GEOTHERMAL RESERVOIR MANAGEMENT. A THIRTY YEAR PRACTICE IN THE PARIS BASIN

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ABSTRACT

The present paper addresses the development and management of large geothermal district heating grids exploiting, since the late 1960s – early 1970s, a dependable carbonate reservoir located in the central part of the Paris Basin, France.

The geothermal reservoir consists of a hot water aquifer, of regional extent, hosted by Dogger pervious oolithic limestones and dolomites, of Mid-Jurassic age, at depths and temperatures ranging from 1450 to 2000 m and 56 to 80°C respectively.

Development of the resource was boosted in the aftermath of the first and second, so called, oil shocks (mid to late 1970s). It led to the completion of 54 geothermal district heating systems, based on the, mass conservative, well doublet concept of heat mining, of which 34 remain online to date.

The paper reviews the main development milestones and related key exploitation and managerial issues which enabled to accumulate a considerable experience with respect to reservoir engineering and maintenance/surveillance of production facilities.

Sustainable development/management problematics are also discussed in the light of geothermal reservoir longevity, innovative (re)designs of mining infrastructures and environmental benefits.

1. HISTORICAL OVERVIEW

The first attempt to exploit the hot waters, hosted in the Dogger carbonate formations of Mid-Jurassic age, dates back to year 1962, at Carrières-sur-Seine, West of Paris. The well, despite its high productivity, was abandoned due to a highly mineralised brine incompatible with the disposal of the waste water in the natural medium (a surface stream). This led, in 1969, Sthal, a private joint venture, to commission the first field application of the geothermal doublet concept of heat mining combining a production well and an injection well pumping the heat depleted brine into the source reservoir.

The doublet (two deviated, 7" cased, wells) produced in self-flowing mode, was put online in 1971, on the henceforth Melun l'Almont emblematic site, South of Paris, to supply heat and sanitary hot water to the local social dwelling compound. It enabled incidentally to design new, titane alloyed, plate heat exchangers able to cope with a corrosive geothermal fluid, a slightly acid (pH = 6), saline (30 g/l eq NaCl) and hot (74°C) brine. The system has been operating satisfactorily since start up, the doublet moving in the meantime towards a triplet array including two injector and one new, innovative, production well combining steel casings and freely suspended, non cemented, fiberglass liners. Noteworthy is that this pioneer achievement was completed independently from any energy crisis nor public subsidies whatsoever. Regarded at the time as a technological, fairly exotic, curiosity, it has been extended since then to the whole Paris Basin geothermal district heating schemes.

The energy price crisis following the 1970's oil shocks led the French authorities to promote, among other alternative energy sources, low grade geothermal heat as base load to district heating grids and other space heating systems. This has been concluded by the development, in the sole Paris Basin, of fifty five geothermal doublets of which thirty four are still operating to date.

This is indeed an outstanding, almost unique of its kind, accomplishment comparable to the heating of the City of Reykjavik in Iceland, which belongs however to a significantly different geological (volcanic rocks, high source temperatures), technical (no reinjection) and socio-economic (insularity) context.

It has undoubtedly benefited from the conjunction of three main driving factors (i) the evidence of a dependable geothermal reservoir (Dogger limestones) of regional extent, identified thanks to former hydrocarbon exploration drilling[1], (ii) a strong, voluntarist, commitment of the State in favour of alternative energy sources and ad-hoc accompanying measures (mining risk coverage, mutual insurance -sinking- funds against exploitation hazards, financial support to district heating grids and miscellaneous incentives), and (iii) last but not least, the location above the geothermal resource of large social dwelling buildings, eligible to district heating, widespread throughout the Paris suburbs.

This stated, the geothermal venture did not avoid contagion from infantile diseases inherent to the implementation of new technologies as evidenced by various symptoms, mainly:

- ***structural:*** lack of expertise from operators (chiefly of the public sector) in managing industrial installations and energy processes with a strong mining impact;
- ***technical:*** insufficient mastering in operating heating grids, under a retrofitted scheme combining several base load, back-up/relief energy sources and fuels, repeated failures of submersible pump sets and, above all, devastating corrosion of casings, well heads and equipments by the geothermal fluid;
- ***administrative and managerial:*** imprecise definition of the duties and obligations of concerned intervening parties (operators, engineering bureaus, heating companies, consultants) and of relevant exploitation/service contracts, inefficient marketing and negotiation of heat sales and subscription contracts;
- ***economic and financial:*** severe competition from conventional fossil fuels (heavy fuel oil, natural gas) penalizing heat sales and revenues, persistent low energy prices in the aftermath of the second oil shock, adding to a debt nearing 85 % of total investment costs in a capital intensive (5 to 8 Meuros), low equity, high interest rate (12 to 16 %) environment ; this clearly placed most geothermal operators in a typically third world situation.

With time and experience, structural and technical problems could be overcome in many respects by systematic monitoring of the geothermal fluid and primary production/injection loop, periodic logging inspection of well casings, innovating workover and chemical inhibition procedures aimed at restoring well performance and preventing corrosion/scaling damage, the latter supported by the State through relevant R & D programmes and funding.

In the early 1990's, the State made it possible to mitigate the debt charge, which was renegociated via a spreading out of annuity repayments and interest rate reductions. Tax deductions were applied to geothermal operators, regarded therefore as energy producers, the most significant one addressing the VAT (set a 5.5 % instead of the former 18.6 % rate). Simultaneously, improved administrative and financial management of geothermal district heating grids could be noticed among most operators.

The revival of a technology, at a time endangered to such a point that its abandonment has been seriously envisaged, could be achieved at the expense of the shutin/cementing of 22 doublets, i.e. ca 40 % of the initial load and of a subsequent loss in heat supplies summarized in the following figures:

	1986 (target)	**2000 (actual)**	**2005**
• number of operating doublets	54	34	34
• installed capacities (MWt)	360	227	220
• yearly heat supplies (heating + SHW) (GWht/yr)	2000	1240	1000

The situation, although stabilised, remains precarious on purely economic grounds. As a matter of fact, falling energy price trends could ultimately condemn geothermal district heating with the exception of, say fifteen, profitable doublets.

The challenge is clear. To remain competitive, the geothermal MWht selling price must stand at ca. 35 €, i.e. no more than 10 % above the natural gas (LCI, lower calorific index) price according to the tariff offered to industrial users. Consequently, gas cogeneration appealed to many geothermal operators, while negotiating renewal of past heat subscription contracts, as a viable issue securing the survival of their grids and installations. Hence, as of late 2003, fifteen combined gas cogeneration plants and geothermal district heating grids were operating, a figure likely to match the twenty mark at the November 2004 deadline.

Gas cogeneration provides stable earnings from sales to the public utility of the whole generated power at a high contractual purchasing price, guaranteed over twelve years, elsewhere partly indexed on natural gas prices, i.e. at reasonable financial risk. Cogeneration supplies cheap heat, as an electricity by product recovered via the cooling of the generating units, gas engines or turbines. Maximization of power revenues causes cogenerated heat to be operated as base (constant) load over the 151 calendar day contractual period (from 1st November to 31st March) at the detriment of geothermal heat, whose contribution during winter drops by 40 %, if not more, when no extension of the existing grid is commissioned in the meantime (only four sites, out of fifteen, to date).

Environmental, clean air, concerns and limitation of greenhouse gas (mainly CO2) emissions should turn geothermal district heating into an asset, favouring its everlastingness if not its (re)development. This, provided both national and EU policies promote relevant legal and fiscal carbon/energy saving credits.

Summing up, the outlook for geothermal district heating seems presently limited to the operation of the thirty four operated doublets on line and to the implementation of gas cogeneration units on two thirds of the existing grids, restricting geothermal heat supplies to ca 1,000 GWht/yr [2].

Privatisation of geothermal doublets/heating grids, widely initiated in the past years under the form of acquisitions, concessions, leases and public service delegations should address, in the short run, over twenty installations equally shared between the three leading heating/energy groups. Only could the Public and an established State policy, as was the case in the mid 1970's/early 1980's, reverse these adverse trends and reactivate geothermal heating which, everything considered, has proven its technological and entrepreneurial maturity [3].

Last but not least, the impact among the Public of recent climatic disasters attributed to global warming and of high oil prices should trigger the necessary stimulus. In this perspective, the taxation of CO2 atmospheric emissions, once scheduled by the Government, at a rate ranging from 30 € (2001) to 75 € (2010) per ton of carbon, is obviously primordial.

2. 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 [2] (see areal extent in Fig. 1a)

Among the four main litostratigraphic units exhibiting aquifer properties, depicted in the Fig. 1b 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 context associated with 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.

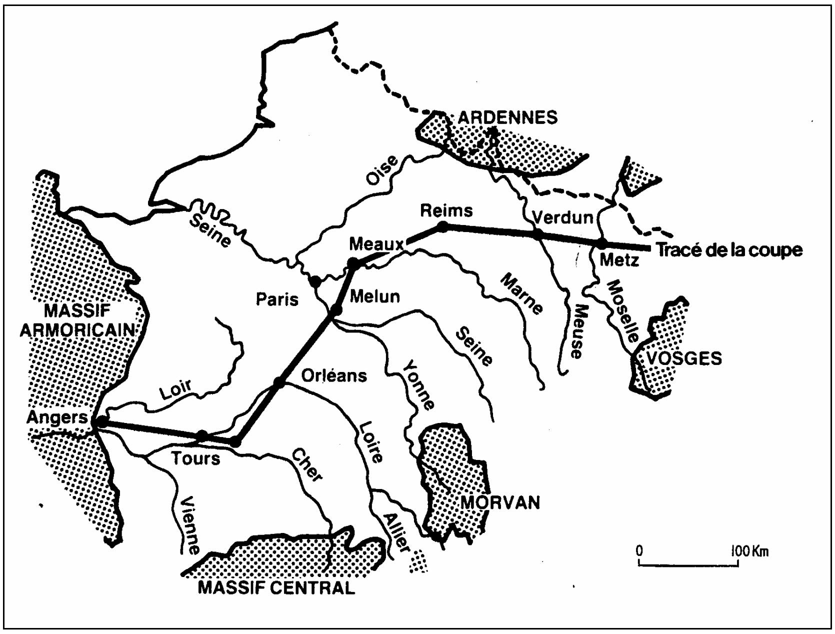


Figure 1a: Paris Basin areal extent [19]

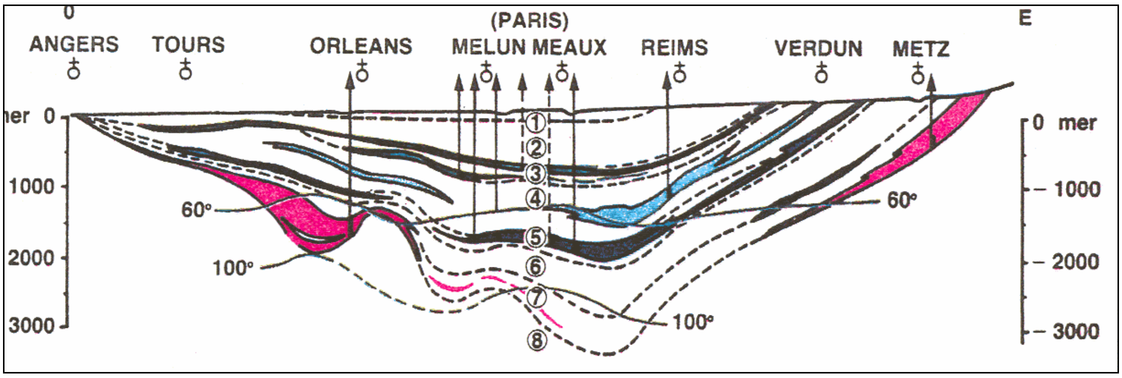


Figure 1b: Cross sectional view of the main deep aquifer horizons [19]

3. DEVELOPMENT STATUS AND MILESTONES

The location of the geothermal district heating sites is shown in Fig. 2. 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.

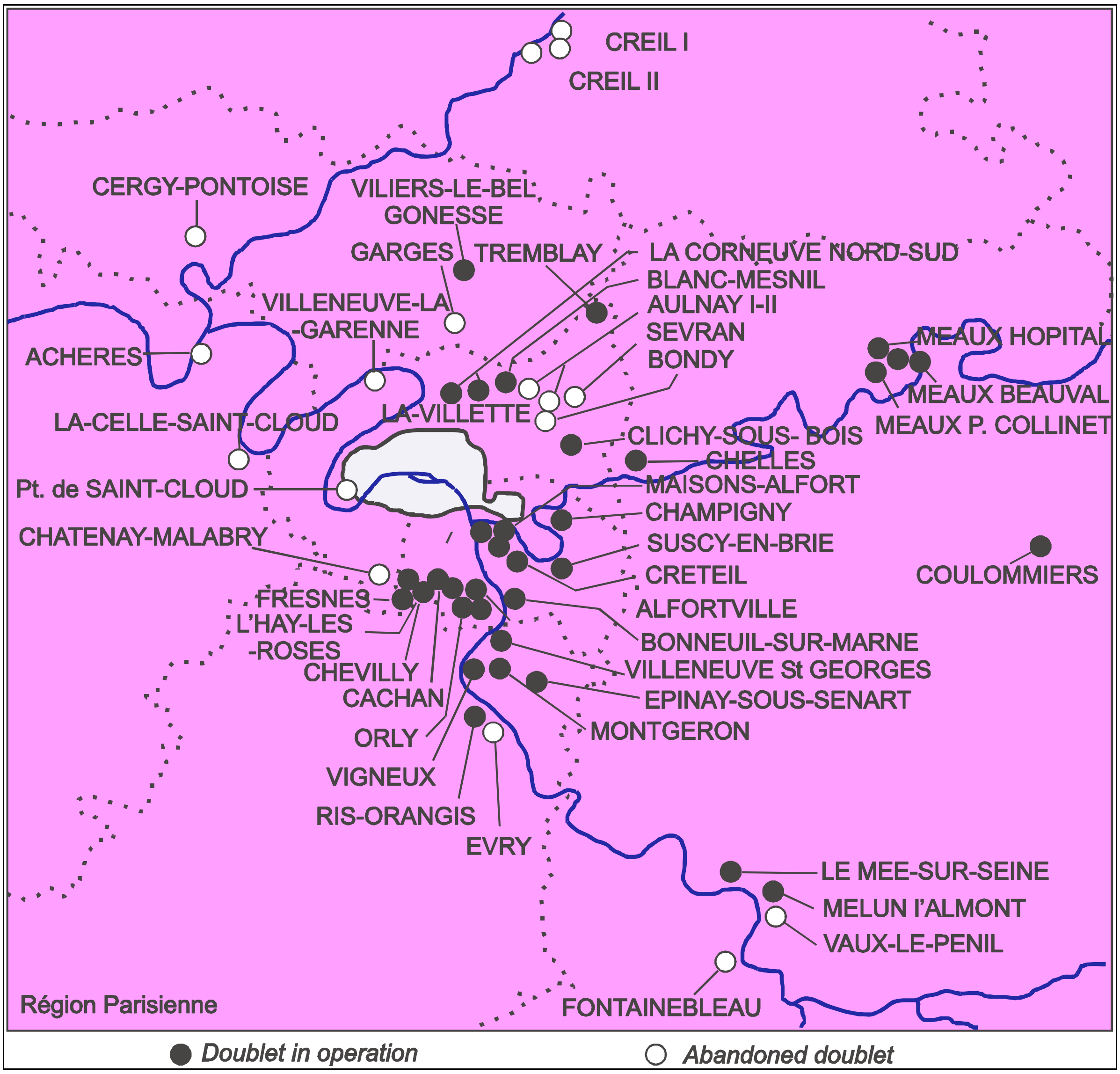


Figure 2: Location of the geothermal district heating sites in the Paris Basin

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

	Target (1985)	Achieved 1990	Achieved 2000	Forecast 2006
Operating doublets	55	43	34	34
Total installed capacity (MWt)	360	260	227	200
Produced heat (GWht/yr)	2,000	1,455	1,240	1,000
Unit capacity (MWt)	6.5	6.0	6.7	5.9
Unit yield (MWht/yr)	36,000	33,800	36,200	30,000
Artificial lift wells	49	36	27	22
Self-flowing wells	6	7	7	12

At the beginning of heating year 1987-88, fifty four doublets were assumed operational, thus close to the anticipated figure. Actually, no more than forty eight were in service, of which one third were undergoing severe exploitation problems resulting in temporary shut in periods, attaining in many instances several months.

In 1990, forty three doublets were serviced and ca 1,450 MWht delivered to the heating grids, i.e. 25 % below initially projected figures. In year 2000 the annual delivery dropped to 1,230 GWht as a result of lesser operating doublets (thirty four) and start up of ten combined geothermal/gas cogeneration systems. Despite this downward trend, optimization of the most performant doublets, which happen to coincide with the most recently completed (third generation) ones, resulted in unit capacities (6.7 MWt and 36,200 GWht/yr) close to initially anticipated targets. However, future implementation of commissioned and projected cogeneration systems is likely to reduce these unit capacities, to those foreseen for year 2006.

The methodology adopted in assessing the reservoir, extracting heat, operating and maintaining the production systems, processing the exploitation data and managing the reservoir, in relation to the timescale and milestones is summarised in the Fig. 3 diagram.

This diagram highlights the following:

- the reservoir could be early assessed, prior to the first oil shock, thanks to previous hydrocarbon exploration-production (expro) which evidenced the attractive geothermal potential hosted by the Dogger reservoir;
- feasibility studies made it possible to locate the candidate development sites in terms of eligible surface heat loads and local reservoir performance/well deliverabilities;
- simultaneously, a risk diagram was defined, for each site, in order to match the critical Q (discharge rate)-T(wellhead temperature) success/failure criteria required to meet economic viability. This set the bases of a, State supported, insurance fund aimed at, in case of a total failure, covering up to 80% of the costs incurred by drilling of a first exploratory well;
- field development (1969-1985) resulted in the drilling/completion of 54 well doublets of which 52 addressed the Dogger geothermal reservoir proper. An almost 100% drilling success ratio was achieved after deduction of the mitigated success/failure (50%) ventures recorded on two sites;
- the Mining Law, applicable to low grade geothermal heat (sources below 150°C) was enforced in 1975 together with a package of accompanying incentives (coverage of the exploration risks, creation of a mutual insurance fund compensating exploitation, heat mining induced, shortcomings/damage, financial support to prefeasibility/feasibility studies and energy savings/fossil fuel replacement);
- these voluntarist measures, decided in the aftermath of the first and second oil shocks, created a legal/institutional/regulatory framework enhanced by various financial (fiscal)/ insurance incentives, which boosted the reclamation of geothermal energy sources in this area. Exploration/exploitation concessions were awarded, subject to approval and control by the ad-hoc competent mining authority, and subsidies allocated accordingly;
- the early exploration stages were subject to the inevitable learning curve hazards, odd equipment design, corrosion/scaling damage, poor maintenance protocols, loose management and financial losses aggravated by high debt/equity ratios negotiated by, mostly public, operators. They could be overcome thanks to improved monitoring, maintenance and managerial policies;
- After infantile disease and teenage geothermal exploitation turned adult, the technologies becoming mature and the management entrepreneurial, setting the premises of sustainable development for the future.

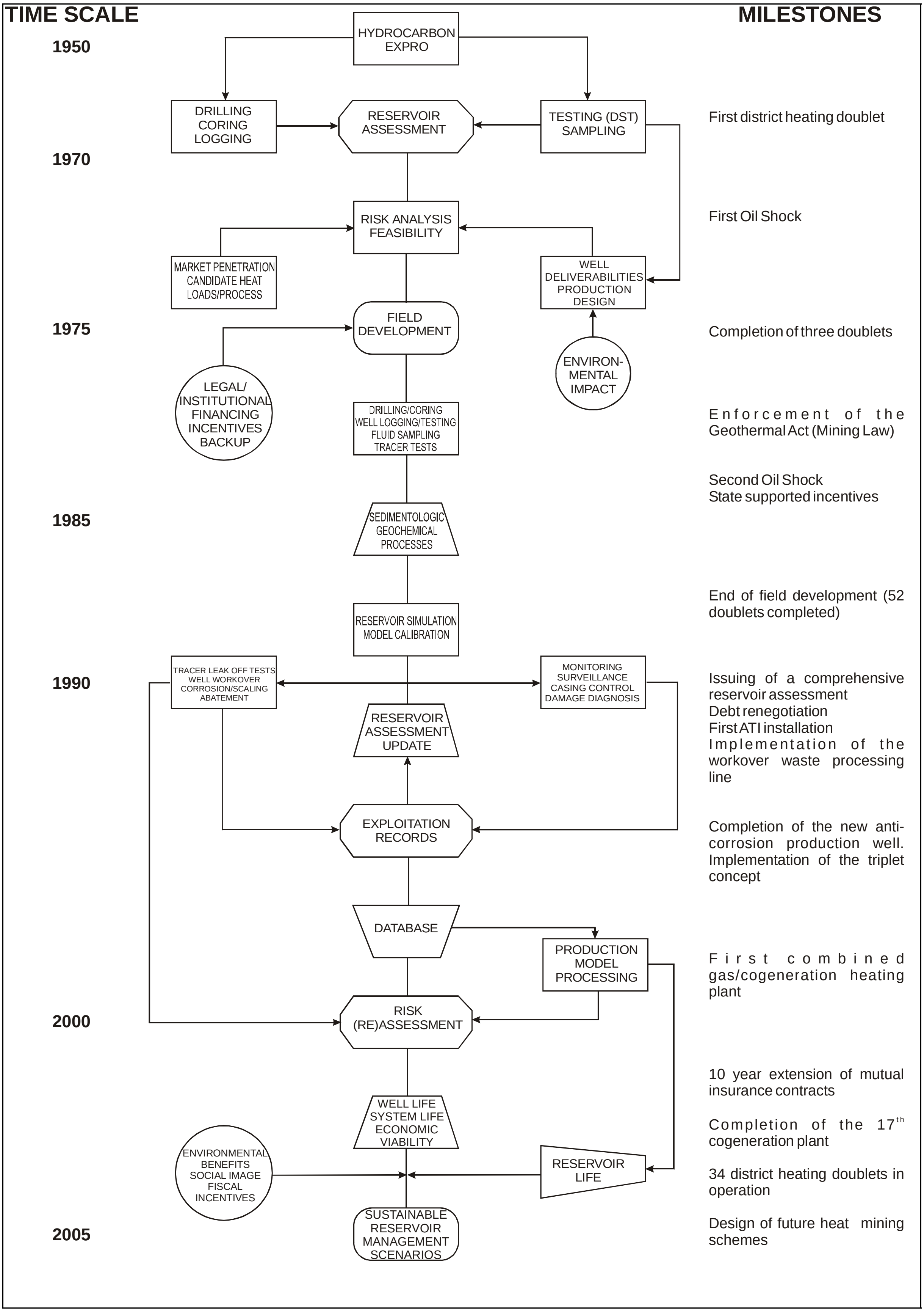


Figure 3: From oil exploration to geothermal sustainable development

Several events are worth mentioning in this perspective:

- the first industrial application in 1969, at Melun l'Almont, South of Paris, 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 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 the operation of a well triplet array 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.

4. Technology outlook

The standard geothermal district heating system is based on the well doublet concept, depicted in fig. 4, and on the surface system and governing parameters sketched in fig. 5. It should be noticed that:

(i) as shown in fig. 4, most well (production/injection) trajectories are deviated from a single drilling pad with wellhead and top reservoir spacing of 10 and ca. 1,000 m respectively. They are produced via, variable speed drive, electric submersible pump (ESP) sets (see fig. 5);

(ii) the heat is recovered from the geothermal brine by, corrosion resistant, titanium alloyed plate heat exchangers;

(iii) geothermal heat is used as base load and therefore combined with backup/relief, fossil fuel fired, boilers, unless otherwise dictated by combined gas cogeneration/geothermal systems;

(iv) district heating complies to retrofitting which means that geothermal heat supply has to adjust to existing conventional heating devices, most often not designed for low temperature service. This has obvious implications on rejection (injection) temperatures and well deliverabilities.

The principles governing geothermal district heating are summarised in table 1. It should be stressed here, that in no way is the heat supply constant but highly variable instead, as it varies daily and seasonally (in summer only sanitary hot water is produced) with outdoor temperatures. This entails variable discharge/recharge rates and injection temperatures, well deliverabilities and production schedules.

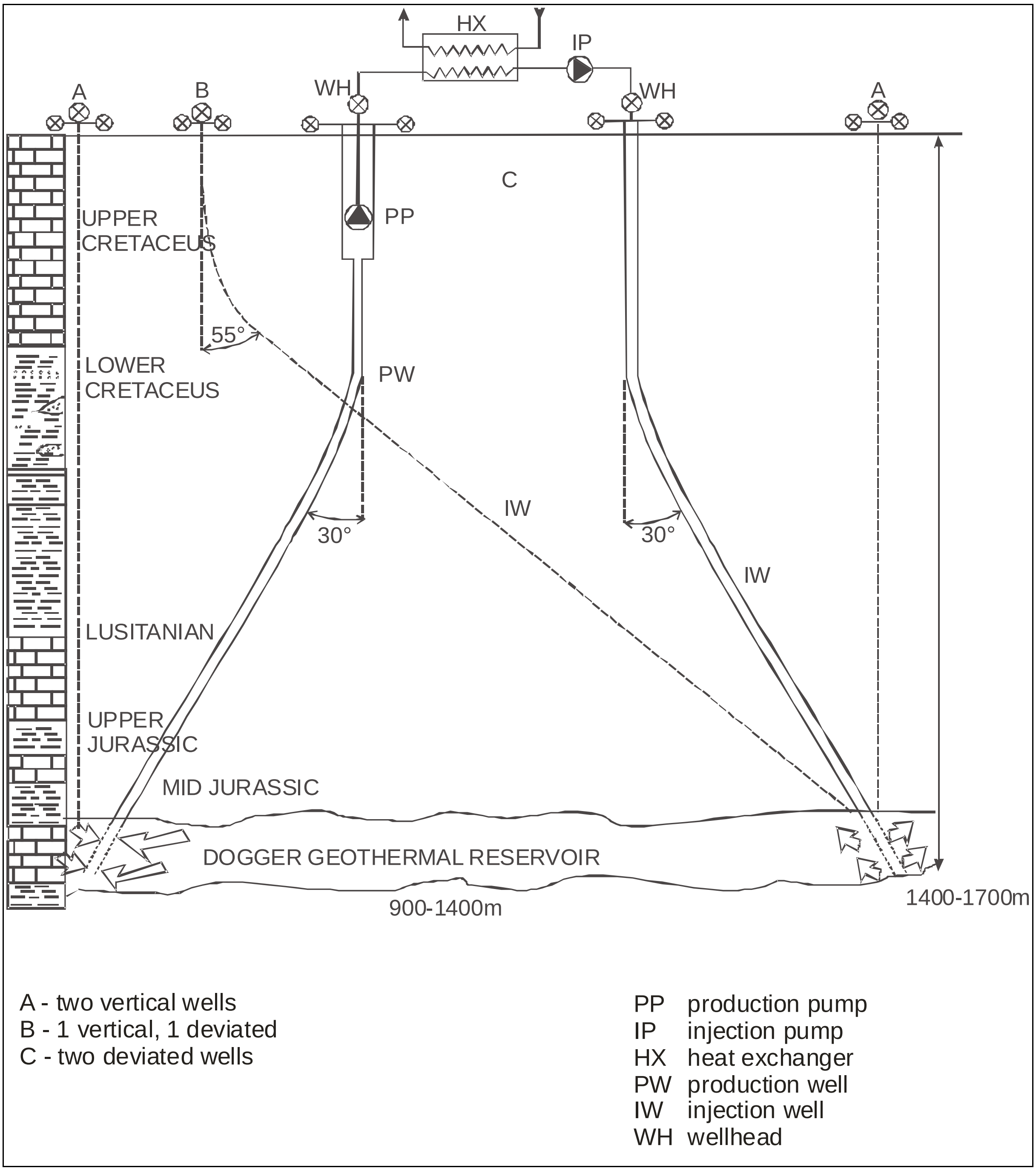


Figure 4: The geothermal well doublet

Equipment performances and lifetime record

Components, including wells, equipping the geothermal loop are itemized, and their recorded and projected lifetimes, listed in table 2. This document speaks for itself. It constitutes the relevant data base for the cost estimates, risk assessment and economic evaluation developed later.

Production technology, with respect to artificial lift and self-flowing mode, is analyzed, alongside pros and cons of the three experienced submersible pump concepts, in[3].

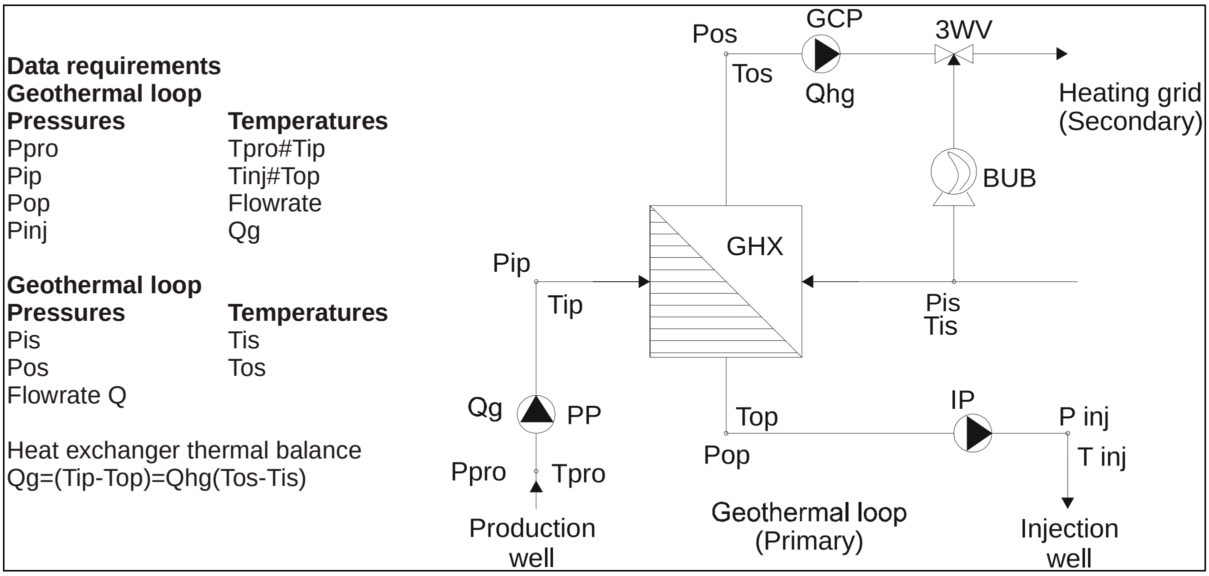


Figure 5: Geothermal district heating parameters

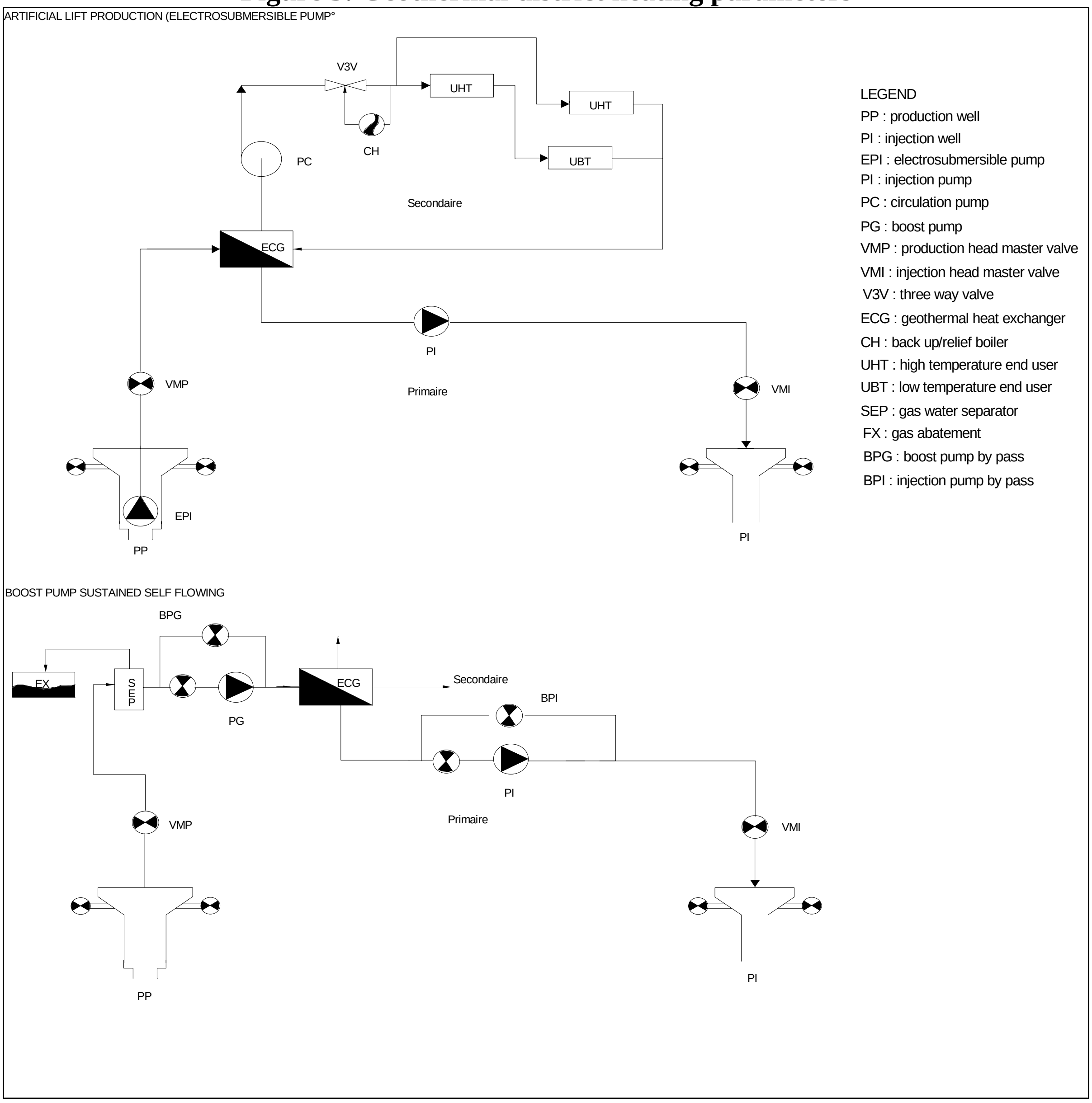


Figure 6: Geothermal well (sustained and self-flowing) production modes

Table 1: Geothermal district heating analysis. System components and parameters(after Harrison et al)

GEOTHERMAL POWER	NETWORK/HEATERS	HEAT DEMAND
$P_g = M_g (\theta_g - \theta_r)$ $M_g = \rho_w \gamma_w q_g / 3.6$	$P_n = M_n (\theta_a - \theta_{ref})$ $M_n = NED \times V \times G / (m_{hi} / m_{ho})$ $m_{hi} = (\theta_{hi} - \theta_{nh}) / (\theta_a - \theta_{ref})$ $m_{ho} = (\theta_{ho} - \theta_{nh}) / (\theta_a - \theta_{ref})$	$P_d = M_d (\theta_a - \theta)$ $M_d = NED \times V \times G / 1{,}000$ $W_d = 24 \times NDD \times M_d / 1{,}000$ $NDD = \int_0^{NHD} (\theta a - \theta) dt$

HEAT EXCHANGE	GEOTHERMAL SUPPLY
$P_{hx} = \eta_{hx} P_g = \eta_{hx} M_g [(\theta_g - \theta_{nh}) - M_{ho} (\theta - \theta_{ref})]$ $\eta_{hx} = \{1 - \exp [- N (1 - R)]\} / \{1 - R \exp [- N (1 - R)]\}$ $N = UA / M_g$ $R = M_g / M_n$	$W_{hx} = \eta_{hx} M_g \{(\theta_g - \theta_{nh}) - m_{ho} \times 24 \int_0^{NHD} [\theta(t) - \theta_{ref}] dt\}$ $GCR = W_{hx} / W_d$
REGULATION CRITERIA $\theta_{no} = \theta_{ref} + m_{no} (\theta_a - \theta)$ $\theta < \theta^*$: maximum geothermal flowrate, back up boilers $\theta^* < \theta < \theta_{ref}$: total geothermal supply	

NOMENCLATURE	
P = power (kW_t)	U = heat exchanger heat transfer coef. ($W/m^2 °C$)
W = energy (MWh_t /Yr)	A = heat exchanger area (m^2)
M = thermal capacity (kW_t/°C)	R = flow ratio
NED = number of equivalent dwellings	GCR = geothermal coverage ratio
NDD = number of degree days	m = heater characteristic (slope)
NHD = number of heating days	q = flowrate (m^3/h)
V = equivalent dwelling volume (m^3)	γ = specific heat (J/kg°C)
G = average dwelling heat loss ($W/m^3 °C$)	ρ = volumetric mass (kg/m^3)
N = number of heat transfer units	θ = temperature (outdoor) (°C)
Subscripts	
g = geothermal	o = outlet
w = fluid (geothermal)	hi = heater inlet
d = demand	ho = heater outlet
n = network	nh = non heating (lowest heater temperature)
h = heater	a = ambient (room)
hx = heat exchanger	ref = minimum reference outdoor
i = inlet	r = rejection (return)

Typical values (Paris area)		
NED = 2,000/4,500	V = 185 m3	θ_{hi}/θ_{ho} =
NDD = 2,500	θ_{ref} = - 7°C	90/70°C cast iron radiators
NHD = 240	θ_r = 40/50°C	70/50°C convectors
N = 5	θ_g = 55/75°C	50/40°C floor slabs
qg = 200/350 m3/h	θ_a = 17/18°C	
g = 1.05 W/m3°C	θ_{nh} = 20°C	

Table 2: Equipment performance. Lifetime record

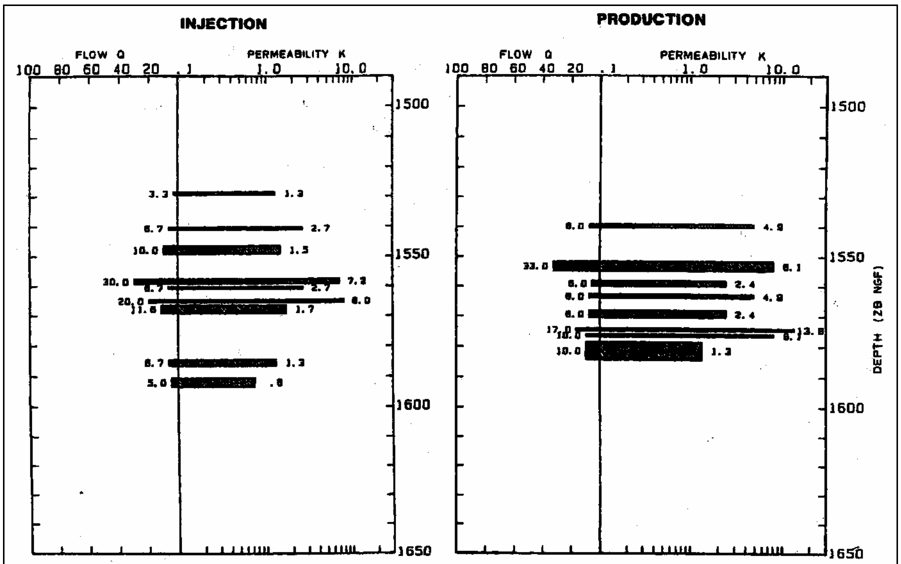
Item	Lifetime (years)	Remarks
Production well	20-25	subject to reconditioning
Injection well	20-25	subject to reconditioning
Casing heads/spools	15	
Master (ball) valves	5	
Wing (ball) valves	5	
Butterfly valves	3-5	
Valve motorization	6-8	
Fiberglass liners	10-15	projected figure
Fiberglass liner well head	8-10	projected figure
Expansion joints	5-8	optional equipment
Geothermal loop piping : - carbon steel	15-20	
- fiberglass	10-15	often subject to odd initial fitting
Filters, strainers, screens	5-8	higher lifetime when duplicated
Desurgers (hammer preventers)	15-20	
Geothermal loop instrumentation/regulation : - pressure, temperature gauges	3-6	require periodical recalibration
- flowmeters	10	electromagnetic types, require periodical recalibration
- pressure/temperature sensors	3-6	require periodical recalibration
- automaton	5	change due to obsolescence
Production pumps : - ESPs	4	safe figure
- LSPs	-	unsufficient record
- HTPs	5-8	could last 10 yrs if no casing inspection required
Production tubing :		
- rubber (I/O) coated carbon steel	8	highly reliable figure
- fiberglass	5	abandoned alternative
Production pump transformer	10	
Water level control line	5	often subject to breakages during pump maneuvers
Injection pump	10	replaced by parts
Surface boost pump	10	replaced by parts ; applicable to self flowing wells
Surface charge pump	5	replaced by parts ; applicable to HTP
Inflatable packer	8	applicable to HTP
Frequency converters	10	replaced by parts : thyristors and control cards
Down hole chemical injection line	5-8	AIT type
Surface metering pump	10	highly reliable figure
Degasser	10	projected figure ; applicable to self flowing wells
Hidden combustion flare	10	projected figure ; applicable to self flowing wells
Geothermal heat exchanger	10	titane alloyed plate type ; replacable by parts (seals and plates)

ESP = Elecrosubmersible pump
LSP = Lineshaft pump
HTB = Hydraulic turbine pump
AIT = Auxiliary injection tubing

5. RESERVOIR ENGINEERING

5.1 Reservoir characterisation

Up to ten productive layers may be individualised on flowmeter logs as shown in Fig. 7a. However sedimentologic (lithofacies) analyses on cores and cuttings allowed to group them in three main aquifer units and permeability and thickness allocated accordingly which confirm the dominant share of the oolithic limestone member. It leads to the equivalent, either single layer or three layer, reservoir representation depicted in Fig. 7b, used later for reservoir simulation purposes[4], [10].



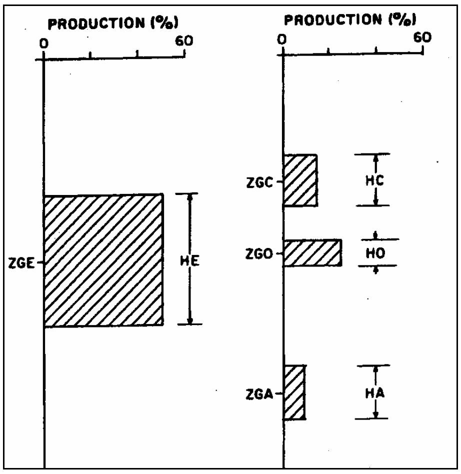
INJECTION

PARAMETER	COMBL.	OOLIT.	ALTER.	TOTAL PAY
H m	2.1	9.6	5.0	16.7
KH Dm	4.2	33.2	5.0	42.4
K D	2.0	3.5	1.0	2.5
Q %	10.0	78.3	11.7	100.0
ZB NGF	1536.6	1560.2	1588.2	1561.1

PRODUCTION

PARAMETER	COMBL.	OOLIT.	ALTER.	TOTAL PAY
H m	1.3	11.2	5.9	18.4
KH Dm	6.3	65.9	8.0	80.2
K D	4.9	5.9	1.3	4.4
Q %	8.0	82.0	10.0	100.0
ZB NGF	1539.8	1563.4	1581.4	1563.3

Figure 7a: Flow permeability spectra on injection and production wells (spacing 1162m) [4]



equivalent single layer reservoir | equivalent three layer reservoir

Figure 7b: Equivalent reservoir model from flowmeter logs

5.2 Reservoir simulation

Three modelling strategies are contemplated:

- ***local modelling restricted to a single doublet neighbourhood,*** assuming homogeneous reservoir properties, and an equivalent monolayer geometry with either constant pressure (recharge) or impervious (no flow) boundary conditions. Three simulators are currently used, either the analytical model described in [5] either TOUGH2 or SHEMAT, discretised field, computer codes. An application of the latter to a 75 year, doublet/triplet projected life under changing well locations and production/injection schedules, is discussed in a second paper [10];
- ***multidoublet areal modelling by means of both analytical and numerical simulators.*** In the first case the reservoir is assumed homogeneous and multilayered. This exercise may exaggeratedly oversimplify the actual field setting in which case a numerical simulator such as TOUGH2 or SHEMAT, taking into account reservoir heterogeneities and a multilayered structure, would be preferred instead;
- ***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 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. In this respect, substituting average doublet figures provided by interference testing, to individual well test value would achieve a relevant smoothing compromise;
- ***a solute transport partition*** can be added to handle the tracer case and track 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 the Dogger database, and to extract multistage subregional/local models whenever required by the operators.

The calibrated reservoir model sets the base for predicting reservoir life and assessing sustainable development and management scenarios.

6. OPERATION AND MAINTENANCE

This vital segment of reservoir exploitation includes three main headings:

(i) monitoring and surveillance of heat production facilities;
(ii) well workover, and
(iii) corrosion/scaling abatement.

6.1 Monitoring and surveillance of production facilities

According to the mining and environmental regulatory framework in force and to site specific agreements, geothermal loop monitoring and surveillance comply to the following protocol :

- ***geothermal fluid:***
  - hydrochemistry (main anions/cations) and corrosion/scaling indicators : iron and sulphide/mercaptane,
  - thermochemistry : bubble point, gas/liquid ratio, dissolved gas phase,
  - microbiology (sulphate reducing bacteria),
  - suspended particle concentrations,
  - coupon monitoring,

- ***loop parameters:***
    - well head pressures and temperatures,
    - production well head dynamic water level,
    - heat exchanger inlet/outlet temperatures,
    - geothermal and heating grid flowrates,
    - heat exchanger balance check,
- ***well deliverabilities:***
    - well head pressure/discharge (recharge) curves (step drawdown/rise tests),
- ***pump and frequency converter characteristics:***
    - voltage, amperage, frequencies,
    - powers,
    - efficiencies,
    - ESP insulation,
- ***inhibitor efficiencies:***
    - corrosion/scaling indicators control,
    - inhibitor concentrations,
    - filming (sorption/desorption) tests,
- ***inhibition equipment integrity:***
    - metering pump,
    - regulation,
    - downhole chemical injection line,
- ***wellhead, valves, spool, filter integrities,***
- ***surface piping (ultrasonic) control,***
- ***casing status:*** periodical wireline logging (multifinger calliper tool) inspection of production and injection well casings.

6.2 Well workover

During a Paris Basin geothermal well life (20 years minimum), a number of heavy duty workovers are likely to occur, addressing well clean-up (casing jetting), reconditioning (lining/cementing of damaged casings) and stimulation (reservoir acidising and casing roughness treatment). The probability level of such events is analysed in the risk assessment section.

6.3 Corrosion and scaling abatement

The geothermal fluid, a slightly acid (pH≈6), saline brine including toxic and corrosive solution gases (H_2S and CO_2), creates a thermochemically hostile environment endangering well casing and surface equipment integrities.

The corrosion and scaling mechanisms in the aqueous CO_2-H_2S system cause these gases to interact with the exposed steel casings, pipes and equipment, forming iron sulphide and carbonate crystal species as a result of corrosion. These aspects had been merely overlooked and impaired dramatically well performances in the early exploitation stage before appropriate downhole chemical injection strategies [6] be successfully implemented to defeat, or at least slowdown, the corrosion process.

Well workover and corrosion/scaling abatement caused the operators to prove technically innovative in the design and implementation of well cleanup jetting tools, continuous downhole chemical injection lines and inhibitor formulations, soft acidising techniques, tracer leak off testing and waste processing lines, discussed in more details in a following paper [10].

6.4 Dogger database

In no way has the Dogger reservoir and exploitation database be designed as archives dedicated to a geothermal saga, but instead as a dynamic monitoring and management tool.

The whole database, discussed in [4], is currently developed, operated and hosted on the Oracle platform and data instructed locally via a Microsoft Access interface.

7 RISK ASSESSMENT

Paris Basin geothermal district heating projects and accomplishments 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 the assessment of exploitation risks will be discussed here.

Exploitation related risks could not be estimated from scratch. A (long term) fund initially financed by the State, was created in the 1980s to cope with the hazards induced by the exploitation of the geothermal fluid. Later, this fund, could be supplied by operators' subscriptions.

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 over a fifteen year well life. This exercise was applied to thirty three doublets. The governing rationale, developed in [4], consisted of (i) listing potential and actual, technical and non technical, risks (ii) ranking and weighting them, then (iii) classifying risks according to three levels (1 : low, 2 : medium, 3 : high), each subdivided in three scenario colourings (A : pink, B : grey, C : 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 (A), five (B) and three (C) scenario colourings. It allowed to allocate a provisional fund to cope with foreseeable exploitation hazards as discussed in [4].

8. THE COGENERATION ISSUE

Cogeneration appeared, in the late 1990s, as a realistic survival alternative to geothermal operators facing severe competition from cheaper fossil fuels, firing conventional boilers, while negociating renewal of end users heating contracts.

Gas cogeneration on geothermal district heating grids raised growing interest, for the simple reason that the power required to produce the heat, which remains largely unused (hardly 10 % of the grid capacity), is sold to the utility at a price guaranteed over twelve years and indexed on gas market prices, with tax incentives added as a bonus, indeed a financially and fiscally attractive issue. The interest is mutual. The gas company increases its market share and sells significant gas quantities to meet the demand of the grid (currently producing between 30,000 and 50,000 MWht/yr). The grid operator purchases cheap heat produced at marginal cost as a by product of power generation.

Practically, candidate (combined cycle) systems consist of natural gas fired engines or turbines driving alternators. Heat is recovered (i) on engines on the cooling circuit and, at a lesser extent, on exhaust gases, and (ii) on turbines via exhaust gases. Heat to power ratios stand around 1.1 (engines) and 1.35 (turbines) respectively. The essentials of gas/geothermal cogenerated system designs are schematized in figure 8a (gas engine) and 8b (gas turbine).

The cogenerator must comply to the following conditions:

- 50 % minimum (global) energy efficiency,

- heat to power ratio higher than 0.5,
- use (self-utilization) of produced heat,
- conformity certified by the competent authority.

The contract is passed with the utility for a duration of twelve years. The cogenerator suscribes a guaranteed installed power and a plant utilization factor (subject to bonus/malus) of 95 %. Cogeneration extends over a 151 calendar day (from November 1st to March 31st) heating period.

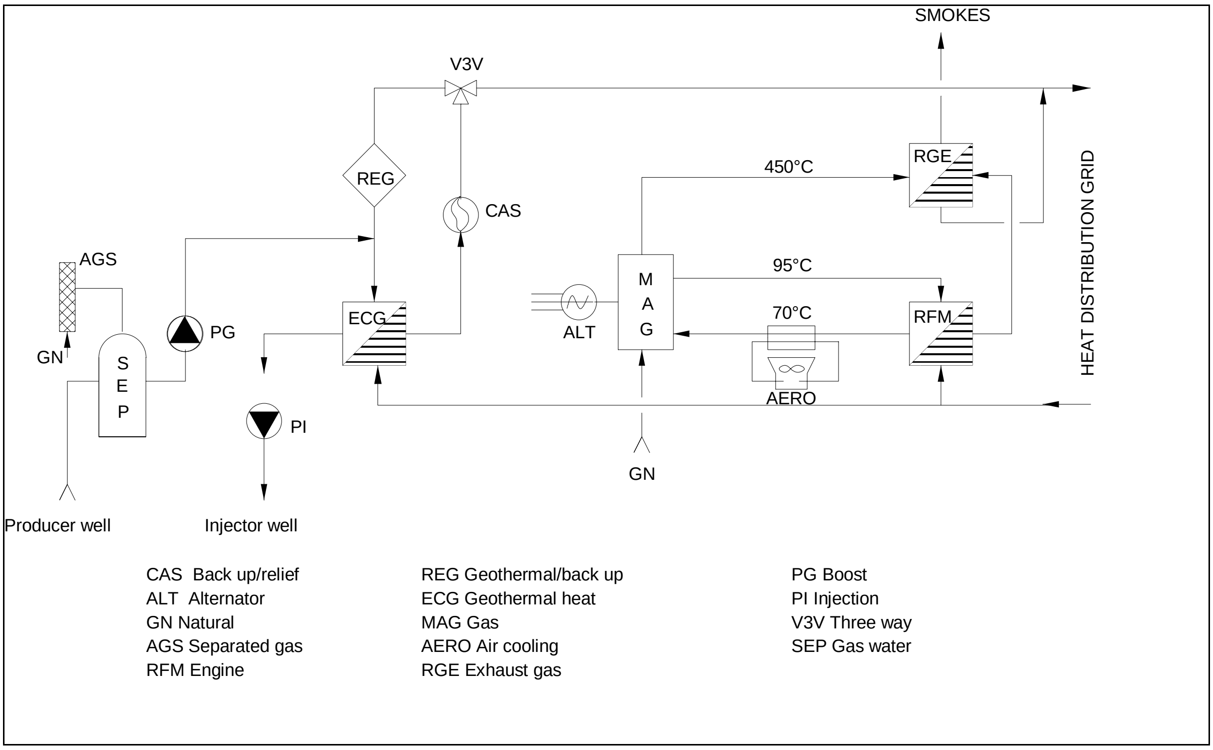
The foregoing have important implications on geothermal production. Power (and heat) is generated constantly, at nominal rating, over 151 days (3,624 hours) to maximize electricity sales. Therefore cogenerated and geothermal heat are operated as base and back-up loads respectively during winter heating. This results in a somewhat drastic drop of geothermal heat supplies. Actually, in many instances artificial lift was abandoned and self-flowing production substituted instead, according to the design depicted in figure 9.

On economic grounds, the following figures, borrowed to two typical cogeneration grids, shape quite attractive with discounted pay back times nearing five years.

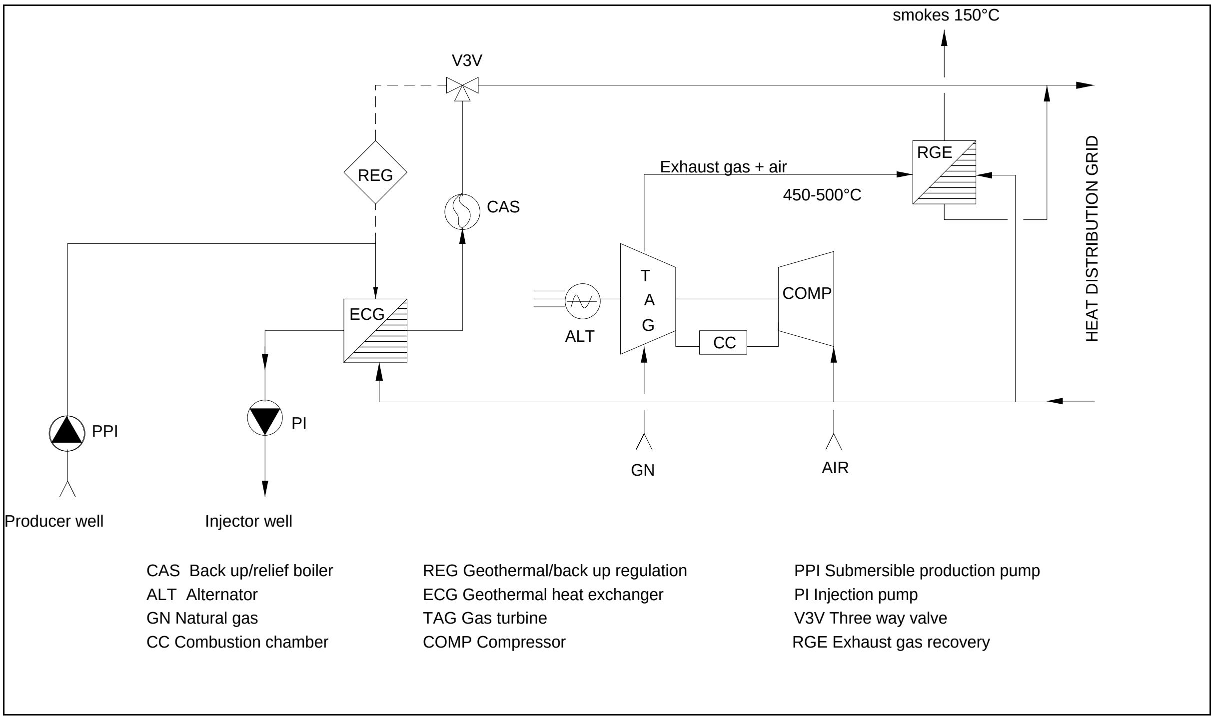
	grid 1	grid 2
Generating unit	gas engine	gas turbine
Power rating (MWe)	4	5.5
Power production (MWhe)	13,100	16,400
Gas consumption (MWht ; HCI)	39,700	57,700
Heat production (MWht)	16,400	21,600
Revenues (10^3 €)	*1,674*	*2,053*
- power sales	1,006	1,259
- heat sales	668	794
Expenditures (10^3 €)	*1,308*	*1,754*
- debt charge	311	320
- gas costs	787	1,092
- maintenance	180	296
- miscellaneous	30	46
Balance (10^3 €)	+*366*	+*299*

Increases in natural gas prices have a penalizing impact, mitigated though, thanks to the contract passed with the utility, which compensates ca 75 % of gas tariff rises. In the aforementioned examples, a 40 % increase in gas prices would result in additional expenditures amounting to 78 (1) and 111×10^3 € (2) respectively.

Cogeneration has become a reality on many operating doublets. At the start of the 2002/2003 heating season, fifteeen cogeneration/geothermal heating grids were on line. Five other doublets are already commissioned and due to operate in 2004. Six new candidate sites are projected. Summing up, within the next years, only ten to twelve doublets should be exploited via the conventional heat exchange/back-up relief boilers heating mode.



a) engine cycle



b) turbine cycle

Figure 8: Cogeneration cycles

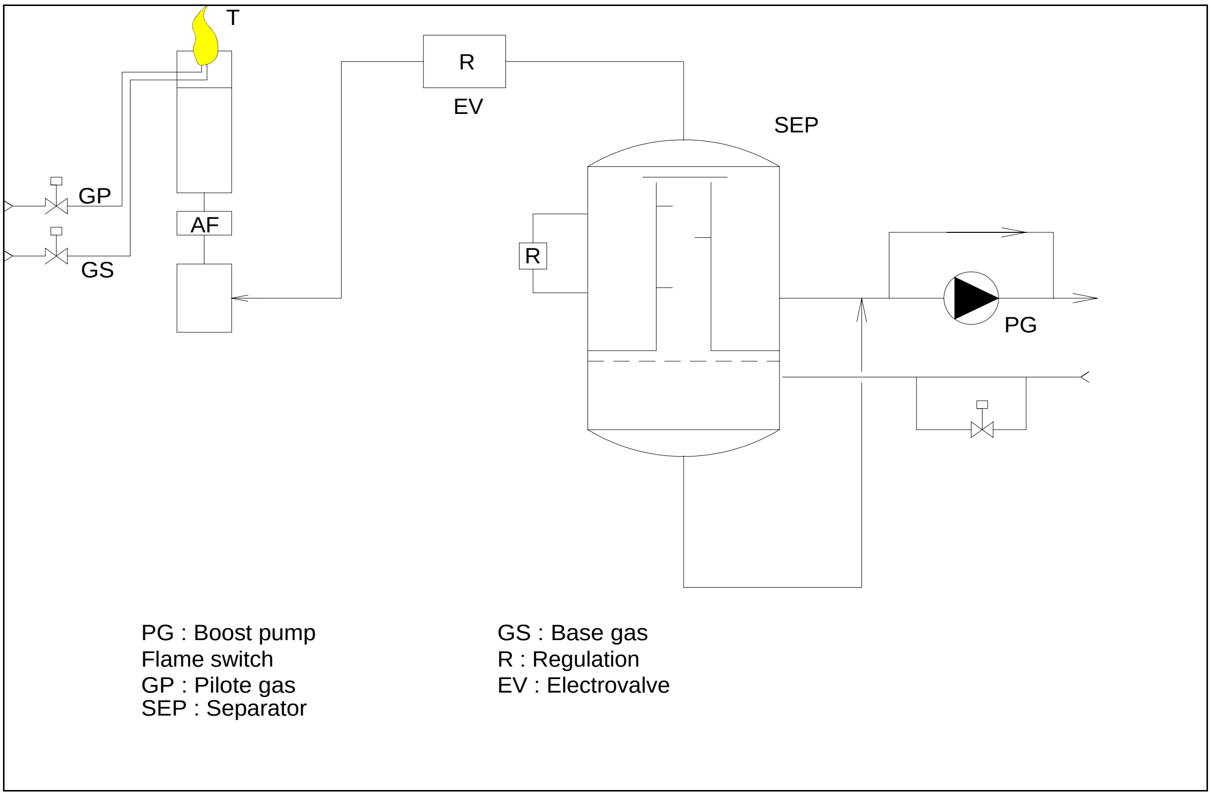


Figure 9: Geothermal solution gas separation and abatement (self flowing production below bubble point)

9. ECONOMY

Total geothermal investment costs amounted in the Paris Basin to ca 500 million € representing a unit investment cost of ca 1,400 €/installed kWt. Investment costs are split as follows (million €):

	Min.	Max.	Mean
- mining (well) costs	1.83	2.74	2.29
- heat plant/primary surface loop	0.61	1.07	0.76
- grid construction/substation modifications ...	4.57	13.72	6.86

It is a generally accepted fact that, under normal feasibility conditions, total investment costs stand close to 10 million €, to which the whole geothermal loop (wells, heat plant, surface piping and equipment) contribute to 30 % and the grid proper to 70 % respectively. From 80 % to 90 % of the investment was provided by (public) bank loans and the remaining 10 to 20 % by public subsidies and grants.

Operation and maintenance costs include three main headings, namely energy (electricity and back-up fossil fuels), light maintenance/monitoring and heavy maintenance /equipment warranty and miscellaneous (provision for heavy duty works, overhead) costs.

The grid (primary and secondary networks) is operated permanently by a heating company with an assigned staff of three to five employees. The geothermal segment is monitored periodically, and serviced occasionally, by a geothermal engineering bureau. A thermal engineering bureau is usually appointed by the geothermal operator to assist the management in controlling grid operation and heat supplies.

Description of the various capital investment and OM cost items relevant to Paris Basin district heating systems may be found in a comprehensive economic review developed in [7].

Revenues address heat sales to end users connected to the grid. These sales include both geothermal and boiler (back-up/relief) generated heat.

Global cash flow streams, selected on sites deemed representative of Paris Basin conditions, are displayed the table 3. It emphasizes the dominant financial share of the debt repayment annuity which often nears 60 % of total expenditure. This, added to back-up/relief boiler costs, sensitive to natural gas prices and to the geothermal coverage ratio, exemplifies the structurally fragile economic and financial balance of Paris Basin geothermal operations. Actually, out of thirty four doublets, fifteen achieve profitability, twelve breakeven and six show a deficit. Prices close to 38 € could hardly compete in the past years with natural gas whose tariffs could afford a near 30 €/MWht figure. It is worth mentioning however, that on several doublets (A, C and D in the table 3, among others), debt repayments will cease in year 2002.

To overcome these financial problems, two issues can be contemplated, in the short term, combined natural gas cogeneration/geothermal grids and, in the medium term, enforcement of an ecotax applicable to greenhouse gas emissions. The latter would definitely secure a more attractive profit margin for the mutual benefit of geothermal producers and end users. Along this line, a typical example of a Paris Basin prospective balance sheet is given in [7] and several revival scenarios of presently abandoned doublets are analyzed in [8].

Table 3: Yearly cost breakdown of several district heating doublets

Item/doublet	A1 (1)	A2 (1) (2)	B	C	D1 (1)	D2 (1) (2)
Total heat supply (MWht/yr)	58,000	43,500	48,888	51,000	40,000	31,000
- geothermal	39,500	32,500	42,000	41,000	26,000	15,000
- back-up boilers	18,500	11,000	6,000	10,000	14,000	16,000
- geothermal coverage %	68	75	87.5	80	65	48
Heat selling price (€/MWht)	38	37	37.5	39	41.5	41.5
Revenues (10^3 €/yr)	2,135	1,598	1808	2006	1646	1285
Expenditure (10^3 €/yr)	2,061	1,607	1764	1886	1492	1349
- debt charge	1,082	1,037	1052	1159	655	488
- power	133	108	157	90	85	79
- back-up fuels	508	302	165	274	384	439
- maintenance	247	224	280	268	276	252
- heavy duty workover provision	55	37	61	50	38	38
- overhead	37	37	49	44	53	53
Balance (10^3 €/yr)	+70	-9	+44	+120	+154	-64

(1) dual doublet management (2) cogeneration on line in 2000

10. SUSTAINABILITY

It addresses the problematics of well longevity and reservoir life in compliance with environmental protection requirements.

It has been proven that geothermal district heating achieves, in the Paris Basin, the yearly savings of ca. 500,000 tons of CO_2 atmospheric emissions, a figure based on a heat production nearing 1,000 GWht/year from dominantly geothermal/natural gas cogenerated systems, deemed a reasonable compromise.

How long can such savings be secured, given that (i) well longevities and thermal breakthrough times hardly exceed twenty to twenty five years, and (ii) a minimum fifty year prerequisite should be allocated to reservoir life?

These are key issues which require thoroughly assessed, prospective, heat demand and offer scenarios and adequately designed mining (well arrays) schemes, both implemented on reservoir simulation models, are discussed in a second paper [10] and in [4], [9].

11. CONCLUSIONS

Based on an experience dating back to the mid 1970's, the following conclusions may be drawn as to the past, present and future of geothermal district heating in the Dogger carbonate reservoir, Paris Basin.

The geothermal source proved dependable with respect to reservoir extent and performance securing easy well completions and high yields. Drillings achieved a 95 % success ratio and well productive capacities currently attain 250 m3/h - 70°C nominal ratings.

Large social dwelling compounds of the Paris suburban belt favoured the district heating development route as a result of suitable heat loads overlying the resource.

The doublet concept of heat mining and retrofitting were the governing rationale in exploiting the resource and heating the end users connected to the heating grid downstream of the geothermal heat exchanger.

Developments benefited from a strong involvement of the State, following the first and second oil shocks (mid to late 1970’s), in favour of alternative energy sources. Relevant supporting policies addressed the areas of legal/ institutional (mining law), risk coverage (exploration and exploitation sinking funds), financial backing (fiscal incentives, subsidizing), project reviewing/commissioning (ad-hoc committees) and heat marketing.

In the mid 1980's, fifty four doublets were on line and exploitation targets set at 360 MWt (installed capacity) and 2,000 GWht/yr (heat production) respectively. Since then recorded figures did not match expectations. As a matter of fact actual figures, as of year 2000, stand at thirty four operating doublets, 227 MWt installed capacity and 1,200 GWht/yr heat supply with a likely 200 MWt/1000 GWht/yr projected for 2005. This situation reflects the learning curve phases, infancy, teenage and maturity, inherent to any new technological development, particularly in the mining field.

Paris Basin geothermal development was soon confronted to three major problems, namely :

- **technical problems**: the thermochemically sensitive geothermal brine caused severe, corrosion/scaling induced, damage to well tubulars and production equipments ; these problems had been clearly overlooked at design/implementation stages,
- **financial problems**: deemed the most critical, they resulted from a massive debt charge (no equity) aggravated by a, low price, depleted energy market in the aftermath of the second oil shock,
- **managerial problems**: they related to the lack of experience and expertise of geothermal operators, the large majority belonging to the public/municipal sector, in handling industrial installations including a significant mining segment ; consequently loose monitoring and maintenance policies were the rule.

This bleak outlook could be progressively overcome thanks to innovative, State supported, chemical inhibition and well restoration technologies, debt renegociation and sound management of geothermal heating grids. These sharp progresses were however accompanied by the abandonment of the twenty or so poorly reliable doublets.

So, everything considered, in spite of a fairly hostile, competing, economic environment geothermal district heating scored well. It demonstrated so far its technological and entrepreneurial maturity and gained wider social acceptance.

Still, economic viability proves fragile and only could gas cogeneration secure the survival of a number of geothermal district heating grids in the late 1990s-early 2000s. Fifteen cogeneration systems are operating to date and it is likely this figure will reach the twenty mark in the near future, unless otherwise dictated by striking oil and gas price increases.

Where to go next?

A major question arises on whether the future of geothermal district heating reduces to the sole gas cogeneration survival scenario in which geothermal heat no longer supplies base load in winter time.

Recent climatic disasters attributed to global warming and greater sensitivity of the public to environmental, clean air, concerns could challenge this trend and turn low grade geothermal heat into a widely accepted asset. Tax incentives, such as carbon and/or energy saving credits should in this respect be decisive in giving geothermal heating a new stimulus.

Prospective developments could, in the short run, address realistically two objectives. First the extension of existing (cogenerated and non cogenerated) geothermal grids to new users. Second the reactivation of abandoned doublets according to a revival, triplet, design combining two injectors (the old wells) and one, new generation, production well.

The latter addresses sustainable reservoir development and management, a key issue discussed in paper [10] and [11].

Ultimately, new district heating doublets should be completed in a few selected Paris Basin localities.

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