperature decline and may be a way to spread drilling costs over two distinct periods.

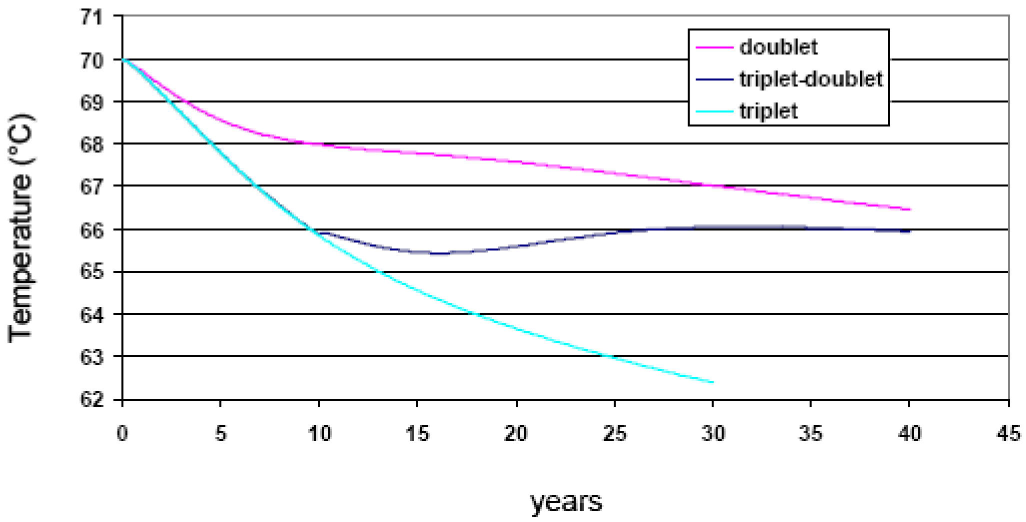


Figure 7 : Production temperatures corresponding to different rehabilitation schemes of a 30 years old isolated geothermal doublet. (Le Brun *et al.*, 2009; Le Brun *et al.*, 2011)
Initial reservoir temperature is 70°C.

## Targeting new resources

Below the Dogger aquifer, some Triassic sandstones units have good reservoir properties and may constitute attractive geothermal targets for district heating (cf. temperature map in figure 8). Unsuccessful attempts at their geothermal exploitation were made in the early 80s: these deep layers proved hotter but much less productive than the overlying Dogger aquifer. Moreover, for the only operation where they have been exploited until now, there were injection related problems with the injectivity index being lower than the productivity index: throughout the one year of operation, one third of the produced flow rate was not being reinjected into the reservoir but disposed into a neighboring river.

To avoid these critical reinjection problems, a possible option would be to produce the hot brines from the Triassic aquifers but inject the cooled brines into the Dogger aquifer. Nevertheless, this solution might trigger geochemical reactions that may impact negatively the properties of the Dogger aquifer, notably its porosity (Castillo *et al.*, 2011).

An alternative option to develop the geothermal potential of these deep aquifers is to resort to more sophisticated, but still rather expensive, well architectures. Indeed, simulation works show that in these clastic environments, horizontal wells are particularly well adapted with higher injectivity or productivity index and a more gradual temperature decline at the production well. Moreover, when drilling horizontal wells perpendicular to the high conductive paths, the production fluid temperature may still not be affected by the cold injection after 30 years of geothermal exploitation (Hamm and Lopez, 2012). If these modeling results are confirmed at a production stage, it would be a promising breakthrough for further developments in geothermal well design.

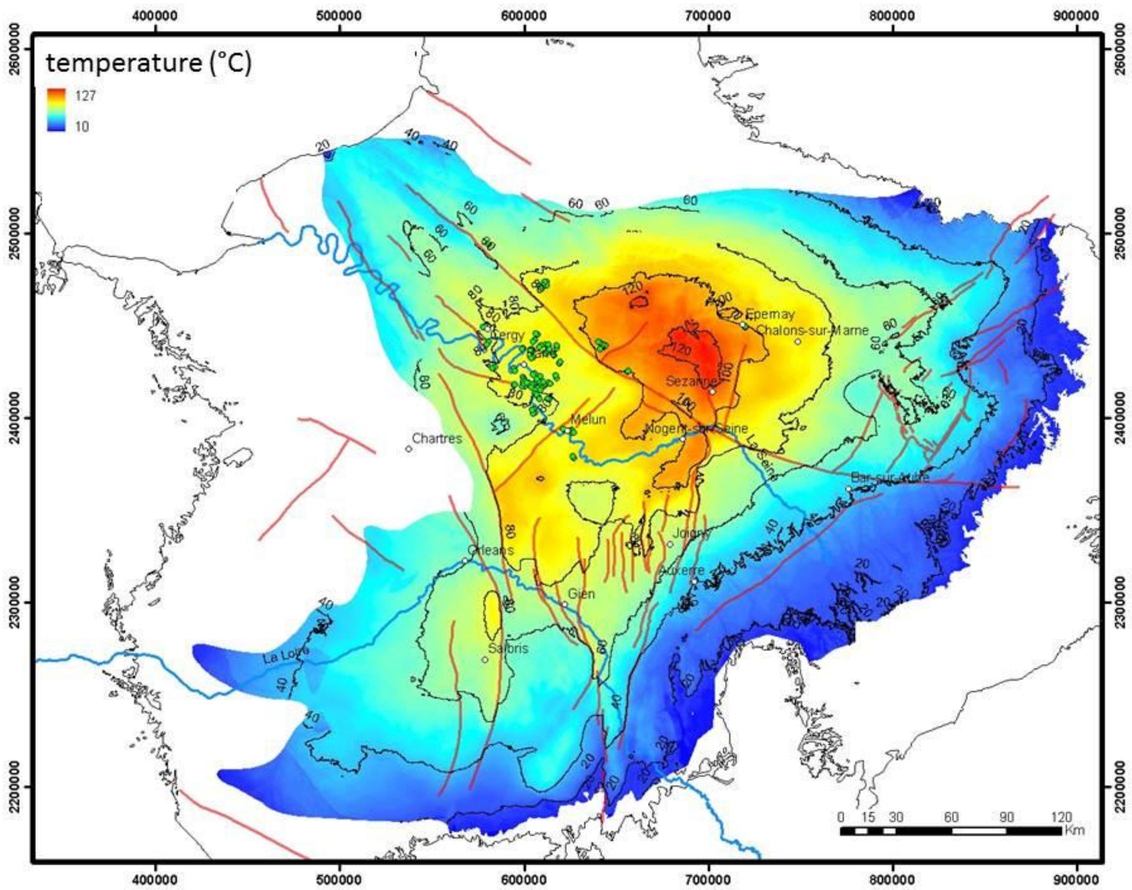


Figure 8: Estimation of the temperature at the top of the Donnemarie sandstones
Donnemarie sandstones are the deepest aquifer units of the Triassic series of the Paris basin (Bouchot *et al.*, 2008)

## Deep Aquifer Heat Storage

Demand for heat is characterized by considerable fluctuations over time. Although there are short period variations in demand (mornings, weekends, etc.), variations in the weather in temperate zones impose a highly seasonal pattern. The thermal power requirement in winter is therefore an order of magnitude greater than in summer, which mainly consists in the household demand for hot water. This pattern of temporal variation requires a heat production capacity that is far greater than the average annual power requirement.

Since most of the energy sources used to meet the seasonal peaks are of fossil origin, they make a significant contribution to $CO_2$ emissions. In addition, some of the energy inevitably produced by various processes may not be needed in the summer and, if it is not collected, will be wasted. In this context, current industrial processes such as incineration of waste and also possible future major solar thermal or thermodynamic systems come to mind. The storage of thermal energy overcomes the temporal mismatch between production and consumption, thereby making it possible to reduce the baseload power capacity and the use of more polluting sources. The economic and environmental advantages of storage will depend on the cost of the storage system and the nature and price of the energy stored relative to the savings provided when the energy is retrieved. The aim therefore is to store “decarbonized” energy that is in excess or has low environmental impact when it is available in the summer and to retrieve it in the winter, so as to avoid use of fossil energies.

In the very long term, seasonal storage of waste heat in the Dogger aquifer could become a way to smooth energy demand during winter peak production periods, and possibly restore the initial aquifer temperatures. Storage in aquifers is especially suited to urban environments as it uses a minimum of surface area. For open loop storage in deep aquifers, the high cost of the drilling required to reach the targeted geological levels makes this solution incompatible with single-occupancy dwellings. Conversely, it is particularly appropriate to district heating systems and provides a geothermal solution that is complementary to conventional heat-mining systems.

This is so because, given their centralized production, heating networks make it possible to envisage large scale and high power storage during periods of low demand. They also allow better control of polluting emissions and development of use of renewable sources and/or waste energy that are difficult to access or to use: deep geothermal energy and also biomass or waste incineration. Seasonal storage of this energy in aquifers makes it possible to increase the annual amount of energy supplied to networks from renewable sources, with a corresponding reduction in wintertime recourse to fossil fuels.

Experience gained from the geothermal exploitation of the Paris Basin suggests the key issues regarding seasonal Aquifer Thermal Energy Storage in the Dogger aquifer are likely to be the high temperature of the stored brine and the cyclical reversal of injection and production wells.

The high temperature of the injected brine, hotter than the aquifer natural state, may produce undesirable chemical reactions. According to preliminary geochemical modeling Dogger brines should not be heated above 105°C to avoid scaling related problems and formation damage (Castillo and Azaroual, 2010).

Concerning the reversal of the production/ injection cycles, no long-term experience is available for the Dogger aquifer, but lessons from the recent deep Neubrandenburg aquifer thermal energy storage project illustrate that final heat consumption and the return temperature in the heating network (i.e., surface installations) are of greater concern than fluctuations that might be related to the deep reservoir (Kabus *et al.*, 2009; Réveillère *et al.*, submitted).

Finally, an interesting point is that selecting a storage temperature so that the initial reservoir temperature is the arithmetic average of the cold injection temperature and the hot storage temperature will make that the energy coming from conventional heat mining will exactly compensate the heat losses due to the injection of hot brines into a warm aquifer (figure 9). Thus, depending on the number and type of wells, several technological configurations may be imagined that are combinations of use of conventional geothermal technology and heat storage.

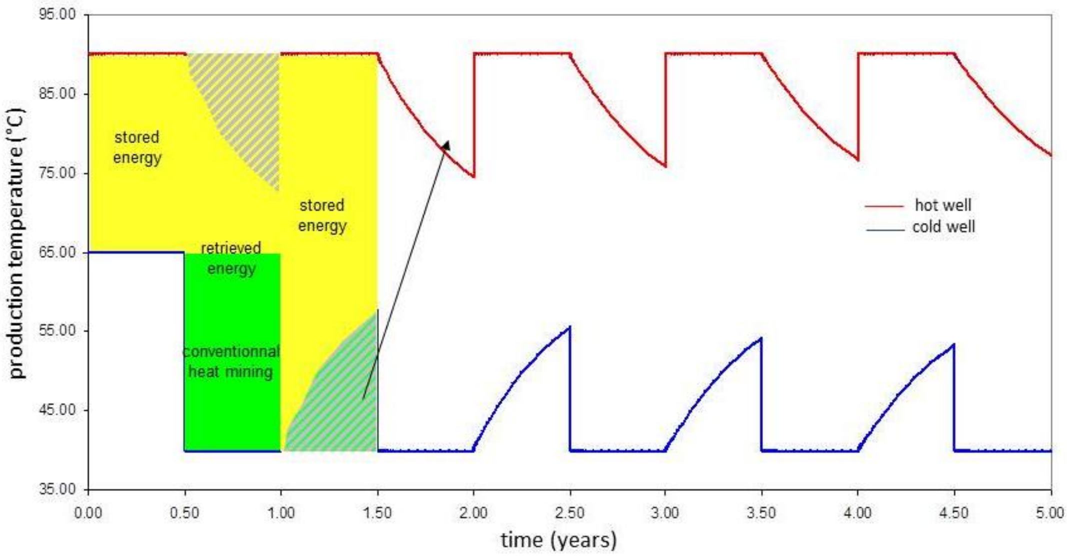


**Figure 9: Stored and retrieved energy during seasonal cycles**
**Initial reservoir temperature is 65°C, heat is stored at 90°C during the summer and cooled brines are injected at 40°C during the winter.**

## Acknowledgments

All the works concerning the conventional geothermal exploitation of the Paris basin aquifers are co-funded by BRGM and the French Environment and Energy Management Agency (ADEME). The works regarding the possibilities for deep aquifer heat storage in the Dogger aquifer has been co-funded by the ANR Stock-E program and the partners of the Geostocal project (CFG Services, CPCU, EIVP, IFPEN, Mines Paristech, Paris-Est Marne la Vallée University).

The first author would also like to acknowledge travel support to the SIMS Conference provided by the International Energy Agency's Geothermal Implementing Agreement (IEA-GIA).

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