A Reservoir Engineering Approach of Low Enthalpy Geothermal Heat Reclamation

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ABSTRACT

By convention, low to medium enthalpy geothermal resources, eligible to geoheat and cold and combined heat and power production, are classified according to depth. Shallow geothermal sources supply heat and/or cold via surface heat pumps and either borehole heat exchanger or groundwater doublet systems. Deep seated geothermal deposits address larger, preferably dependable, sedimentary reservoir environments and higher heat loads provided by district and greenhouse heating uses.

Development forecasts in Europe for geoheat and cold production stand in year 2030 at 260 GW_t (installed capacities) and 380 TWh_t (yearly production), achieving a 5 to 3 growth ratio from now on. For Europe alone (EU 28), 1.80 GW_t and 260 TWh_t/yr are projected, implying dramatic, eight and five fold, growth ratios respectively, indeed a challenging objective.

This problem is analysed in the light of the European resource environments, available knowhow/best practice and foreseeable technological improvements, from a reservoir engineering standpoint.

In so doing the present paper focuses on the deep geothermal segment which displays distinctive reservoir settings and farming technologies, bearing in mind they often share common resource management and environmental concerns with shallow geothermal practice.

Accordingly, the most rewarding contributions in the areas of well architecture, water injection, geomodelling, advanced heat pump technology, combined heat and cold production and storage, reservoir longevity are reviewed and their implications on sustainable reservoir management strategies discussed.

Introduction

By convention, and also structurally, low to medium enthalpy geothermal resources are classified depth wise according to the systems and processes schematised in Fig.1.

Shallow sources (depths < 400 m) are the more diversified with respect to (i) designs - borehole heat exchangers (BHE)/ ground source heat pumps (GSHP), non reversible, mono-functional (either production or injection) and reversible bi-functional (production and injection) ground water wells doublets, (ii) uses - heating or/and cooling, aquifer thermal energy storage (ATES), and (iii) market (domestic individual homes, collective residential or business buildings). Although limited in loads (5 to 1 000 kW_t), they represent the largest geothermal market share - over 80% installed capacities (EU 27) as of year 2010. As far as GSHPs are concerned, it is the largest resource base exploitable anywhere on the mainland provided it is inhabited and enjoys a nearby power source.

By contrast, deep seated (1 000 - 4 000 m) geothermal sources address larger loads (3 to 15 MW_t) but their heat extraction for geothermal district heating (GDH), cooling (GDC), heating/ cooling (GDHC) and greenhouse heating (GGH) uses are restricted to those areas where a dependable hot water reservoir and a large heat market (10 000 to 50 000 MWh_t/yr) are geographically matched. Wherever the geothermal resource meets the adequate enthalpy threshold (temperature in excess of 90-100°C), combined heat and power (CHP) systems, based on Organic Rankine Cycle (ORC) conversion technology, can be contemplated.

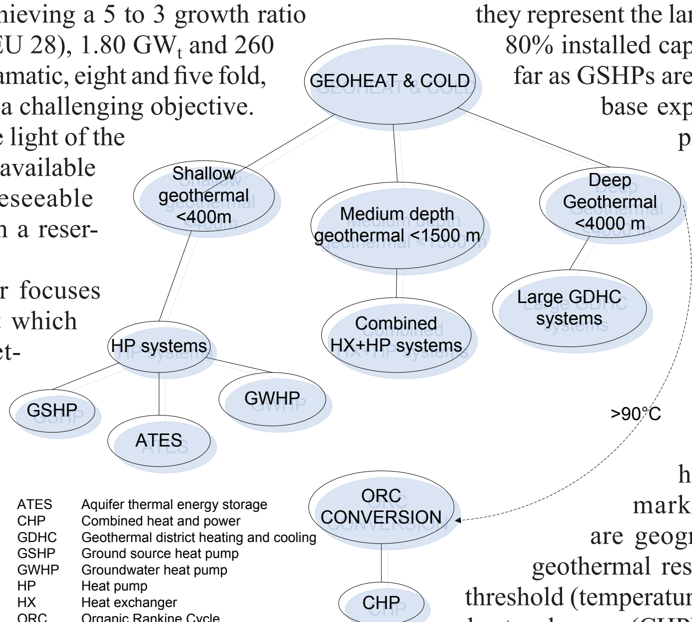


Figure 1. Geoheat and cold spectrum.

Whether or not the waste heat can be regarded as a geopower by product depends on the revenues generated by (most often feed in tariff - FIT - supported) power sales *vis-à-vis* heat sales. The Molasse Basin of Southern Germany (Münich area) is a typical example of a vast CHP, GDH shared development. Here, the abundant, if not prolific, resource would have never been reclaimed without FIT support.

Medium depth, tiepid water aquifers represent a compromise between shallow GWHP and deep GDH systems. Their commercial exploitation requires the addition to direct heat exchange of a heat pump (HP) boosting module, compensating, the low thermal level of the resource.

Geothermal development is at a sensitive crossroads, a problem echoed by ambitious geoheat and cold development objectives. According to authorized corporate sources (IGA, EGEC), installed capacities and yearly heat (cold) productions should amount in year 2030 to 260 (worldwide)/180 (EU 28) MW_t and 380 (worldwide)/260 (EU 28) TWh_t respectively. Such target figures correspond in Europe alone (EU 28), to an eight (installed capacities) to five (yearly production) fold growth ratio from now on, indeed a challenging enterprise.

Although shallow sources are expected to play a leading role in bridging the gap, much is anticipated from deep geothermal accomplishments, the focus of this paper.

The latter will be analysed in the light of the European resource environments, available know how/best practice and foreseeable technological improvements in a reservoir engineering perspective.

Accordingly, following an introductory outlook, the most rewarding contributions in the areas of well architecture, water injection, geomodelling, advanced heat pump technology, combined heat and cold production and storage, reservoir longevity are reviewed and their implications on sustainable reservoir management issues discussed *in fine*.

Outlook

Resource Environments

Europe at large(i.e. continental, Iceland and Turkey) exhibits a variety of geothermal resource settings displayed in Fig. 2 sketch map, which relates to distinct geodynamic environments and uses.

Large Sedimentary Units Subdivided Into:

– Intracratonic basins (Paris-Hampshire, Aquitaine, Tajo, Castillan, Rhone-Langedoc, West Yorkshire-Netherland, North German, Danish, Warsaw, Thracean)

– Orogenic belt foredeeps (Pyrenean, Ebro, Caltanisetta, North Alpine, Po Valley, Apenninic, Carpathian)

– Marginal/back arc basins (Pannonian, Transylvanian, Aegean)

These generally multiple, aquifer systems with normal, low and high geothermal gradients respectively, favouring direct uses, among which geothermal district and greenhouse heating holds a prevailing share.

- ***Tertiary-quaternary continental rifts*** (Rhine Graben, Limagne, Rhone - Bresse, Campidano, Pantelleria) eligible to medium enthalpy/CHP prospects and, ultimately, to EGS developments. (two EGS plants operating already at Soultz, FR and Landau, DE).
- ***Orogenic fold-belts and foreland platforms,*** often associated with deep faults and upwelling thermal circulations thus favouring medium enthalpy reservoirs, providing sound design data for closed and open systems.
- ***Crystalline massifs*** (Iberic Meseta, Armorican, Central France, Bohemian, Rhodope) with hot springs and hydrothermal fault systems.
- ***Recent "in plate" Pliocene/Quaternary volcanism*** (Catalunya, Chaine des Puys, Eifel, Campidano, Susaki), regarded as candidates for medium enthalpy, if not EGS, projects.
- ***Active subduction zones, volcanic island arcs, active magmatic and recent or active extensional horst and graben settings***, hosting high-enthalpy volcano-tectonic structures eligible to power production from either dry steam (Central Tuscany) or liquid dominated (Iceland, Western Anatolia) sources.

From the low/medium enthalpy stand points the scope of this paper is focused on the sedimentary basins and orogenic belt foredeeps, definitely the best candidates to direct use and combined heat and power applications.

The ground source heat pump technology does not require any particular prerequisite other than (preferably inhabited) land and power source accessibility.

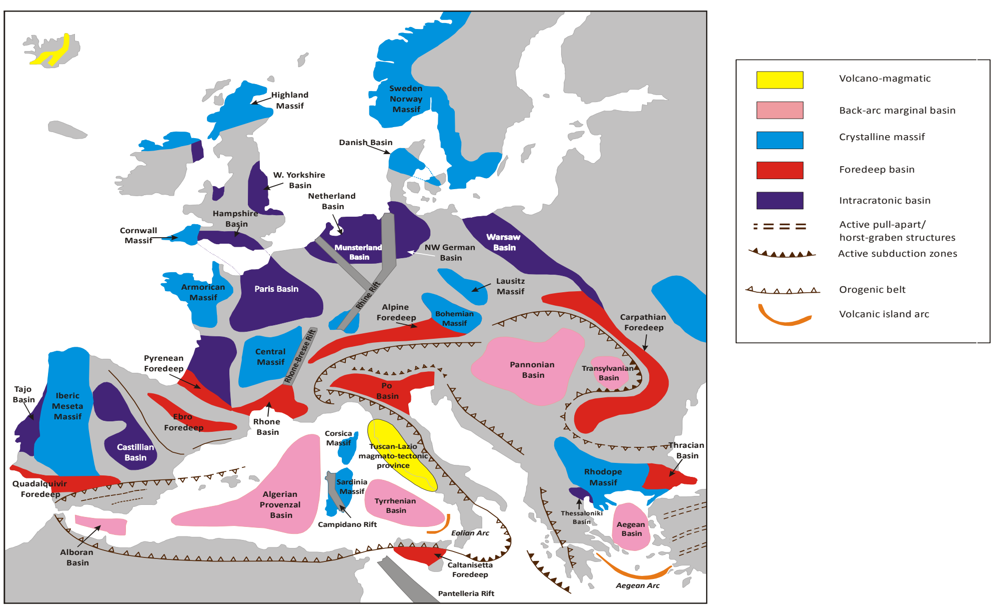


Figure 2. European geodynamic environments (after C. Sommaruga & P. Ungemach).

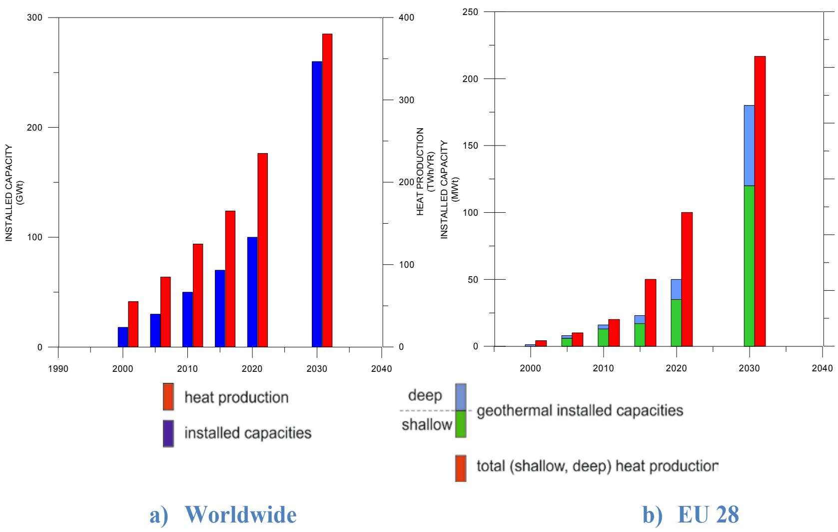


Figure 3. Geoheat development. Past and projected status (Ungemach, personal comm).

Status

As of late 2012 the capacities of geoheat and cold installed worldwide amounted to ca 60 GW_t and yearly production to 150 TWh_t. In the European Union (EU 28) figures stand at ca 20 GW_t and 40 TWh_t respectively. Fig. 3 (Ungemach personal comm) reflects the dominant share (15 GW_t) held by shallow (< 400 m) geothermal sources *vis-à-vis* their deep (< 4 000 m) counterpart, a contrast which highlights the fast growth rates noticed in the past years with respect to ground source (GSHP) and groundwater heat pump systems. This trend is however diminishing as a result of fast developing geothermal district heating (GDH) and, more recently, greenhouse heating (GGH) grids.

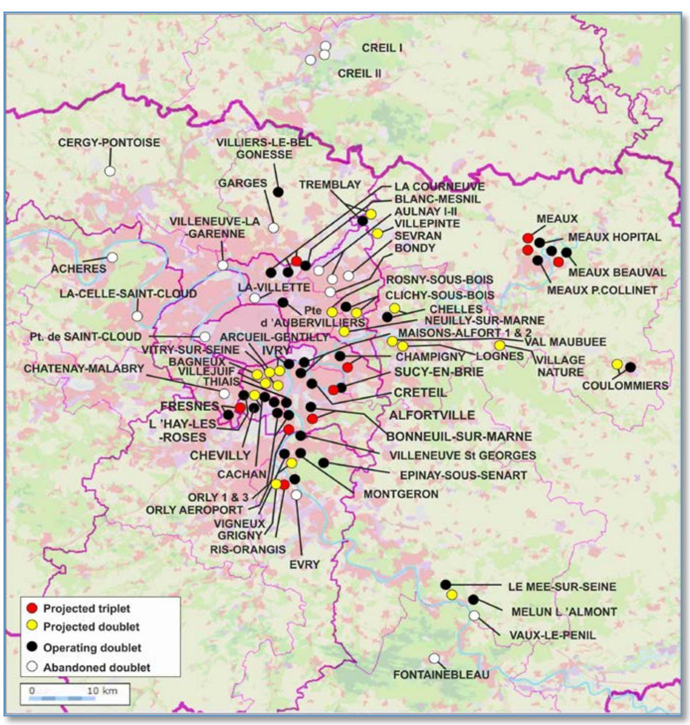


Figure 4. Paris Basin GDH status (@ Jan. 2014).

As far as the latter systems are concerned the major development areas take place in the Paris, Molasse, The Netherlands and the Pannonian basins.

The doublet concept of heat farming, combining a production well and an injection well pumping back the heat depleted brine into the source reservoir, was first pioneered in the Paris Basin in the early 1970s. It was later extensively duplicated in the aftermath of the oil shocks to reach 52 completed doublets in the mid 1980s of which 34 remained online in 2010 (Fig. 4).

Here an attractive heat resource to demand adequacy - a dependable carbonate reservoir (55 to 85°C and 10 to 60 Darcy meter formation temperatures and transmissivities) of regional extent (# 10 000 km²) matching a huge heating market (Paris suburban areas) was counterbalanced by a thermochemically (corrosion/scaling) sensitive formation fluid, a slightly acid hot brine including a CO_2/H_2S enriched solution gas phase. This created, among other shortcomings relating to the infantile diseases inherent to any new energy route, a somewhat chaotic and long lasting learning curve until the process be thoroughly mastered.

During the past decade the Molasse basin of Southern Germany became a priority development objective with sixteen GDH and CHP doublets completed so far, four commissioned in the very near future mapped in Fig. 5 and ca fifteen or so later projected.

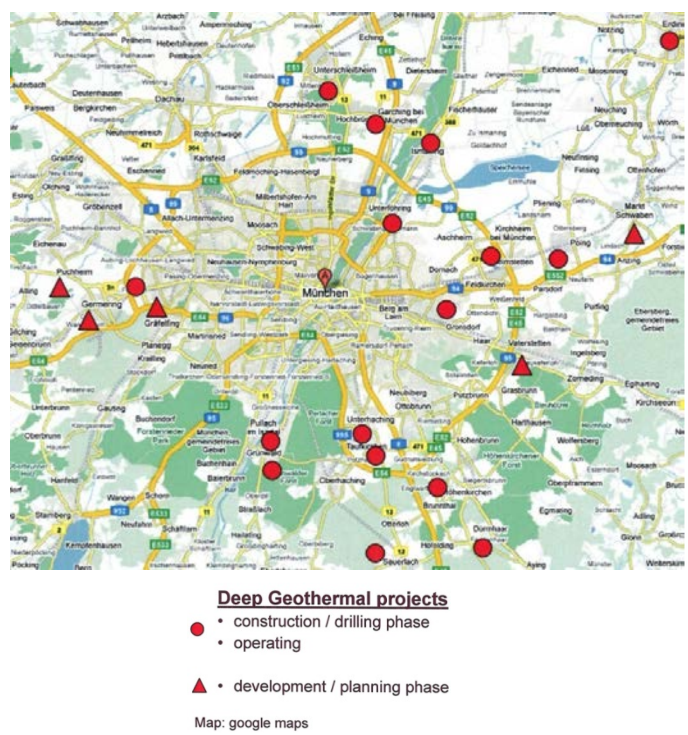


Figure 5 . Deep geothermal projects. Molasse Basin (source: Erdwerk).

Fracturing (natural !) is the dominant porosity/permeability mechanism governed by karstification and dolomitization of the Malm carbonate reservoir, whose tectonics are illustrated in the

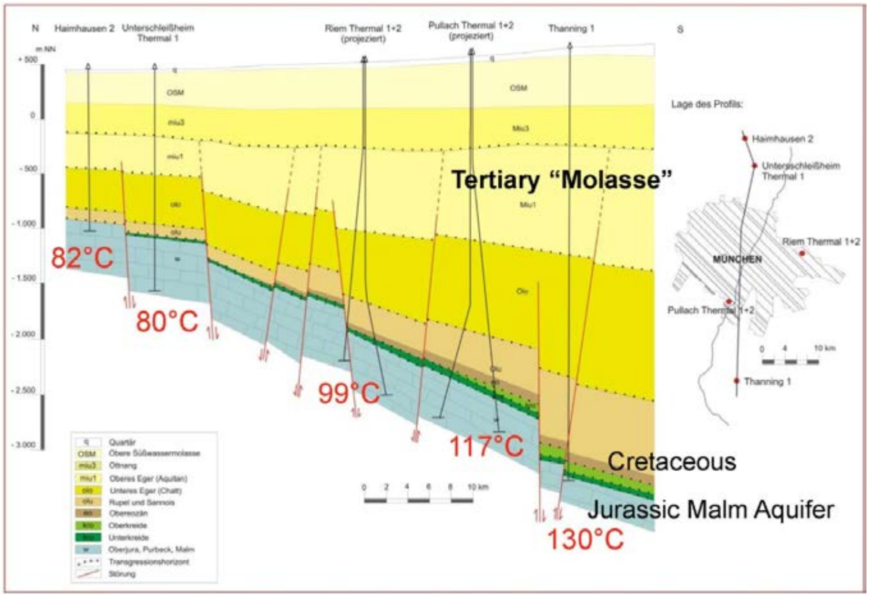


Figure 6. Geological cross section Munich Area N-S. (source: Erdwerk).

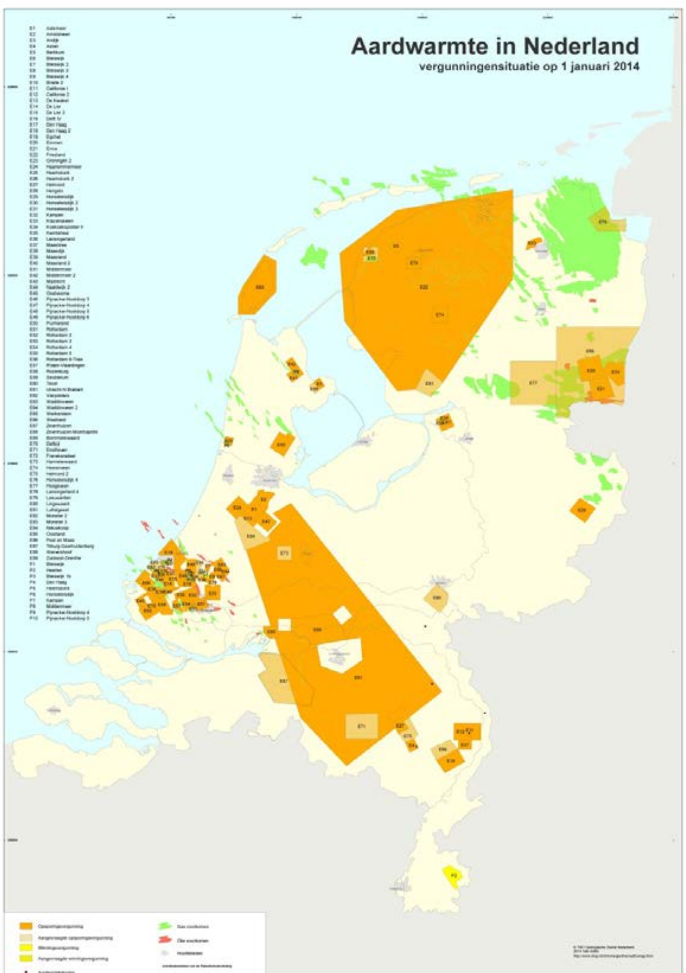


Figure 7. The Netherlands geothermal district and greenhouse heating locations and concession map as of 1 January 2014 (source: Van Heekeren, TNO).

en echelon dipping trend depicted in Fig. 6 cross section. Noteworthy is the feed in tariff (FIT) policy promoted by the state in favour of geothermal electricity and (at a lesser extent) heat which was decisive in initiating and consolidating this daring (and costly) development stream.

Most of the Dutch territory holds an important geothermal potential (Lokhorst & Wong, 2007) hosted by Permo-Triasic (Rotliegend, Buntsandstein) and Lower Cretaceous sand and sandstone clastics at 2 000 to 3 000 m depths. In 2006, greenhouse farmers completed the first deep seated space heating doublet in Bleijwijk, initiating a trend illustrated by the hundred or so concessions, mapped in Fig. 7, awarded by the Ministry of Economic Affairs. Since then 12 GDH doublets have been completed (see Fig. 7) and at least 50 more should be scheduled in the next decade to meet the 800 MWt target set by the State (Van Heckeren, 2013). The Netherlands are a known petroleum province, extensively drilled for hydrocarbon exploration and production purposes, easing the implementation of a data base (NLOG), managed by TNO, for the benefits of geothermal developers.

A similar situation exists in the Great Hungarian Plain (*Pusta*). Here, farmers have recovered abandoned dry oil and gas exploration wells for GGH uses. They were further followed by GDH projects applying, contrary to their predecessors, the doublet mining scheme, which had been previously discarded or delayed by fears addressing injectivity damage in sensitive Pannonian clastics and also for economic reasons.

Targets

According to authorized sources [IGA (2010) and EGEC (2012)], worldwide and European (EU 28) projections shown in Fig. 3 foresee Geoheat and Cold installed capacities and yearly productions targeted at 260/180 GW_t and 380/260 TWh_t respectively in year 2030.

These definitely ambitious goals could be regarded as optimistic. Instead they are deemed reasonably conservative given that (i) the growth trends are backed by a twelve year (2000-2012) record, and (ii) they do not account for a significant CHP input from EGS (Enhanced Geothermal Systems) plants.

It should be noted that, complementary to IGA worldwide forecasts, EU 28 installed capacities distinguish contributions from shallow and deep seated geothermal sources. Figure 3b clearly highlights the greater input from shallow geothermal. Close to four in year 2010, the (shallow to deep) ratio is expected to drop to two in 2030, meaning that deep geothermal, mainly GDHC and GGH, is progressively bridging the gap.

Summing up and provided the technical and non technical barriers constraining its development that can be overcome, the previous objectives are accessible via existing and maturing technologies.

Technological Barriers

Based on knowledge acquired from experience, technological transfer and research, the following headings, likely to constrain Geoheat reclamation, need to be addressed.

(i) risk assessment and mitigation at both exploration (mining risk) and utilization (exploitation) hazards levels;
(ii) reservoir assessment;
(iii) life cycle analysis; and
(iv) sustainable resource/reservoir management.

Technological Requirements

Risk Analysis

According to Battini and Van Wees (2010) project economic performance may be appraised through its net present value (NPV) written as follows:

$$NPV= (POS \times NPV_0) - (I - POS) \times AC \quad [1]$$

POS = probability of success
NPV0= NPV of a successful project outcome [2]

AC = abandonment cost in case of project failure

This methodology, calling on value chain integration models and Monte Carlo sampling useful in overall planning and project ranking, is less rewarding if not academic when contemplating individual projects. Hence, an alternative, more pragmatic, approach has been sug 1gested by Ungemach and Antics (2012) and Antics and Ungemach (2010). It is summarized hereunder:

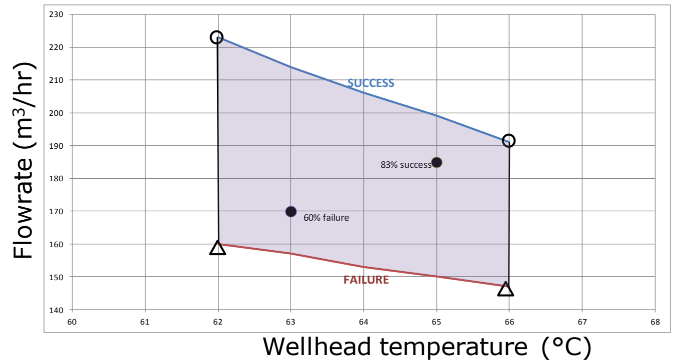
$$POS= (POS)_{ex} \times (POS)_{pro} \quad [3]$$

Where:

$(POS)_{ex}$ = exploration POS
$=(POS)_{tec} \times (POS)_{temp} \times (POS)_{flow}$
$(POS)_{pro}$= exploitation POS
$(POS)_{tec}$= technical POS [4]

$(POS)_{temp}$= bottomhole temperature POS
$(POS)_{flow}$= well deliverability POS

The technical POS depends essentially on the drilling force (equipment specification and crew/supervision skills). The resource/reservoir POSs depend on subsurface temperature patterns and reservoir performance. They can be quantified by the area of the flow (Q) vs. temperature (T) diagramme, bound vertically by two hyperbols $QT = (QT)_{max}$ and $(QT)_{min}$ and laterally by $T = T_{min}$ and T_{max} limits, an exercise illustrated in Fig. 8. They obviously relate to a target NPV (and internal rate of return, IROR) criterion in designing risk guarantee policies. Temperature predictions are generally accurate thanks to heat flow mapping and 3D subsurface temperature modelling. The main unkown refers to flowrate estimates and reservoir performance, which depend on porosity/permeability (matrix vs fractured) typologies, best assessed through 2D and (preferably) 3D seismic (re)processing and structural geomodelling, thus reducing uncertainties to acceptable levels. Such was the strategy implemented while exploring the Malm reservoir in the Molasse Basin (Schubert et al. ERDWERK, 2008). Alongside a heavy duty rig force, easing borehole side tracking, it proved successful in intersecting deep buried karstic conduits as advocated by Schubert et al. 2006, and Erdwerk (2012) in a comprehensive review paper.



Numerical application:

CAPEX=12 10^6 € | r=10% (total success)
OPEX= 5 10^5 € | Full equity (no debt)
n=20 years | Subsidies=0 ; 25% CAPEX
nh=8256 hr/yr | c=35 ; 40 ; 45 €/MWht
r=5% (total failure) | T_i=40 ; 45 ; 50°C

Figure 8. GDH risk assessment. Success/failure criteria.

Worth mentioning are also the data bases made available in the Netherlands (Thermogys, NLOG), Germany (Geotis), France (Infoterre) and Central Europe (Transenergy) which contribute to mitigating geological uncertainties.

Exploitation POS_{pro} addresses chiefly well injectivity and fluid thermochemistry induced shortcomings which are later discussed.

Last but not least, a reporting code similar to those set up in Australia and Canada (Lawless et al. 2010) would help in normalising the reporting of exploration results and resource estimates for the benefit of geothermal developers and investors.

Heat Extraction

Optimising geoheat exploitation addresses, among other requirements, adequate well architecture, reliable injection design, efficient corrosion/scaling abatement and heat pump integration to deep GDH/GGH systems.

Well Architecture

Candidate well trajectories, (i) vertical, (ii) deviated (conventional design), (iii) horizontal legs draining one or several layers (multilaterals), and (iv) sub-horizontal drains intersecting the whole pay interval (innovative design) respectively are depicted in Fig. 9.

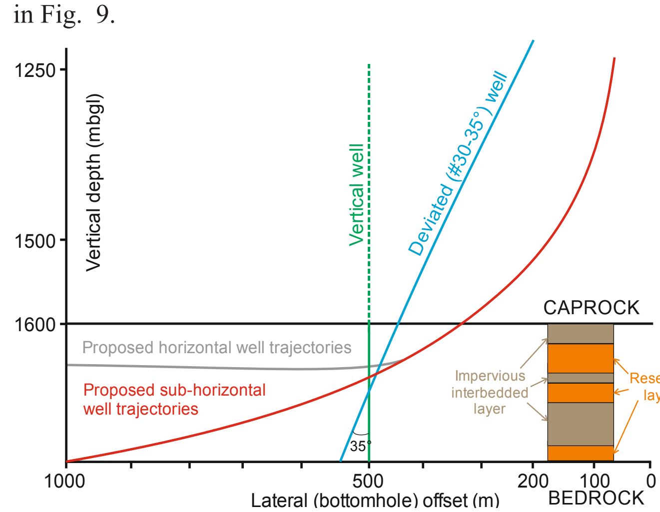


Figure 9. Candidate Well Trajectories.

Horizontal drilling is nowadays a routine practice in oil and gas well completions. It became soon popular in the geothermal industry given the dramatic productivity gains achieved, especially in low permeability, slim pay zones and fractured reservoir settings. Actually, assuming a homogeneous and isotropic reservoir, steady state and axisymmetrical radial flow, Joshi (1991) reports productivity improvement factors ranging from three to five in comparison to a vertical well.

The sub-horizontal well design, crossing the entire pay interval of a stratified multilayered geothermal reservoir, shapes quite attractive compared to conventional vertical well architectures.

Here, the productivity could be increased by a factor two as exemplified hereunder.

Dupuit equation for a horizontal wellbore (Joshi, 1991):

$$q_h = \frac{Ckh\Delta p}{\mu_0 log\left(\frac{4r_d h}{L}\right)} \qquad L>>h \qquad \textbf{[5]}$$

Where:

k = permeability (Darcy)
h = layer thickness (m)
L = drain length (m) [6]
r_d = drainage area radius (m)
Δp = pressure (bar)
q_h = flowrate (m^3/hr)
μ_0 = fluid dynamic viscosity (cp)
C = a system unit dependant constant

Similarly, the Dupuit equation for a vertical well may be written:

$$q_v = \frac{Ckh\Delta p}{\mu_0 log\left(\frac{R_0}{R_w}\right)} \qquad [7]$$

With:

q_v = flowrate (m^3/hr) [8]
R_0 = influence radius(i.e. where $\Delta p = 0$) (m)
R_w = vertical well radius (m)

Hence:

$$\frac{q_h}{q_v} = \frac{\log\left(\frac{R_w}{R_0}\right)}{\log\left(4r_d\frac{h}{L}\right)} \qquad [9]$$

Numerical application:

H = 20 m
L = 1 000 m
R_0 = 1 000 m
r_w = 0.1 m
r_d = 500 m
$\frac{qh}{qv}$ = 2.5

Practically one should regard a twofold improvement a realistic figure.

Promis et al. (2011) have investigated the impacts on cooling kinetics and pressure drawdown transients of various multilateral and (sub)horizontal drainage paths on a two layered sandwich structure (Antics et al. 2005) totalizing a 200 m3/h withdrawal rate. The results are listed next.

Well Architecture	Thermal Breakthrough Time (years) (*)	Pressure Drawdown @ 70 years (*) (**) (bar)
Two multilaterals, 1 000 m long, well	45.5	0.15
One (sub)horizontal drain, 500 long, well	29	0.45
One (sub)horizontal drain, 1 000 m long, well	42.5	0.30

(*) 1°C thermal depletion (**) not accounting for skin and well losses

show that the benefits, on both thermal breakthrough and pressure transients responses, are manifest as one would have inferred intuitively from four (two productive, two injective) multilateral drains. Still, the 1 000 m long (sub) horizontal paths remain competitive compared to their vertical and inclined well replicae.

The well profile described in Fig. 10 has been designed (GPC IP, 2012) to accommodate a 400 m^3/h productive (injective) capacity i.e. a 1.6 increase *vis-à-vis* the performance (250 m^3/h) of conventional well architectures.

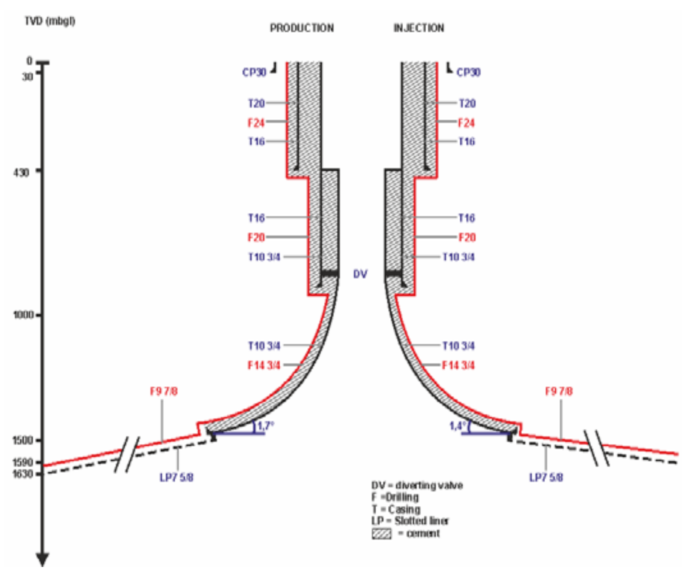


Figure 10. GDH doublet (sub) horizontal well profiles.

Another advantage expected from this design is the limitation of the number of doublets required to meet the production objective, an exercise (Promis et al. 2012) summarised in Fig. 11. Here, one (sub) horizontal doublet, rated 400 m^3/h, substitutes for two, each 200 m^3/h rated, conventional doublets completions. Not only does it secure significant cost savings, it also avoids undue premature cooling breakthroughs and incidentally favours heating grid interconnection.

Water Injection

Water injection may become a sensitive matter, severely reducing GDH performance in thermochemically exposed and fine grained structured fluid and reservoir settings.

Fluid thermochemistry addresses the impacts of (native vs imported) fluid compatibilities and cooling kinetics on the solubilities of selected mineral species. Both have been investigated by various authors (Castillo et al. 2011; Borozdina et al. 2011 and 2013) though rock-water interaction and reactive solute transport modelling applied to carbonate and clastic reservoirs.

They showed, for either single well or doublet configurations, that scaling (over saturation, precipitation)/solubilisation (undersaturation, dissolution) of sensitive - calcite, silica, silicates, anhydrite, among other - mineral species were limited for the low (10-20°) allocated (re)injection temperatures. However, the limitations of these geochemical models lie essentially on the adopted (matrix) porosity typology which may occasionally prove somewhat misleading while tackling fractured reservoir environments.

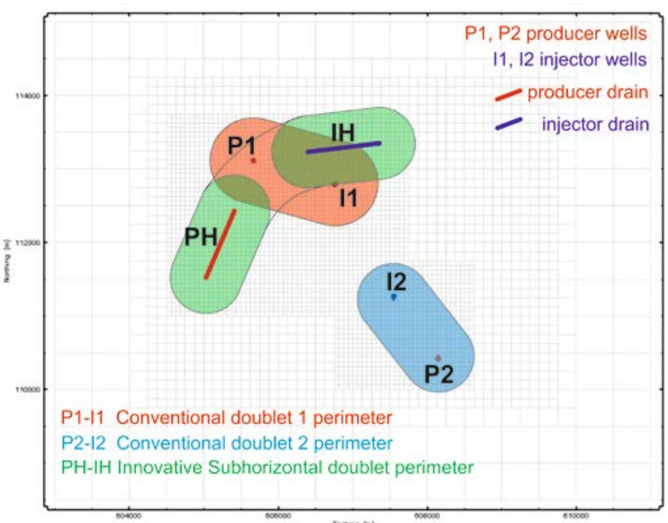


Figure 11. Conventional (deviated) vs innovative (subhorizontal drains) doublet well locations (reservoir impacts).

Well damage caused by entrainment and injection of suspended solids in fine grained sedimentary reservoirs, alongside remedial procedures, reviewed by Ungemach (2003), emphasize the paramount importance of preventive particle filtering and well completions, an example of which is displayed in Fig. 12.

In these respects guidelines may be sought from the prototype system implemented in Copenhagen, described by Malher et al (2010), featured hereunder:

Reservoir	=	Bunter sandstone
Transmissivity	=	6 darcy meter
Depth	=	2 600/2 700 mbgl
Salinity	=	190 g/l
Bottomhole temperature	=	73°C
Bubble point	=	20 bar
Minimum rejection (absorption HP sustained)	=	17°C
Completion	=	slotted liner
Nominal flowrate	=	235 m^3/h
Injection pressure	=	70 bar

Filtering facilities
- Upstream heat exchanger(s)
  - Prefiltering (30 μm) self cleaining unit
  - Filtering (2 μm) filter bags
- Downstream heat exchanger(s)
  - Cartridge (1 μm) filters

This was indeed, a geothermal sand control success story.

Corrosion/Scaling/Toxic Gas Abatement

Corrosion damage of Paris Basin geothermal wells, undergone by operators during the early years, endangered GDH exploitation to the stage its abandonment was once seriously considered.

Corrosion originates from a thermochemically hostile CO_2/H_2S aqueous system, interacting with the casing metal lattice, generating iron sulphide crystal species and dramatic exploitation losses, leading ultimately to wall piercing.

Implementation of downhole chemical inhibition lines injecting, at the source of the damaging mechanism, chemical inhibitors (hydrophobic filming agents of the fatty amin family), proved efficient in defeating the corrosion process thus securing the target production objective (Ungemach, 2001). Whenever wellhead production pressures fall below bubble point, the separated gas phase needs to be either (re)injected in the source reservoir through a Venturi type device or, better, burned in a hidden flare incinerating vessel.

Heat Pump Integration

The scope of conventional GDH applications should be widened to retrofit high temperature heaters and accommodate district cooling needs by using performant, centrifugally driven compressor, heat pumps and low inlet temperature water absorption chillers.

PROJECTED WELL / RESERVOIR PERFORMANCE

Top reservoir depth	1,500 m
Static WHP	-5 bars
Total pay	400 m
Net pay (h)	110 m
Effective porosity (Ø)	0.2
Permeability (k)	100 mD
Transmissivity (kh)	11,000 mDm
Skin factor (S)	-2
Formation temperature	90ºC
Average injection temperature	35ºC
Fluid (eq. NaCl) salinity	2.5 g/l
Fluid dynamic viscosity (production) (μp)	0.32 cp
Fluid dynamic viscosity (injection) (μi)	0.73 cp
Total compressibility factor (c_t)	10^{-4} $bars^{-1}$
Fluid density (ρp) at 90ºC	965.34 kg/m^3
Fluid density (ρi) at 35ºC	994.06 kg/m^3
Target injection rate (Q)	150 m^3/hr
WHP (150 m^3/hr, 35ºC)	20.5 bars
Sandface velocity (v_{sf})	0.23 cm/s
Velocity at completion outlet (v_{co})	0.61 cm/s

Figure 12. Injection well design in a sandstone environment.

For instance, shallow cold/tepid (14 to 25 °C) aquifers can be harnessed for district heating and cooling purposes as exemplified by the Milano Canavese project (Piemonte, 2008), which incidentally reconciles energy, water management and land conservation concerns. Here, the near overflowing Po valley water table aquifer is exploited to heat and cool a suburban district by large (10 MW_t) thermocentrifugal heat pump units operating in the 12-90°C and 5-30°C temperature ranges respectively. The spent water (re)injection is stopped whenever required by ground water (overflowing) levels.

The dual HP assembly shown in Fig. 13 serves both the needs of winter heating, serviced by two HPs, and summer sanitary hot water supply, mobilising one HP, from a 55°C geothermal source which otherwise would never be reclaimed.

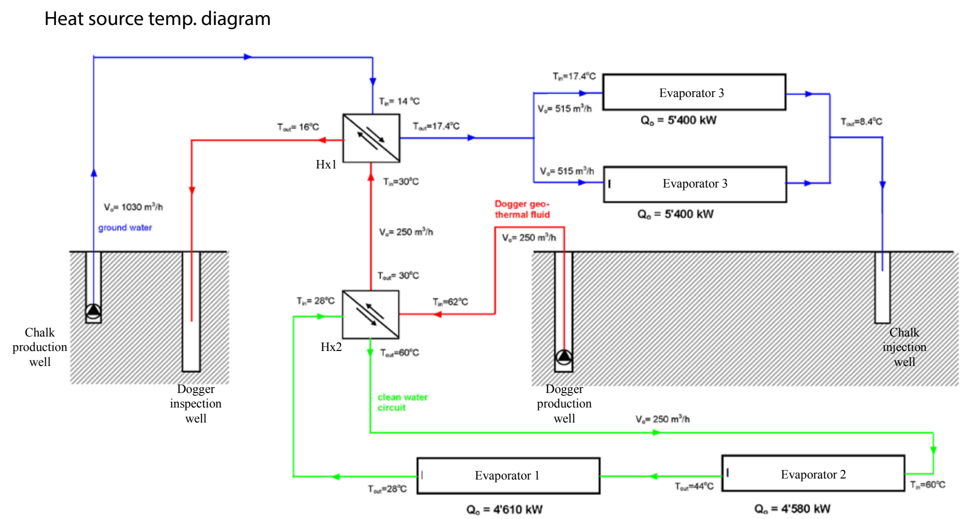


Figure 14. Preheating of shallow ground water (from 14 to 17.4°C) via direct heat exchange with deep geothermal water (Dogger reservoir) (Source: Friotherm, 2009).

GDHC grids combining (i) two, one shallow (cold), one deep (hot), aquifers, and (ii) topping/bottoming, i.e. boosting production and depleting injection temperatures respectively, operating simultaneously in heating and cooling (thermorefrigerating) modes have been designed as illustrated in Fig. 14 layout.

Here, the deep reservoir provides heat only from a 62°C (wellhead) source temperature. The shallow aquifer supplies both heat and cold from a 15°C wellhead ground water temperature and is used as a thermal energy storage capacity, storing alternatively (seasonally) heat (cooling cycle) and cold (heating cycle).

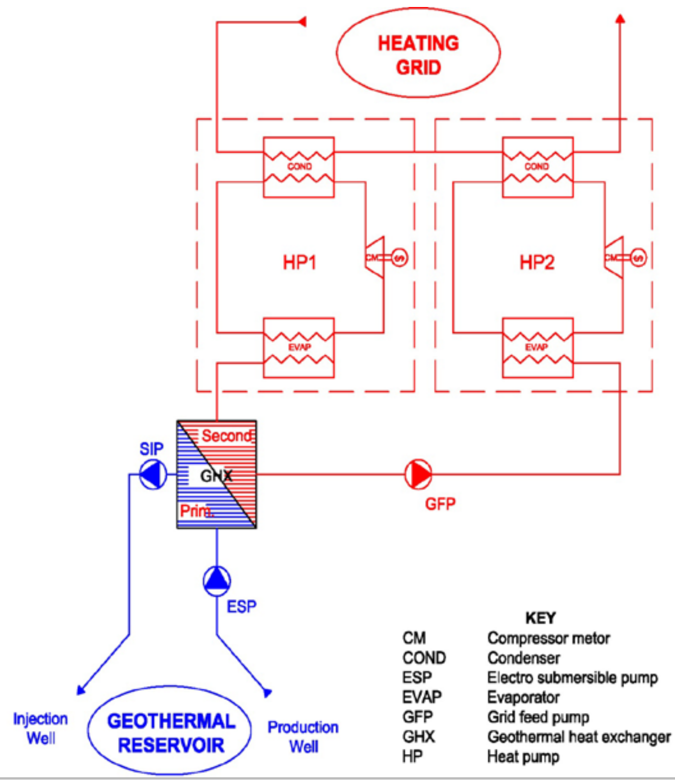


Figure 13. Heat pump sustained twin (winter/summer) design.

Design hot water and chilled water temperatures are set at 90°C and 5°C by -7°C and +34°C outdoor temperatures respectively. Both aquifer supplies are heat pump sustained for either heating, cooling or both, using thermocentrifugal compressor technology.

A conventional thermal design would allocate 60°C/28°C and 14°C/5°C evaporator inlet/outlet temperatures for the deep and shallow aquifers heating cycles and a 33°C/47°C shallow aquifer condenser inlet/outlet temperature (cooling cycle).

Instead, an appropriate design (i) lowering the condenser outlet (heating) temperature to 80°C (against 90°C previously), (ii) diminishing the deep aquifer rejection temperature from 28°C to 16°C, and (iii) increasing the shallow aquifer evaporator inlet/outlet temperature range by 3.4°C would result in upgrading by 30% the overall system COP (yearly average).

Furthermore, the cooling segment is to be credited a significant improvement when associated to heating, regarding both sustainability and energy efficiency. Summer cooling results in hot water injection into the source reservoir, therefore delaying cooling kinetics compared to district heating alone. Simultaneous heating and cooling, known as thermorefrigerating, leads to adding ***both*** heating and cooling COPs.

The deep aquifer is assigned a sole heating function, the superficial aquifer a dual heating and cooling supply.

Absorption chillers capable of accommodating hot water geothermal sources in the 70-80°C temperature range would similarly extend the scope of geothermal district cooling.

Sustainability Issues

Sustainability aims basically at prolonging reservoir life ahead from the twenty-five to thirty year standard assigned usually to GDH life cycle undertakings, seeking a two to preferably three fold increase.

Renewability assessments, indeed a thought provoking exercise, attempted by various authors have been reviewed by Ungemach & Antics (2010). Worth mentioning are the cursory calculations applied to the Paris Basin GDH systems, which estimated the time required to resupply the amounts of heat withdrawn at ca 80 000 years (Ungemach, 1988), which clearly highlight the intrinsically exhaustible nature of geothermal exploitation. Hence, the requirements for managing this structural, conductive recharge vs advective production, unbalance address well longevity, reservoir life and resource management key issues.

Well Longevities

Conventional (steel cased) well physical life in thermochemically adverse environments hardly exceeds thirty years, a life span requiring due to chemical inhibition protection.

The well concept described in Fig. 15 is a material response to corrosion damage. Its architecture combines steel propping casings and freely suspended (production/injection), corrosion resistant, fibreglass liners. The free annulus eases liner replacement whenever the material undergoes material destructuring (weep), therefore avoiding the drilling of a new well. It offers also a facility to inject fluids for either integrity control or/and chemical/bacterial inhibition purposes.

Furthermore, the material smooth surface status minimises drastically, at least by one half compared to steel cased boreholes, well losses. Such a design, implemented in year 1995 on a geothermal production well south of Paris, has been operating since than at high (300 m^3/h) flowrate without any particular well servicing or workover whatsoever, a score which surprisingly did not appeal to geothermal developers, demonstrating in this instance a fairly conservative, delicate euphemism, attitude!

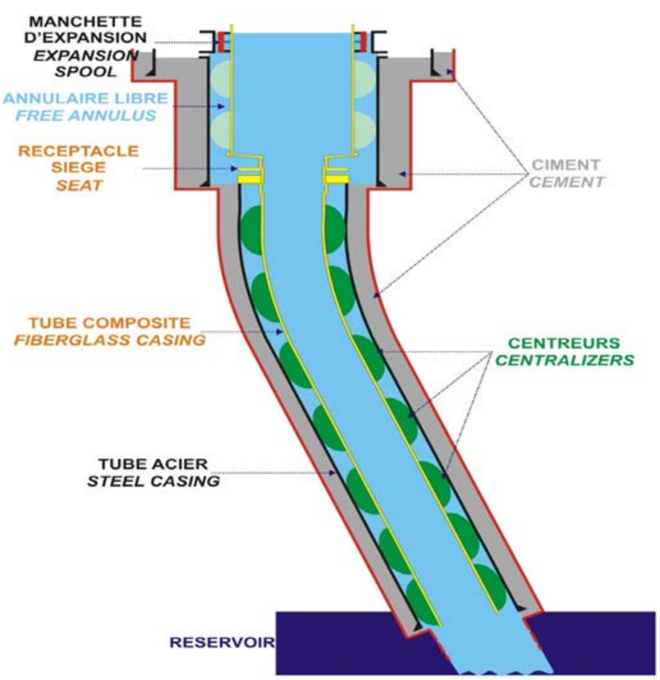


Figure 15. Anti-corrosion fibreglass lined well design.

Reservoir Life

It is by convention assimilated to the thermal breakthrough time induced by brine injection, a theoretical threshold figure which practically is set equivalent to a 1°C drawdown tolerance. Its value depends on reservoir structure and performance and bottomhole well spacing; the lower the transmissivity, and the larger the number of productive layers (and confining aquitards) and the wider the well spacing the longer the breakthrough.

There are various strategies for sustaining reservoir life among which combined heating and cooling (GDHC) systems and optimised well arrays are the best candidates.

GDHC systems, which require the addition of HP to the sole GDH heat exchange segment, offer the advantage of either delaying (heat vs cold unbalance) or ideally suppressing (heat vs cold balance) reservoir cooling kinetics, depending on heat and cold loads. External (solar thermal, waste heat) sources could also contribute, especially in summer periods, to resplenishing the heat reserve.

Well triplet arrays have been advocated for extending GDH life expectations. The mining scheme (Ungemach et al. 2007) consists of (i) reconditioning, after due relining, the former doublet into two injectors combined with a new, large diameter, fibreglass lined production well (triplet stage), and (ii) abandoning ultimately the two refurbished injectors, replacing them by a new, fibreglass completed, production well (second doublet stage). This three stage mining sequence is becoming reality with the implementation and commissioning to date of three and five such projects respectively in the Paris area.

Other candidate configurations - quadruplets, five spot arrays - may be completed from a single drilling pad to maximise heat recovery from the source reservoir within the boundaries of the existing and projected mining licenses.

Resource Management

Several important management issues may be contemplated with respect to resource to demand adequacy, dual reservoir completion and unbalanced, heat vs cold, shallow ground water and ground source HP systems.

A typical resource to demand compatibility dilemma, portrayed in Fig. 16 , displays a dense population of existing and projected concession perimeters, a situation likely to persist in the future owing to a growing demand. Mitigation may be sought from either

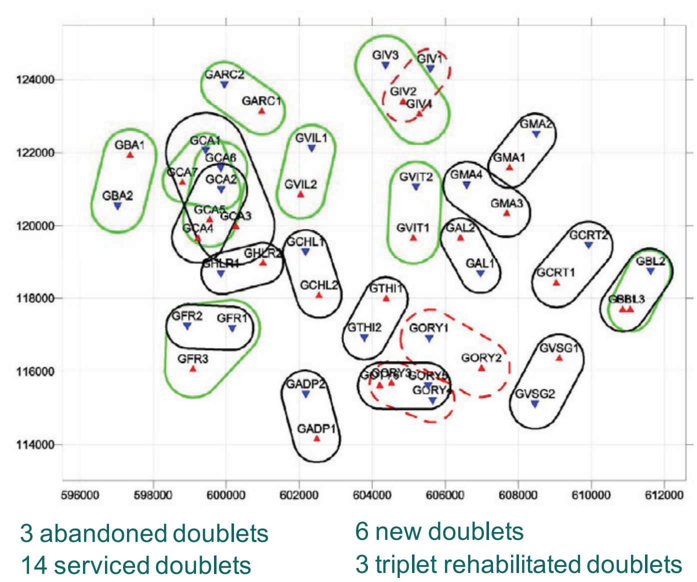


Figure 16. GDHs doublet/triplet compatibilities. Paris South. Existing a,d projected GDH status (source: BRGM, 2012).

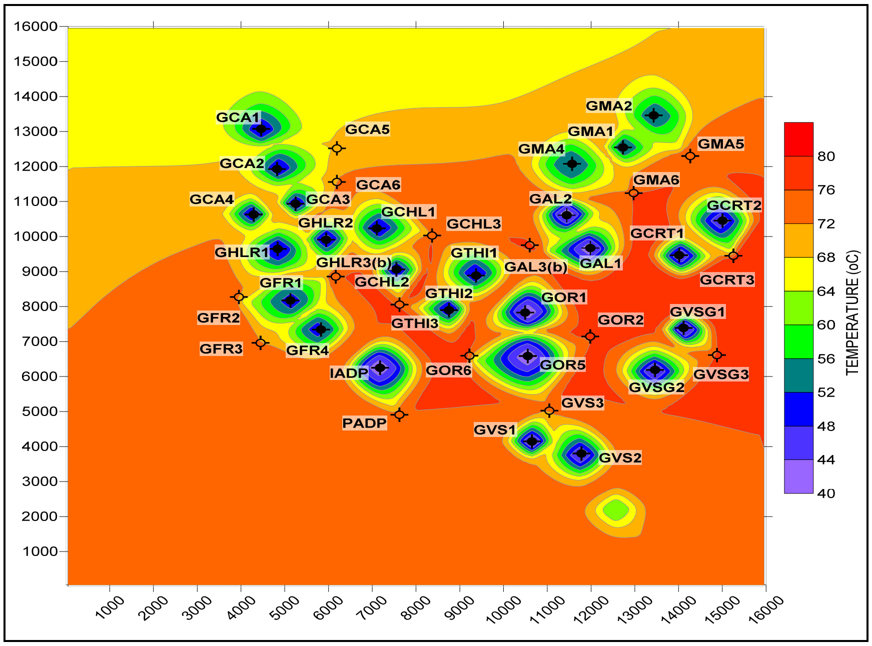


Figure 17. Multidoublet/triplet exploitation (1984-2035). Paris South. 2035 Temperature status (source: M. Papachristou, 2011).

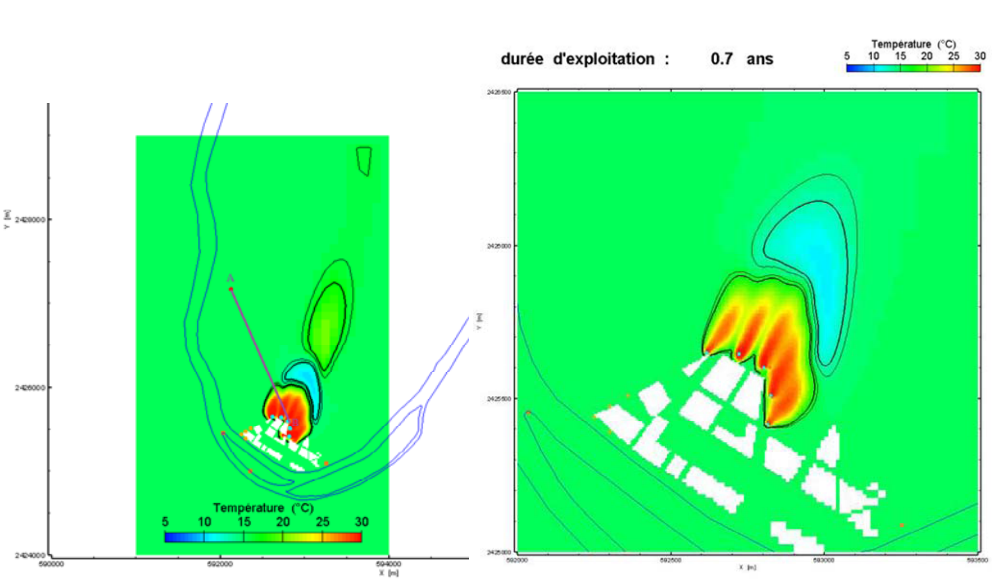


Figure 18. Shallow geothermal. Heat and Cold unbalance. Hot plume tracking.

(i) triplet arrays shown in Fig. 17 to prevent undue premature cooling of production facilities, or/and (ii) previously commented high capacity (sub) horizontal doublet designs.

As regards injectivity limitations, a daring compromise has been investigated by Castillo et al (2011). It aims at exploiting a deep seated hot water source hosted in Triassic (Buntsandstein) sandstones and (re)injecting the heat depleted brine into the overlying Jurassic (Dogger) carbonate reservoir. This design takes advantage of both higher Triassic source temperatures and easier Dogger injectivity engineering. Although no significant chemical incompatibilities are foreseen, this scheme arises the problem of whether the Triassic aquifer can be mined for the sole benefit of the Dogger GDH (inlet temperature, no pressure depletion), a strategy which requires approval from the Mining Authority. As regards shallow geothermal sources, unbalanced heat and cold loads may lead to acute soil and groundwater thermal pollution, either cold (dominant heating) or hot (dominant cooling). Such is the case of the simulated hot plume response downstream from an excess cooling demand, depicted in Fig. 18. Similarly, dense concentrations of, heating dedicated, domestic GSHPs would ultimately cool the exposed soils and occasionally impact HP performance. Here, enforcement of appropriate, updated, mining and environmental regulatory frameworks is needed to prevent such conflicting situations.

Conclusions

The European (EU 28) low grade heat development perspective has been reviewed with emphasis placed on reclamation of deep (> 400 m) geothermal sources, eligible to district/greenhouse heating (GDH/GGH) and district heating and cooling (GDHC) uses, and reservoir management issues.

The European territory enjoys geodynamic environments, in particular large sedimentary systems and marine carbonate and continental clastic deposits, hosting hot and tiepid reservoirs, often matching abundant urban and rural heat and cold loads, favouring thusfar diversified direct uses applications.

The community elsewhere benefits from an experience built up over a thirty year practice/learning curve, supported by a mature, often innovative, technology and relevant reservoir management strategies.

From the foregoing the following conclusions may be drawn as whether the challenging development objectives (180 GW_t and 260 TWh_t installed capacities and yearly heat production i.e. eight and five fold growth ratios respectively from now) set for year 2030 be met by operators.

(v) The major GDH/GGH developments concentrated in the Paris, Pannonian, Molasse and Netherlands basins should continue playing a leading role in the next decades thanks to a growth potential secured by dependable reservoir settings and surface uses;

(vi) Exploration risks should be mitigated by generalising at regional, national and European levels, thoroughly documented data bases, reporting codes, properly dimensioned drilling rigs and incentive risk guarantee policies;

(vii) Maximizing heat extraction requires increased well discharge and depleted temperatures, best achieved via innovative well architecture and thermocentrifugal heat pump designs. A two fold increase, compared to conventional designs, may be anticipated from (sub) horizontal well trajectories intersecting the whole productive interval of a multilayered reservoir, and upgraded heat recovery and system life likewise. Thermocentrifugal compressor technology enables water driven HPs to deliver 80 to 90°C condenser outlet/grid inlet and depleted 25 to 10°C grid rejection/injection well temperatures, therefore widening the use and reclamation of low to very low enthalpy sources.

(viii) Well longevities may be expected from enhanced water injection practice, advanced, corrosion resistant, completion designs and corrosion/scaling abatement protocols. Water injection, long feared by geothermal operators, is nowadays mastered thanks to customized completion and particle filtering designs as exemplified by a Danish project addressing a sensitive clastic sedimentary environment. Long lasting fibreglass well completions and downhole chemical injection proved effective in defeating corrosion/scaling in hostile thermochemical settings.

As a result, demanding resource management strategies are becoming a reality, demonstrated by the Paris Basin GDH scheme now entering its second thirty year life cycle, in response to an increasing doublet population, space restrictions, reservoir thermal life, well hydrodynamic interferences among other concerns. Summing up, the geothermal community possesses the tool box; it still requires daring technological and entrepreneurial skills to meet the industry development challenge.

References

Antics, M., and Ungemach, P.: Quantifyng Risk in Geothermal Development. The High Enthalpy and the Low Enthalpy Case, *Proceeding World Geothermal Congress*, WGC 2010, Bali, Indonesia, 25-29 April, 2010.

Antics, M., Papachristou, M., and Ungemach, P.: Sustainable Heat Mining. A Reservoir Engineering Approach. *Proceedings. Thirthieth Workshop on Reservoir Engineering*, Stanford University, Stanford, California, Jan. 31 - Feb. 02, 2005.

Batini, F. and Van Wees, J.D.: Innovative Approach for Risk Assessment in Green Field Geothermal Project; *GRC Transactions*, Vol 34, 2010, 21-25

Borozdina, O., Ratouis, T., Ungemach, P. and Antics, M.: Thermochemical Impact of Cooled Brine Injection. Paper submitted to the *European Geothermal Congress*, Pisa, Italy, 3-7 June, 2013.

Castillo, C. et al : Assessing the Geochemical Impact of Injection of Cooled Triassic Brines into the Dogger Aquifer (Paris, Basin, France: A2D) Reactive Transport Modelling Study. *Report BRGM/SGP-TR*-191. BRGM, Orleans, France.

EGEC: Geothermal Market Report : 2nd Edition, Dec. 2012*, European Geothermal Council*, Brussels. Belgium.

ERDWERK : Overview of Geothermal Conditions in the Molasse Basin, *PPT presentation*, Taufkirschen, March 2012.

Joshi, S.D.: Horizontal Well Technology. *PenWell Publishing* CO.,1991, Tulsa, Oklahoma, USA.

Lawless, J.V., Ward, G. and Beardsmore, G.: The Australian Code for Geothermal Reserves and Resources Reporting. Practical Experience. *Proceedings of The World Geothermal Congress, WGC 2010*, Bali, Indonesia. April 25-30, 2010.

Lokhorst, A. and Wong, Th. E. : Geothermal Resources in the Netherlands, in Geology of the Netherlands (Wong, Batjes & de Jaeger Edrs). *Royal Netherlands Academy of Arts & Sciences*,2007, 343-346.

Lund, J.: Direct Utilization of Geothermal Energy 2010 Worldwide Review. *Proceedings at the World Geothermal Congress, WGC 2010*, Bali, Indonesia, 25-29 April, 2010.

Mahler, A. and Magtengaard : Country Update Report for Denmark. *Proceedings Word Geothermal Congress, WGC 2010*, Bali, Indonesia, 25-29 April, 2010.

Papachristou, M. : The Use of Numerical Simulation in Low Enthalpy Geothermal Reservoir Management. The Paris Basin Case, *PHD Thesis*, 02 Dec. 2011. Aristotle University, Geology Dpt. Thessaloniki, Greece.

Promis, M.P., Ungemach, P. and Antics, M. : Subhorizontal Geothermal Well Completion : a Promising Outlook (2013) Paper submitted to the *European Geothermal Congress* , Pisa, Italy, 3-7 June, 2013.

RHC-ETP: Strategic Research Priorities for Geothermal Technology, *European Technology Platform on Renewable Heating & Cooling*,2012, Brussels, Belgium.

Schubert, A., Höfule, R. And Böhm, F.: Geothermal doublets Münich Riem and Pullach. Isartal in comparison: geological and drilling concepts for minimizing the geological risk in the deep Malm aquifer, *Openfile report*, 2008,Erdwerk, Augsburg, Germany.

Ungemach, P.: Reservoir Engineering Assessment of a Low Enthalpy Geothermal Field. Paris Basin. Geothermal Reservoir Engineering. Okadan, E (edr), *Kluwer Academic Publishers*,Dordrecht, The Netherlands, 1988, 241-284.

Ungemach, P.: Handling of Corrosion and Scaling. Shortcomings in Low Enthalpy Geothermal Environments, *European Summer School on Geothermal Energy Applications*, Oradea, Romania, April 26-May 5, 2001. Text Book (Rosca, M. edr), 113-127.

Ungemach, P. : Reinjection of Cooled Geothermal Brines into Sandstone Reservoirs, *Geothermics*, **32**,2003, 743-761.

Ungemach, P., Papachristou, M. and Antics, M. : Renewability vs Sustainability. A Reservoir Engineering Approach. *Proceedings of the European Geothermal Congress 2007*, Unterhaching, Germany. 30 May-1 June, 2007.

Ungemach, P., and Antics, M.: The Road Ahead Toward Sustainable Geothermal Development in Europe *Proceedings World Geothermal Congress, WGC 2010*. Bali, Indonesia, 25-29 April 2010.

Ungemach, P., Antics, M., Lalos, P., Borozdina, O., Foulquier, L., and Papachristou, M. : Geomodelling and well Architecture, Key Issues to Sustainable Reservoir Management. *Proceedings Thirtysixth workshop on Geothermal Reservoir Engineering Stanford University*, Stanford, California, Jan. 31- Feb. 2, 2011.

Van Heekeren, E.V., : Communication given at *Geothermie Update 2013 Conf.*, Amsterdam, The Netherlands, 17 April, 2013.