

Sustainable Geothermal Reservoir Management

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ABSTRACT

The non-renewability, at human time scale, of geothermal energy sources arises the problematic of reservoir longevity and sustainable mining of heat in place.

Clearly, well and reservoir life are the core of sustainable development and management strategies.

These key issues are reviewed and discussed in the light of pertinent methodologies among which reservoir and production engineering, water injection and risk assessment take an important share. The impact of the so called externalities is also discussed.

The foregoing are illustrated in a selected case study addressing the Paris Basin geothermal district heating scheme, which consists of seventy production and injection wells operating to date, supplying geothermal heat to ca. 150,000 dwellings. Here, systematic water injection practice, exploitation monitoring and periodical well inspection set the bases of a relevant reservoir management protocol, highlighted by the coupling of a reservoir/exploitation database to various (scale dependant) reservoir simulation tools.

The paper is concluded by the modelling, on typical district heating systems, of the future exploitation trends and reservoir pressure/temperature patterns, using the TOUGH2 and SHEMAT simulation codes, over a seventy five year life projection. Model runs show that neither cooling nor severe pressure depletions occur on the production wells after seventy five years, provided the producer/injector wells be periodically (every 25 years) (re)completed and drilled at adequate reservoir locations. Hence, the contemplated scenario achieves sustainability.

The exercise proved rewarding in that it convinced the operators and energy planners that geothermal reservoir and system life could extend far beyond project life (twenty to twenty five years) expectations. Incidentally, it shows that lifetimes nearing one hundred years cannot be regarded any longer as utopia.

1. INTRODUCTION

Once a geothermal resource has been identified and the reservoir assessed, leading to a conceptual model of the geothermal system, reservoir development and relevant management issues come into play.

In the broad sense, reservoir management is an extension of reservoir engineering. Whereas the latter addresses key issues such as heat in place, reservoir performance, well

deliverabilities, heat recovery, water injection and reservoir life, reservoir management aims at optimised exploitation strategies in compliance with technical feasibility, economic viability and environmental safety requirements.

Reservoir management also involves resource management, a matter that raises growing interest in the perspective of sustainable development of alternative, preferably renewable, energy sources as highlighted by the debate on Global Warming/Climatic Changes and recommendations of the recent World Environmental Summits (Kyoto Protocol) towards reducing greenhouse gas emissions.

The foregoing arise the crucial question on whether geothermal heat is a renewable energy source. It is not, at human time scale, for the simple reason that the heat is abstracted from the reservoir via convection and resupplied by conduction.

Hence, longevity of heat mining should be sought through properly balanced production schedules and designed water injection strategies in order to achieve sustainability. This is indeed a challenging accomplishment, in which reservoir/resource management takes an important share.

Pressure decline and temperature depletion with continued steam and heat production arise the essential problem of reservoir life, a main concern for geothermal reservoir engineers and managers.

The minimum lifetime assigned to the exploitation system is that required to achieve return on invested capital, according to given economic criteria (the usual Discounted Cash Flow –DCF- analysis and related ratios, Pay Back Time – PBT -, Internal Rate of Return – IROR – and Net Present Value – NPV), taking into account the uncertainties provided by a risk analysis. This is the basic entrepreneurial approach long adopted until the advent of sustainability, a concept largely inspired by the environmental consequences of global warming and climatic changes.

Thus far, achieving sustainable development of an exhaustible resource, meeting reservoir longevity/environmental protection concerns and economically competitive standards, is what engineering and farsighted management of geothermal reservoirs is all about. It suggests the integrated approach to sustainable reservoir management strategies outlined in fig. 1. diagram.

The maximum life should comply to the original definition of sustainability, issued in 1987, quoted by Rybach and Eugster (2002): *“Meeting the needs of the present generation without compromising the needs of future generations”*. As regards geothermal energy, this means practically the ability of a geothermal heat mining system to secure production over very long times.

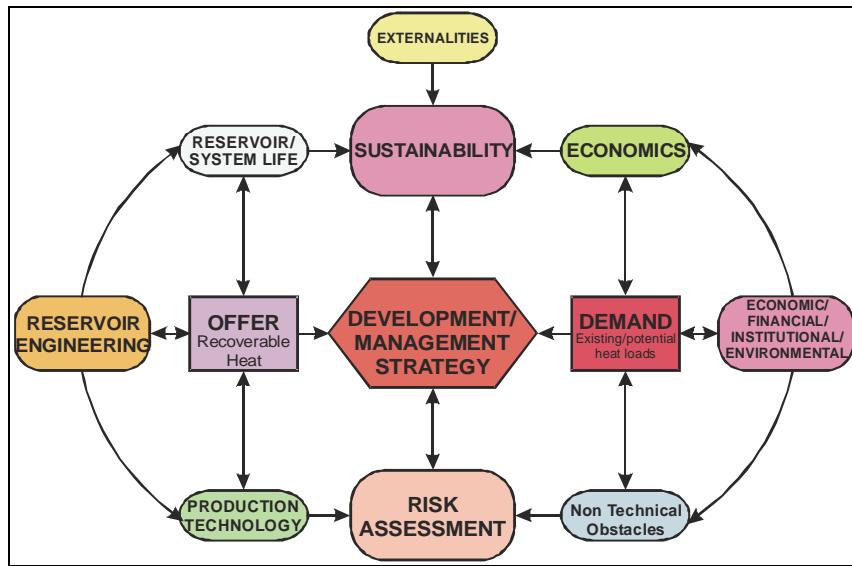


Figure 1: Reservoir management diagram (Ungemach and Antics, 2003)

It is worth mentioning here that, further (prior in several instances) to reservoir depletion, geothermal operators have already devoted significant efforts, in the Geysers, Larderello, Paris Basin fields among others, toward water (re)injection, a major issue of sustainability developed later in this paper.

The foregoing will be illustrated in a case study addressing the Paris Basin, a well documented sedimentary reservoir of regional extent, exploited since the 1970s for geothermal district heating purposes.

It will be concluded by the simulation, on a selected area, of past and future exploitation trends and reservoir pressure/temperature patterns, in response to various demand and offer scenarios, over a seventy five year life projected until year 2060.

2. CASE STUDY

2.1 Resource and reservoir setting

The Paris Basin area belongs to a large intracratonic sedimentary basin, stable and poorly tectonised, whose present shape dates back to late Jurassic age (Housse and Maget, 1976 and Rojas, 1989) (see areal extent in Fig. 2).

Among the four main lithostratigraphic units exhibiting aquifer properties, depicted in the Fig. 3 cross section, the Mid-Jurassic (Dogger) carbonate rocks were identified as the most promising development target.

The Dogger limestone and dolomite are typical of a warm sea sedimentary environment associated to thick oolithic layers (barrier reef facies). The oolithic limestone displays by far the most reliable reservoir properties as shown by the present geothermal development status. Reservoir depths and formation temperatures range from 1,400 to 2,000 m and 56 to 80°C respectively.

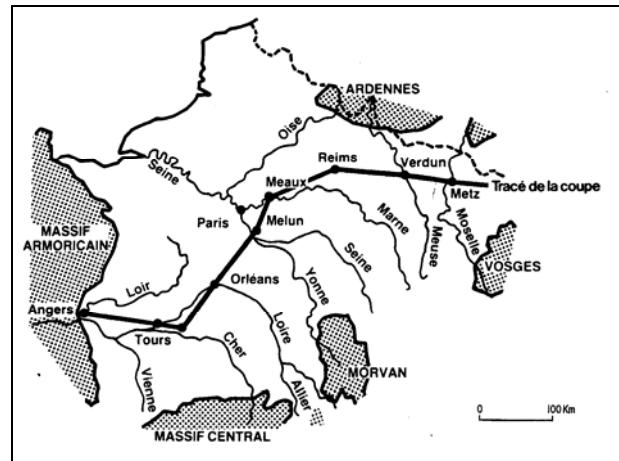


Figure 2: Paris Basin areal extent (Rojas, 1989)

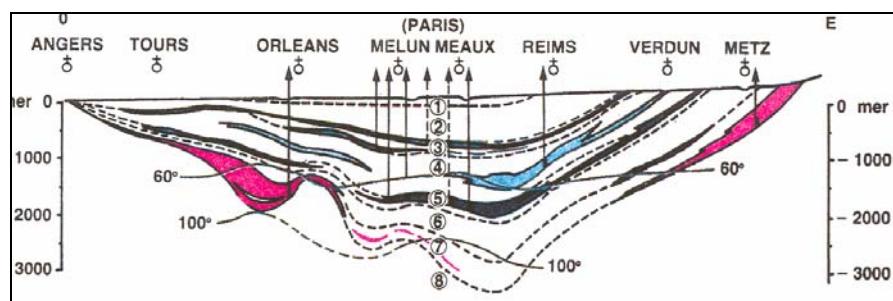


Figure 3: Cross sectional view of the main deep aquifer horizons (Rojas, 1989). (5) - Dogger Aquifer (Mid Jurassic)

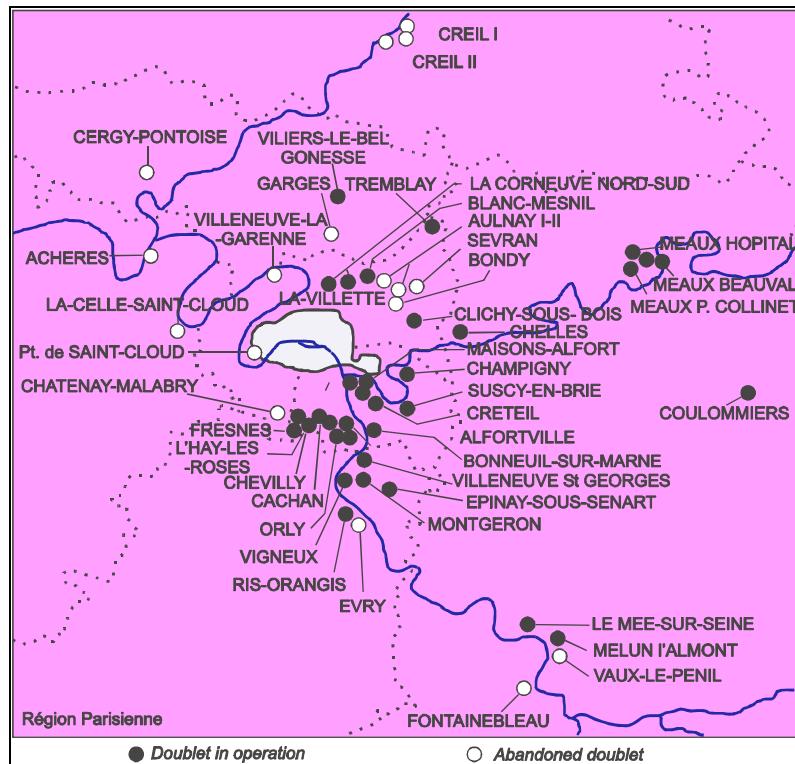


Figure 4: Location of the geothermal district heating sites in the Paris Basin (Ungemach, 2001)

A thorough synthesis of the Dogger geothermal reservoir can be found in the comprehensive review edited by Rojas (1989).

2.2 Development status and milestones

The location of the geothermal district heating sites is shown in Fig. 4. They consist of thirty four (as of year 2003) well doublets supplying heat (as heating proper and sanitary hot water, SHW) via heat exchangers and a distribution grid to end users.

Relevant figures, from early expectations to reality, are summarized hereunder:

Target	Achieved trends		Forecasts	
	(1985)	1990		2005
Operating doublets	55	43	34	34
Total installed capacity (MW _t)	360	260	227	200
Produced heat (GWh/yr)	2,000	1,455	1,240	1,000
Unit installed capacity (MW _t)	6.5	6.0	6.7	5.9
Unit heat production (MWh/yr)	36,000	33,800	36,200	30,000
Artificial lift wells	49	36	27	22
Self-flowing wells	6	7	7	12

The latter highlights four major events regarding sustainable management and development issues:

- the first industrial application in 1969, at Melun l'Almont, South of Paris (Fig. 4), of the well doublet system of heat mining, irrespective of any energy price crisis whatsoever. Despite its innovative and premonitory character, it was regarded at that time as a technical, somewhat exotic, curiosity;

- The initiation, in the early 1990s, of downhole chemical injection lines and of relevant corrosion inhibition protocols;
- the drilling/completion in 1995 at the, henceforth emblematic, Melun l'Almont site of the new anticorrosion well design, combining steel propping casings and removable fiberglass production lining and of a well triplet array operation which, as later discussed, are likely to meet the requirements of increased well longevity and reservoir life;
- the advent, since 1998, of gas fired cogeneration systems equipping nowadays one half of the existing geothermal district heating plants which should secure both economic and sustainable reservoir exploitation issues.

2.3 Technology outlook

Well integrities had long been a critical concern owing to the, initially overlooked, thermochemical shortcomings which, if not defeated, would have caused irreparable damage.

Accordingly, specific remedial/preventing techniques were implemented in the areas of well workover (cleanup jetting, waste processing) stimulation (soft acidizing), tracer applications (leak off testing), corrosion control, and suitable monitoring/surveillance protocols discussed by Ungemach (2001), Ventre and Ungemach (1998) and Ungemach et al., (2002).

Undertakings in corrosion control of well tubulars focused on two preventing routes (i) downhole chemical inhibition via adequate injection lines and agents, and (ii) material definition of newly completed wells.

2.3.1 Downhole chemical inhibition

The consequences of the hostile thermochemistry of the, Dogger hosted, geothermal fluid, a hot (60 to 80°C), slightly

acid ($\text{pH} = 6$), saline brine with a CO_2 and H_2S enriched dissolved gaseous phase, have long been noticed and reported in literature (Ungemach, 1997). This thermochemically sensitive fluid environment caused severe corrosion of tubulars and equipments and heavy metal (essentially iron) sulphide deposition and of other, more or less exotic, crystal species. The corrosion mechanism in the $\text{CO}_2/\text{H}_2\text{S}$ aqueous system and subsequent forming, under soluble or crystallized (scale) states, of iron sulphides or carbonates is outlined in the figure 5 sketch. The corrosion process caused irreparable damage to more than ten doublets in the early development stage (mid to late 1980s) before suitable inhibition procedures were designed, field proofed and implemented on most doublets operating to date.

In order to prevent corrosion/scaling damage or at least to slow down damaging kinetics, continuous chemical injection lines, of the AIT (auxiliary injection tubing) coiled tubing type, have been designed to inhibit the process at its initiation, i.e. at bottom hole. A number of inhibition formulations have been tested in various fluid and production environments. In the Paris Basin, commonly used agents belong to the monofunctional (anticorrosion/filming) and bifunctional (anticorrosion-biocide) types [7]. The first type is recommended in the Northern areas, which exhibit high dissolved H_2S contents, and the second in the Southern part with lower dissolved H_2S and high microbiological (sulphate reducing bacteria) activity

2.3.2 New well concept

The novel geothermal well concept was designed to reduce corrosion and scaling that had severely affected the integrity and lifetime of Paris Basin geothermal district heating wells. This new generation geothermal well, which represents a material alternative to corrosion, was successfully completed in March 1995 (Ungemach, 2001).

Under this new design, the wells are completed by combining cemented steel casings and fiberglass liners while the annulus is kept free as shown in figure 6. The casings provide mechanical strength (propping function), while the liners furnish chemical resistance (corrosion and scaling protection). The free annular space allows (i) circulating

corrosion/scaling inhibitors and/or biocides, which otherwise would need to be circulated using a downhole chemical injection line, and (ii) removing and, if necessary, replacing the fiberglass liner whenever damaged. It is noteworthy that this design can accommodate a submersible pump set, in which case the upper fiberglass lining is placed under compression, and the lower one is freely suspended under its own weight. Vertical displacement of the fiberglass lining is elsewhere eased by an expansion spool and fiberglass centralizers (not by couplings as often contemplated in other centralizing designs). Here, due to exceptional reservoir performance, artificial lift was no longer required; instead self-flowing at high production rates prevails, leading to a simplified design.

The well, put on line in late March 1995, demonstrated high productivity, producing about 70°C fluid at a rate of 200 m^3/hr at 2.5 bars well head overpressure. It has been connected to two existing wells (one producer and one injector); the whole system operates according to a triplet (two producers, one injector) array.

2.4 Risk assessment

Paris Basin geothermal district heating projects, as one would expect for similar undertakings, faced five levels of risks, exploration (mining, geological), exploitation (technical, managerial), economic/financial (market, institutional, managerial), environmental (regulatory, institutional) and social acceptance (image) respectively. Only exploration and exploitation risks will be discussed here.

2.4.1 Exploration risk

The mining/geological risk could be minimized here thanks to two favourable factors and incentives. First, the existence of a dependable hot water aquifer (Dogger limestone and dolomite) of regional extent evidenced thanks to previous hydrocarbon exploration/step out/development drilling, which enabled to reliably assess the geothermal source reservoir prior to development. This resulted later in a 95 % geothermal drilling success ratio. Second, the coverage by the State of the geological risk, amounting to 80 % of the costs incurred by the first, assumed exploratory, drilling.

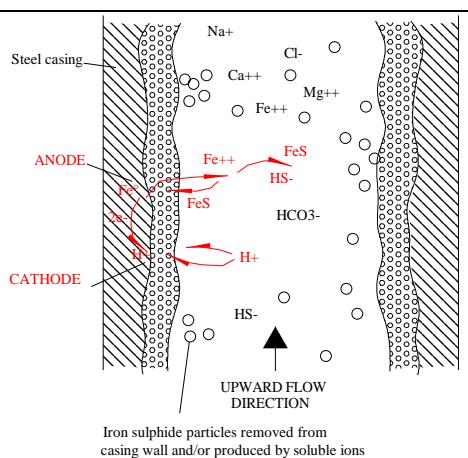
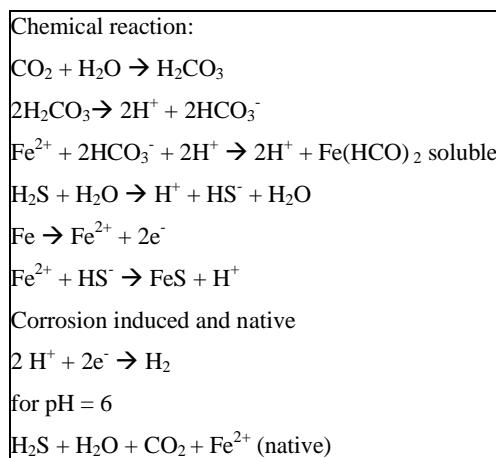


Figure 5: Iron dissolution and sulphide precipitation process in presence of aqueous H_2S and CO_2 (Ungemach, 1997)

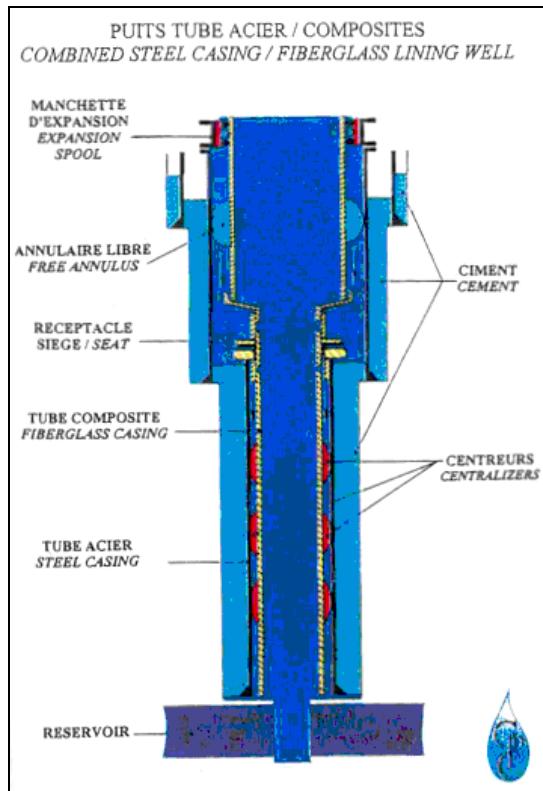


Figure 6: Anti-corrosion geothermal well concept (Ungemach, 2001)

2.4.2 Exploitation risks

Those could not be estimated beforehand. It soon became obvious that the, initially overlooked, hostile thermochemistry of the geothermal fluid provoked severe corrosion and scaling damage to casing and equipment integrities resulting in significant production losses. A prospective survey, commissioned in 1995, aimed at assessing the exploitation risks and related restoration costs, projected until year 2010. The results of this exercise, applied to thirty three doublets, are discussed by Ungemach (2001). The governing rationale consisted of (i) ranking and weighting potential and actual, technical and non technical, risks into three categories and according to available well monitoring/casing inspection records and local thermochemical environments, and (ii) classifying risks into three levels (low, medium, high), each subdivided in three scenario colourings (pink, grey, dark), regarding projected workover deadlines and expenditure. This analysis led to a symmetric distribution, i.e. eleven sampled sites per risk level, each split into three, five and three scenario colourings respectively.

The next step applied the workover/repair unit costs to concerned wells, required works and forecasted schedules, thus leading to generic expenditure breakdowns.

In conclusion, an average provision of ca 186,000 €/yr has been recommended to cope with future exploitation hazards resulting in a 12 % increase of initially anticipated OM costs. Noteworthy is that, as of year 2003, the well heavy duty workover record matched earlier projected figures.

3. SUSTAINABLE RESERVOIR DEVELOPMENT

The theme of sustainability deserves a few introductory comments.

Apart from projects abandoned at exploratory stage or aborted after early production trials, almost none of the fields developed in the past decades have yet ceased commercial exploitation.

Larderello, the eldest geothermal field exploited to date, has commemorated in 2004 its one century exploitation mark and the Geysers are approaching the half century line.

Clearly, water injection, whatever the fears (and early failures) related to production/injection well spacing and short-circuiting hazards, particularly acute in the sensitive liquid dominated fractured environments, is a key issue in sustaining reservoir performance and exploitation longevity.

So, everything considered, a hundred year life for a steam producing reservoir can no longer be regarded as unrealistic. This, irrespective of the field ownership/concession statute, of either aggressive (cash flow oriented) or moderate (resource conservative) exploitation strategies. This, in spite of the exhaustible nature of the resource.

Regarding the Paris Basin low enthalpy geothermal reservoir, projecting an exploitation scenario over fifty six years, from 2004 to 2060, proved a challenging, thought provoking, exercise, for the following reasons:

- based on available exploitation records, the well life is deemed to seldomly exceed twenty five years;
- reservoir life is assessed from the system thermal breakthrough time, to which a few more years can be added at the expense of a 10% loss in well thermal deliverability, i.e. a total twenty five to thirty year life;
- which production schedules and injection temperatures should be allocated for the future fifty years, bearing in mind that new building/insulation/heating standards and novel designs in heating/cooling processes and devices be substituted to the existing ones;
- could centralised cooling be designed to fit into the existing heating/SHW grids?. This would indeed be an attractive alternative adding a seasonal input to the sole SHW summer supply. It could be implemented, either via absorption cycles (constant cold supply) eased by the existence of combined gas cogeneration/geothermal plants or by adequately designed semi-centralised (substations) heat pump systems (variable supply).

These two latter issues obviously require thorough prospective investigations, at present in the early elaboration stage.

However, as far as modelling is concerned, both the available reservoir assessment and exploitation database status make it possible to quantify future pressure/temperature patterns and reservoir life expectations according to the following reservoir simulation strategies (Ungemach and Antics, 2003).

- local modelling, restricted to a single doublet neighbourhood, assuming homogeneous reservoir properties and an equivalent monolayer structure with either constant pressure (recharge) or impervious (no flow) boundary conditions. Two simulators are currently used, either the analytical model described in (Griegarten and Sauty, 1975) or the TOUGH2 (Pruess, 1991)

discretised field, computer code. The latter is applied to the preliminary case study;

- multidoublet areal modelling by means of both analytical and numerical simulators. In the first case the reservoir is assumed homogeneous and single layered (2D). This exercise may exaggeratedly oversimplify the actual field setting, in which case a numerical simulator such as TOUGH2 or SHEMAT (Clauser, 2003) (taking into account reservoir heterogeneities), and a multilayered (3D) structure, as illustrated in fig. 7, would be preferred instead as exemplified in the second demand/offer simulation trial;
- regional or subregional modelling, encompassing the whole exploited domain or a significant fraction of it, which, by all means, requires a numerical simulator to meet actual reservoir conditions. This poses the problem of the interpolation of the, space distributed, field input data, which is currently achieved by geostatistical (Krigging) methods. In the Dogger reservoir, however, the process can be biased, for permeabilities and net thicknesses, by the locally strong variations evidenced by well testing at doublet scale between the production and injection wells, introduced in a regional context. Therefore, values derived from interference tests, integrating a larger reservoir area would be more meaningful and assigned accordingly to each doublet location;

A solute transport partition can be added to handle the tracer case and track the migration of a chemical element (iron, as a corrosion product for instance) continuously pumped into the injection wells.

Summing up, the general modelling philosophy consists of using a calibrated regional model as a thorough reservoir management tool, online with an exploitation database, and to extracting multistage subregional/local models whenever required by operators needs.

3.1 Local modelling of a single doublet/homogeneous reservoir configuration

It addresses a setting representative of the conditions prevailing in the area, whose reservoir/fluid characteristics and production/injection schedules are featured in table 1. The projected scenario includes three periods of twenty five years each programmed as follows:

Table 1: Local modelling. The single doublet/homogeneous reservoir case

• Reservoir characteristics													
- intrinsic transmissivity (kh) = 30 Dm							- rock grain density = 2700 kg/m ³						
- net reservoir thickness (h) = 20 m							- formation heat conductivity = 2.1 W m ⁻¹ °C ⁻¹						
- intrinsic permeability (k) = 1.5 D							- rock grain specific heat = 1000 J kg ⁻¹ °C ⁻¹						
- effective porosity (ϕ) = 0.16							- initial doublet spacing (d) = 1250 m						
- initial reservoir temperature (T_0) = 72°C							- area simulated = 20 km ²						
- heat flow production = 0.09 W/m ²													

• yearly production/injection schedule

Period	1985-2010					2011-2035					2036-2060				
	doublet ⁽¹⁾					triplet ⁽²⁾					doublet ⁽³⁾				
Mining scheme	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Annual prod./inj. schedule	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Time (months)	3	4.5	8.5	10	12	3	4.5	8.5	10	12	3	4.5	8.5	10	12
Flowrate (m ³ /h)	250	160	80	160	250	150	150	80	150	150	125	150	80	150	125
Inj. Temp. (°C)	50	40	62	40	50	40	40	62	40	40	30	30	62	30	30

⁽¹⁾ initial doublet: 2 deviated wells (steel cased 9"5/8)

⁽²⁾ intermediate triplet: 2 injection wells (initial reconditioned doublet, 7" steel lining), 1 new anticorrosion (steel/fiberglass lined), large diameter deviated well

⁽³⁾ final doublet: 3 anticorrosion (steel/fiberglass lined), large diameter deviated (existing producer and newly completed injector) wells.

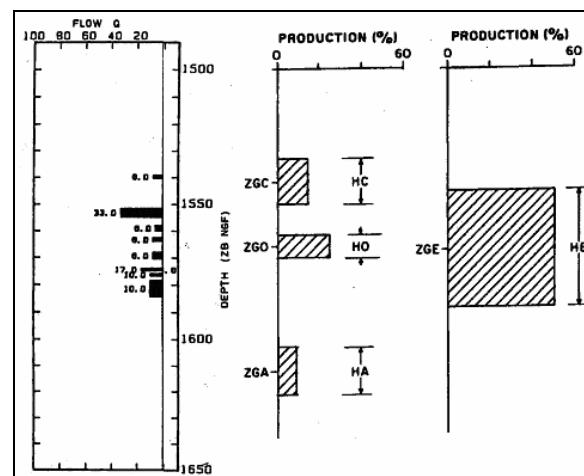


Figure 7: Equivalent reservoir model assessed from flowmeter logging; adapted from Rojas (1989)

- the doublet is produced during the first twenty five years according to the existing seasonal production rate /injection temperature schedule;
- starting on year 26, the existing wells are converted, after due reconditioning (lining), into injector wells and a new, long lasting, steel casing/ fiberglass lining well is drilled to the North and the system operated according to a triplet design. Flowrates and injection temperatures are estimated from a combined geothermal/ gas cogeneration plant performance;
- on year 51, the two injector wells are abandoned and a new injection well is drilled to the South. The doublet revisited system is exploited, with the cogeneration plant, at lower flowrates and injection temperatures, as a result of upgraded low temperature heating processes. No distinct cooling alternative was considered so far. These preliminary runs did not evidence any thermal breakthrough whatsoever during a seventy five year life span. Furthermore, they validated a heat mining scheme, moving successively from the initially completed well doublet, to triplet and, again, doublet well arrays at appropriate locations and spacings.

However, regarding future trends in heat demand the exercise was merely deterministic and restricted to a, somehow speculative, scenario more or less perpetuating the “*statu quo ante*” heating scheme. In so doing it ignored assessments of future demand scenarios integrating, among other parameters, demographic trends, energy needs and ratios, foreseeable building/social dwelling/city planning standards and policies, environmental regulations and subsequent legal/institutional implications and fiscal incentives. This requires an integrated multidisciplinary approach and shared deterministic/probabilistic modelling methodology.

3.2 Subregional modelling of a multidoublet/heterogeneous reservoir area

It handled a more realistic exploitation and reservoir setting, materialised by the multidoublet arrays and heterogeneous reservoir conditions depicted in fig. 8. The simulations, in this instance, were run by means of the SHEMAT software (Clauser, 2003). The domain modelled, 130 km² in area, is assumed bidimensional, subject to (i) to vertical conductive heat recharge, and (ii) constant head/constant temperature (i.e. recharge) lateral boundary conditions.

Heat extraction designs replicate, on each of the three simulated grids (GLCS, GLCN, GBMN), the previously modelled – initial doublet, intermediate recompleted triplet, final doublet – well arrays as shown in fig. 8.

The demand scenario is summarised in table 2. It reflects (i) the past production rate/injection temperature histories, input as yearly averaged figures, recorded since startup (1983) and extrapolated until year 2010 from operators' estimates, and (ii) the future demand schedules accounting for upgraded production/distribution facilities and, environmentally enhanced, market penetration opportunities. It adds also a significant district cooling segment. As a result, the total heat withdrawals increase from 55,000 MWh_t (2010), to 80,000 MWh_t (2011-2035), and, ultimately, 97,000 MWh_t (2036-2060).

Simulation results mapped in fig. 9 (2010), 10 (2035) and 11 (2060) outputs indicate no thermal breakthroughs thus securing the projected heat production scenario.

Maximising heat generation without penalising grid operation by undue, premature, cooling of production wells was the target assigned to the so called offer model.

Reservoir simulations led to a maximised heat/cold offer, over the 2011-2060 period, of 155,000 MWh_t, based on yearly production rate/injection temperature schedules set at 150-175 m³/h and 30°C respectively, thus achieving gains of 90% (2011-2035) and 60% (2036-2060) compared to the demand scenario figures.

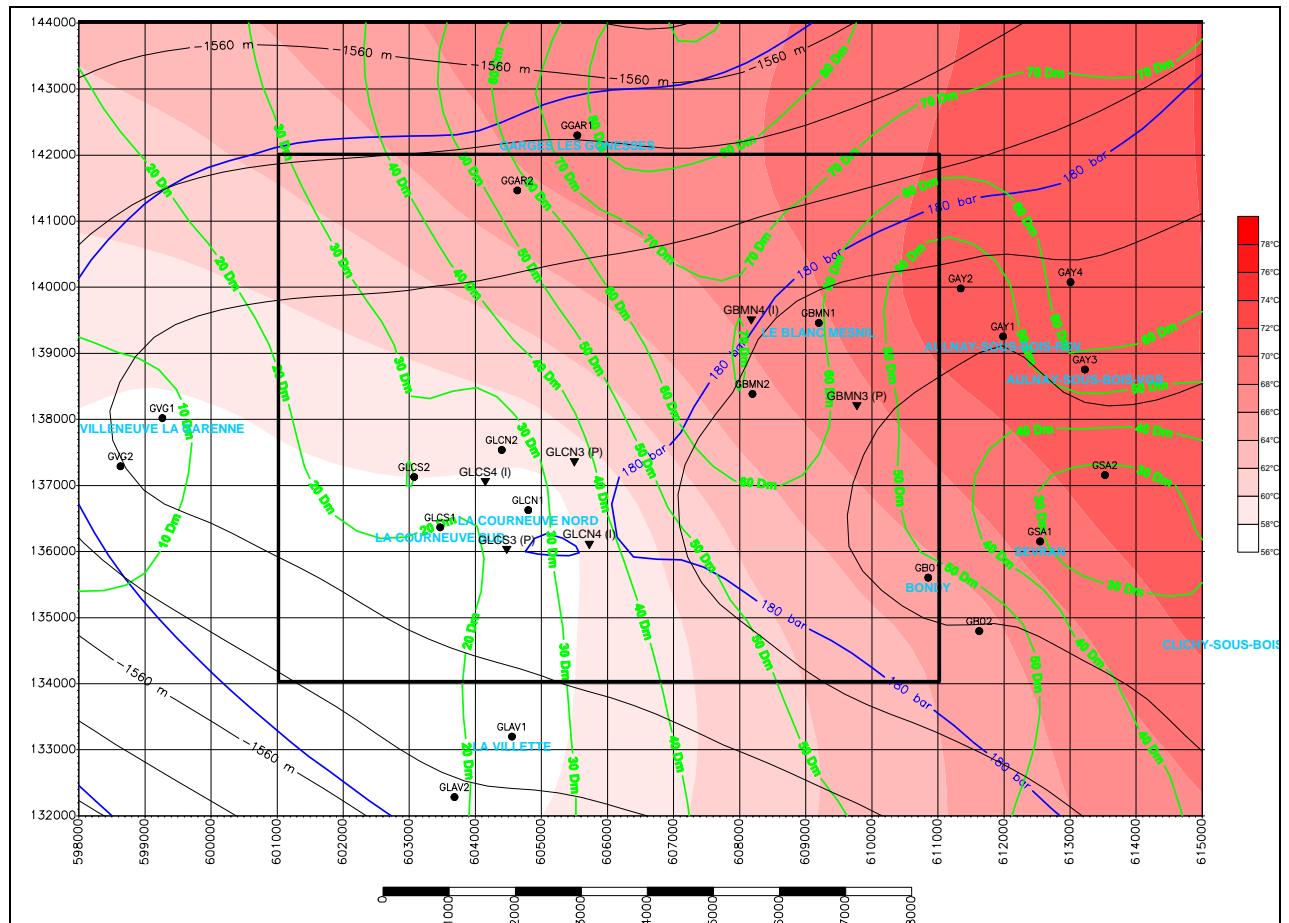


Figure 8: Multidoublet simulated area. • GLCS1: existing well, ▼ GLCN3: future well, P: Production well, I: Injection

well, □ : simulated area, -1500m- : top reservoir depth, -180 bar- : pressure at top reservoir depth, -20Dm- : iso-transmissivity contour line

Table 2: Simulation Paris Nord. Production/injection schedule. 1983-2060

WELL NAME	TYPE	1983-1989		1990-1997		1998-1999		2000-2001		2002-2003		2004-2010		2011-2035		2036-2060	
		Q (m ³ /h)	Ti (°C)														
GLCS1	P	-132		-132		-132		-90		-90		-80		57.5	38		
GLCS2	I	132	42	132	42	132	42	90	42	90	42	80	40	57.5	38		
GLCS3	P													-115		-118	
GLCS4	I															118	32
GLCN1	I	156	43	156	43	156	43	156	43	156	43	160	42	77	38		
GLCN2	P	-156		-156		-156		-156		-156		-160		77	38		
GLCN3	P													-176		-154	
GLCN4	I															154	32
GBMN1	P	-163		-152		-145		-145		-130		-80		65	48		
GBMN2	I	163	48	152	50	145	52	145	52	130	53	80	45	65	48		
GBMN3	P													-130		-110	
GBMN4	I															110	40
DOUBLET	YEARLY HEAT PRODUCTION (MWh _h)																
GLCS		18000		18000		18000		14250		14250		12500		20200		27600	
GLCN		22800		22800		22800		22800		22800		25000		34300		39000	
GBMN		31800		26700		22600		22600		19000		18000		25400		30000	
TOTAL		72600		67500		63400		59650		56050		55500		79900		96600	

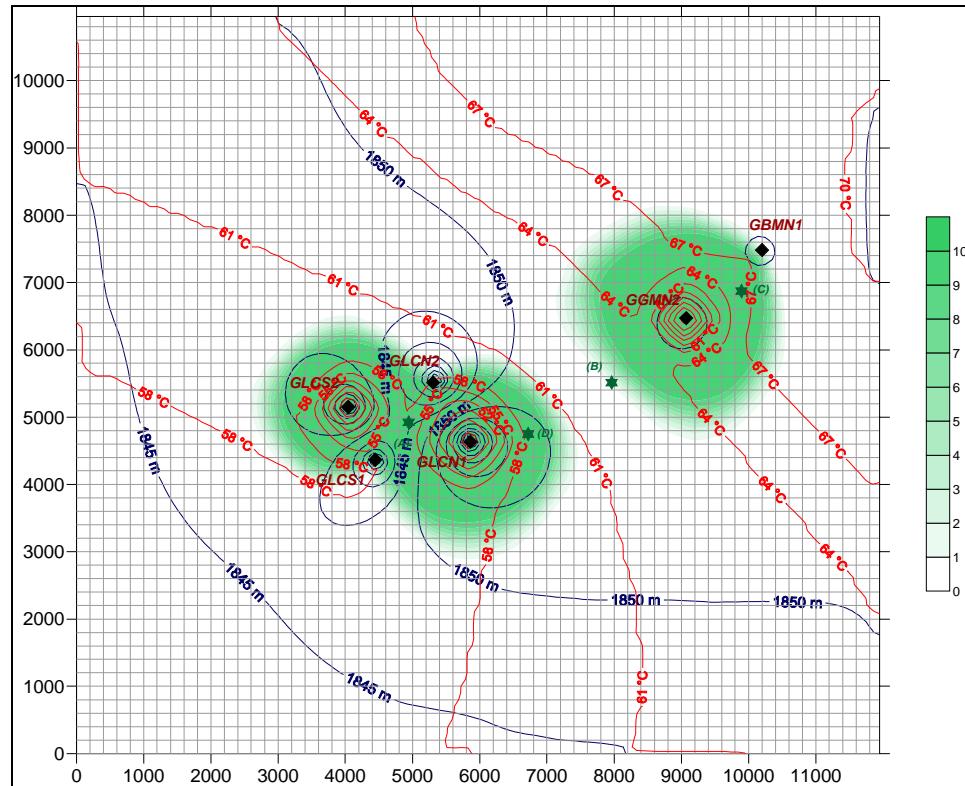


Figure 9: Simulated head/temperature/diluted injected water concentration contour map. SHEMAT processing. Time 27 years. ♦ GLCN : well name, (A)-(D): model control points, **—1845m— iso-head contour line, **—58°C—** : iso-temperature contour line, green colour gradation: injected water concentration.**

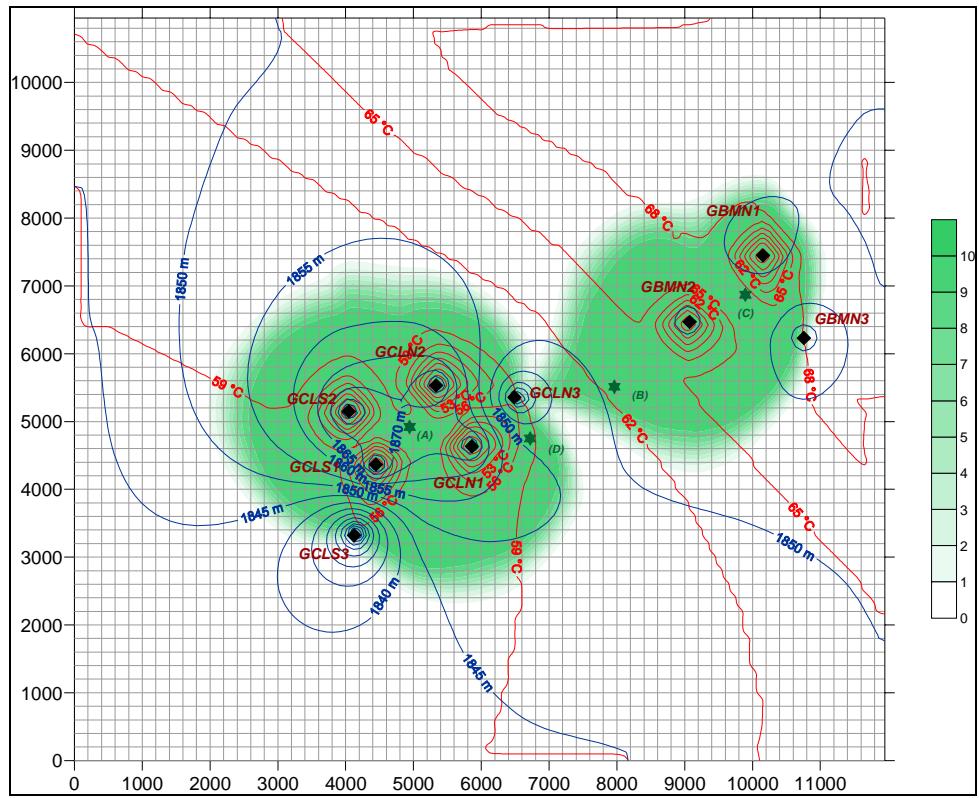


Figure 10: Simulated head/temperature/diluted injected water concentration contour map. SHEMAT processing. Time 52 years. ♦ GLCN : well name, (A)-(D): model control points, -1845m — iso-head contour line, -58°C — : iso-temperature contour line, green colour gradation: injected water concentration.

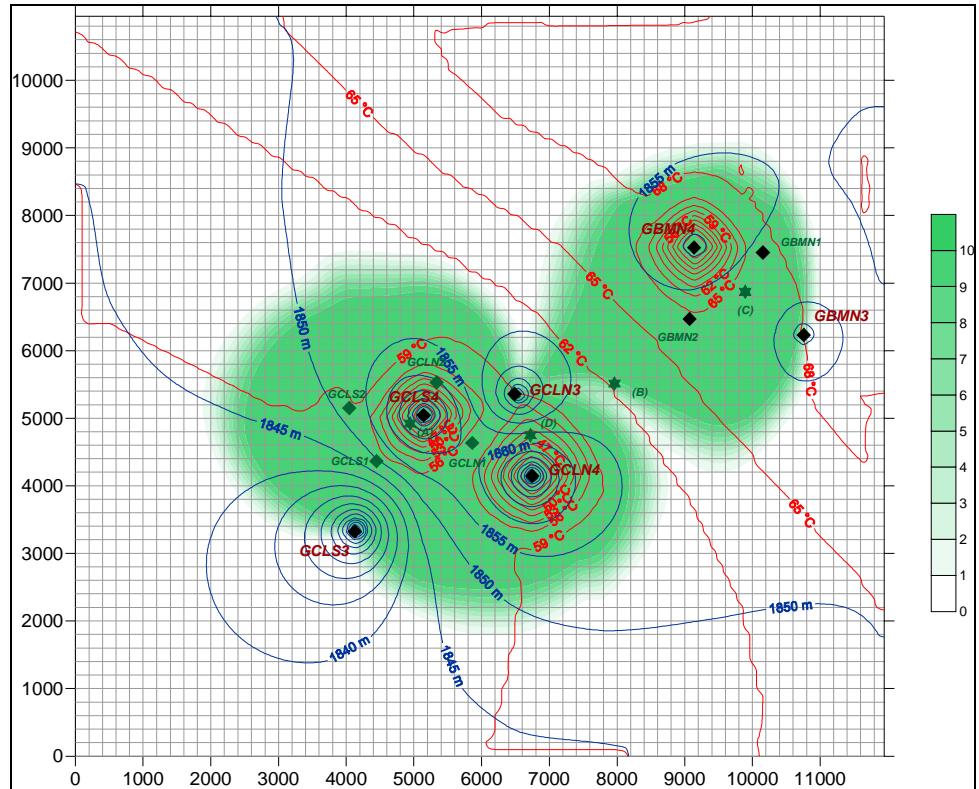


Figure 11: Simulated head/temperature/diluted injected water concentration contour map. SHEMAT processing. Time 77 years. ♦ GLCN : well name, (A)-(D): model control points, -1845m — iso-head contour line, -58°C — : iso-temperature contour line, green-colour gradation: injected water concentration.

4. DISCUSSION

Given the uncertainties inherent to any modelling exercise, the reliability of the previously simulated scenarios will be discussed with respect to sensitive issues such as (i) well (physical) and reservoir (thermal) life, (ii) reservoir assessment and simulation issues, (iii) heat demand forecasts, (iv) economic implications, and (v) non technical impacts known as externalities.

4.1 Well life

The age of the sixty eight production/injection wells operating to date is averaged at already twenty years, in spite of hostile thermochemical and densely populated urban environments. This is to be credited to mature, field proofed, well damage repair (workover) and preventing (downhole chemical inhibition) technologies and protocols.

The risk assessment survey, carried out in the mid 1990s, estimated that a typical Paris Basin geothermal well would undergo a heavy duty workover every eight to ten years under technically safe and economically acceptable standards, a conclusion matched since then on most installations. Hence, a twenty five years life is no longer questioned.

The completion of the anticorrosion, fiberglass lined, well concept pioneered in 1995 should upgrade this figure. In fact, samples collected on an earlier (1992) lined well showed no damage after a twelve year exposure to the geothermal fluid.

4.2 Reservoir life

The recovery of heat in place can be expressed as:

$$R = \eta \frac{T_0 - T_r}{T_0 - T_e} \quad (1)$$

where R is the recovery factor, T_0 , T_r and T_e the formation, injection and mean yearly outdoor temperatures respectively and η the efficiency of the heat abstraction scheme from a reservoir volume of areal extent A and average thickness h over a period t_p , given by:

$$\eta = \frac{Q}{A h} \frac{\gamma_f}{\gamma_t} t_p \quad (2)$$

where Q is the average yearly flowrate and γ_f , γ_t the fluid and total (rock+fluid) heat capacities ($Jm^{-3}^{\circ}C$) respectively, the latter equal to:

$$\gamma_t = \phi \gamma_f + (1 - \phi) \gamma_r \quad (3)$$

with ϕ =porosity and γ_r =rock heat capacity.

Numerical application:

$$\begin{aligned} Q &= 150 \text{ m}^3/\text{h} & t_p &= 25 \text{ years} & A &= 20 \text{ km}^2 \\ h &= 20 \text{ m} & \phi &= 0.15 & \gamma_r &= 2.14106 \text{ Jm}^{-3}^{\circ}C^{-1} \\ \gamma_f &= 4.186106 \text{ Jm}^{-3}^{\circ}C^{-1} \\ T_0 &= 70^{\circ}C & T_i &= 40^{\circ}C & T_e &= 10^{\circ}C \\ \eta &= 0.14 & R &= 0.07 \end{aligned}$$

would Q be set to $300 \text{ m}^3/\text{h}$ and A to 15 km^2 , all other parameters unchanged, then $\eta=0.37$ and $R=0.19$.

These cursory calculations show that, irrespective of temperatures, the upgraded efficiencies and recovery factors require higher flowrates and smaller “influenced”

areas, which was precisely the objective sought from the doublet and multidoublet well arrays completed in the Paris area.

In the doublet configuration the cooling of the production well (at a distance d from the injection well) is currently approximated from the thermal breakthrough time t_B derived, assuming a purely convective heat transfer, from the following equation:

$$t_B = \frac{\pi \gamma_t d^2 h}{3 \gamma_f Q} \quad (4)$$

Its application to a typical doublet setting, i.e. a 1,100 m well spacing, an average $160 \text{ m}^3/\text{h}$ flowrate and a 20 m net pay interval would lead to a ca. 10.6 years thermal breakthrough time. No such cold front arrival times have been noticed so far among the 34 doublet exploited since 18 to 22 years. Furthermore, bearing in mind that the cold front breakthrough is delayed by a $\gamma_t/\phi\gamma_f$ ratio (equal, under the previous assumptions to 3.9) vis-à-vis the hydraulic (mass transfer) front arrival time, the latter should have been observed 2.7 years after doublet startup. It has not been the case. Only did microbiological shows (drastic increase in sulphate reducing bacteria attributed to early contamination of injected waters) brought some evidence of a hydraulic breakthrough after 16 years operation. This means that the arrival of the cold front could be expected ca. 62 years after doublet completion.

This mismatch is a consequence of exaggeratedly conservative assumptions, reducing the actual multilayered reservoir structure to an equivalent single layer configuration, whose effective thickness (net pay) cumulates the thicknesses of individual producing layers assessed from flowmeter logging. This may be hydraulically correct as long as no significant interlayer cross flow occurs. It has, however, the clear disadvantage of neglecting the conductive heat resupply from the confining aquitards. This was the clear conclusion drawn from early simulations, predicting premature cooling of production wells.

The inclusion of heat conductive recharge set the bases for pertinent modelling, reconciling simulation outputs with factual evidence and relevant, presumably reliable, forecasts.

4.3 Reservoir assessment

It has been previously stated that the Dogger geothermal reservoir enjoys among the best documented background knowledge recorded to date. It lacks, however, observation wells and tracer surveys enabling to monitor the pressure/temperature patterns and sample the fluids away from the exploited doublets and to directly assess actual thermal breakthrough times, easing accordingly model calibration. Unfortunately, neither abandoned doublets could be reconverted into piezometers nor tritium injection experiments be implemented; still the need remains.

It should be stressed that in no way were individual, short time, well tests affected by the multilayered reservoir structure, neither by the significant vertical and lateral heterogeneities displayed by the, geostatistically derived, distribution of the reservoir parameters. Test interpretation, conducted assuming a homogeneous, single layer equivalent reservoir, proved consistent with monitored downhole pressures and well deliverabilities, achieving a good match between calculated and observed figures.

In a few instances interference tests using the injector as observation well were performed, showing an average transmissibility higher than the figure usually assessed via harmonic mean.

It is recommended that, in the future, interference testing, using downhole pressure/temperature gauges in both wells, be promoted in order to substitute average doublet transmissivities to the single well, often contrasted, criterion.

4.4 Simulation issues

The pros and cons of TOUGH2 and SHEMAT simulators will not be discussed here. Both issued pressure/temperature patterns consistent with recorded data, within the aforementioned limitations (no observation wells and no actual tracer transit times). This is attributed to the hybrid reservoir model outlined hereunder, whatever the simulated case, either isolated doublet/homogeneous reservoir or multidoublet/heterogeneous reservoir configurations.

It combines a single layer, equivalent, reservoir and two dummy, hydraulically impervious and thermally conductive, layers acting as vertical heat exchange boundaries. The lower (bed rock) boundary supplies a constant local terrestrial heat flow (density). The upper (cap rock) boundary handles two variable heat exchange components (i) a positive inflow aggregating the conductive inputs from the intermediate and confining aquitards, assumed at constant temperature, and (ii) cap rock either positive (inflow) or negative (outflow) heat flow depending upon the status reservoir/cap rock temperature gradient. In so doing the cap rock temperatures are either calculated by a semi-analytical approach (TOUGH2) or assigned at constant value lower than the initial reservoir temperature (SHEMAT). In the SHEMAT version the aquitard inflow component has been arbitrary reduced to account for heat exhaustion, likely to occur in the thinner layers.

The two simulated options achieved a good match on the preliminary – single doublet/homogeneous reservoir runs, thus securing predictions by the SHEMAT operated multidoublet/heterogeneous reservoir case.

Obviously, future feasibility studies should focus on three dimensional reservoir simulations, encompassing the

canonical initial steady state, calibration and prediction suite.

In addition, emphasis ought to be placed on a concise assessment of vertical conductive heat transfers, indeed a key reservoir longevity issue.

4.5 Heat demand projections

As previously discussed, these matters, in the absence of a multidisciplinary team approach capable of apprehending prospective forecasts, remained merely conservative and, by all means, speculative.

In this respect, the heat “offer” scenario provides an interesting compromise by maximising heat production and related, earlier commented, recovery and efficiency factors. The so assessed heat offer may represent a challenging opportunity to alternative energy planners and, would they exist, far sighted decision makers.

4.6 Economics

Based on table 3 figures, the contemplated scenarios are deemed economically attractive compared to conventional fossil, chiefly gas, fired and other renewable energy systems. This statement reflects the prevailing energy (heating/cooling) pricing trends, the status of state of the art, mature technologies, mastered mining risks and, last but not least, operators’ entrepreneurial and managerial skills.

The advent of an ecotax, to the benefit of generating processes meeting clean air concerns, would obviously boost competitiveness of geothermal heat.

4.7 Externalities

These actually would deserve a specific dissertation which falls out of the scope of the present review.

However, worth mentioning is the environmental impact of geothermal district heating which already achieves annual savings of ca. 500,000 tons of CO₂ atmospheric emissions. These savings, incidentally, contribute to reducing the so-called environmentally provoked diseases (asthma among others). In addition, the promotion of centralised district cooling is likely to achieve significant power savings and avoid excessive grid loading.

Table 3: Selected Economic Figures (constant 2004 €)

MINING INVESTMENTS (10 ³ €)	
• 2011-2035	
- Existing doublet reconditioning/lining.....	450
- Drilling/completion of a new, corrosion resistant, production well.....	3,000
- Miscellaneous equipments/fittings.....	150
	TOTAL
	3,600
• 2036-2060	
- Abandonment (cementing) of the initial well doublet	350
- Replacement of the production well fiberglass liner.....	450
- Drilling/completion of a new, corrosion resistant, injection well	2,750
- Miscellaneous equipments/fittings.....	200
	TOTAL
	3,750
COMPARATIVE FIGURES	
<i>Capital investments (10³ €)</i>	
• Natural gas cogeneration plant (rated 5 MWe) / Conventional, steel cased (9"5/8), well doublet	4,600 / 3,600
<i>Cost prices (€)</i>	
• MWh, geothermal / MWh, cogeneration	5-8 / 3-4
ECOTAX PROJECTED IMPACTS (Carbon atmospheric emission tax)	
Impact on a 30,000 MWh/yr district heating doublet	50€/t
Unit price impact	200,000
	7€/MWh,

5. CONCLUSIONS

Owing to the exhaustible nature of geothermal resources, sustainable heat mining is of utmost importance in designing and implementing relevant exploitation strategies aimed at reconciling users' demands with reservoir longevity concerns.

The latter require (i) dependable reservoir properties, (ii) reliable heat extraction technologies, and (iii) appropriate databases and reservoir simulation tools.

These issues were illustrated on a case study, borrowed to the well documented Paris Basin district heating scheme, which benefits from a thirty year exploitation record and thirty four ongoing district heating well doublets.

The review addressed a carbonate reservoir of regional extent, hosting a thermochemically hostile fluid, a hot saline brine including a CO₂/H₂S enriched solution gas phase, making injection of the heat depleted brine into the source reservoir an environmental prerequisite, alongside pressure maintenance and heat recovery concerns.

Clearly, corrosion/scaling, initially overlooked, shortcomings and water injection proved the most sensitive problem areas, an attribute, as a matter of fact, shared by most geothermal reservoirs worldwide, would they be hosted either by low or high enthalpy, fractured or not, consolidated carbonate and loose clastic sedimentary or volcanic rock environments.

These could be overcome thanks to adequate remedial/preventing – well workover, downhole chemical inhibition – and design – new anticorrosion well concept, doublet modelling – strategies which, alongside risk assessment surveys, played a dominant role in upgrading reservoir performance and optimising well deliverabilities thus securing exploitation longevity.

While approaching the twenty five year deadline assigned to geothermal district heating projects and to well life, the question arose as whether there was a life after. Or, would the geothermal route be abandoned and natural gas fired systems, already coexisting with geothermal heat exchange on twenty cogenerated grids, be substituted instead.

The foregoing were a matter of debate among involved parties and a first answer provided by local and subregional reservoir simulation of two sustainable development scenarios addressing successively (i) isolated well doublets and (ii) multiwell doublet arrays.

Simulations of future trends in heating/cooling demand together with adequately spaced/located triplet/doublet designs, proved consistent with expectations as no thermal breakthroughs occurred over a fifty year life, extending from year 2011 to 2060. Noteworthy is that, in the multidoublet case, the heat offer exceeded by more than 50% the anticipated demand.

In addition, economic figures, especially when boosted by environmental tax incentives, shape quite attractive on the grounds of reliably assessed capital investment and operation/maintenance costs.

The next step, (in progress), designed as a thorough reservoir management tool, focuses on regional, basin wide,

reservoir simulations operated online with an exploitation database.

Summing up, here, as already noticed from the geothermal exploitation record scored worldwide, lifetimes nearing one hundred years should not be any longer regarded as utopia, whatever the scepticism once disclosed by conventional energy planners.

So, everything considered, sustainable geothermal energy development has a good chance.

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