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The Road Ahead Toward Sustainable Geothermal Development in Europe

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ABSTRACT

As of late 2008, the geothermal community scored a 12,000 MW_e and 31,000 MW_t geopower and geoheat capacities installed worldwide of which 1,300 MW_e and 10,000 MW_t located in Europe (including Iceland and Turkey). EGEC (European Geothermal Energy Council) set targets at 5,000 MW_e and 25,000 MW_t respectively. Figures assessed from authorised energy institutional sources have estimated, on the bases of present reserve assessment standards and power conversion processes, the geothermal power potential recoverable worldwide and in Europe at ca 140,000 and 10,000 MW_e respectively. Furthermore, reclamation of the energy, stored as heat, over Continental Europe, to a depth of 5 km at temperatures above 150°C, would yield a 25,000 MW_e generating capacity. Similar conclusions could be drawn for heat with a European dependable reserve base nearing 100,000 MW_t.

Clearly, to meet the aforementioned Geopower and Geoheat development targets, new resource and utilisation environments need to be explored and assessed, efficient production/conversion technologies designed and demonstrated and the life cycle of existing and future systems extended to secure sustainability requirements. The foregoing will be highlighted through selected case studies and development obstacles, constraints and incentives discussed accordingly.

Meeting those ambitious geopower and geoheat development objectives requires that efforts, based on reliable reverable reserve assessments and sustainable heat mining technologies, focus on the following priorities:

- Shallow geothermal (< 400 m). Intensification of the heat pump load.
- Deep geothermal (< 4000 m). Harnessing the huge medium enthalpy reserve and CHP openings; implementation of district heating/cooling grids.
- Ultra deep geothermal ($\geq$5000 m). Mobilise an ad-hoc task force for making the EGS premises a reality, by first concentrating on the mid-grade poorly convective EGS sites before tackling the low grade, conduction dominated, EGS frontier.

Last but not least, geothermal development requires that a large geothermal market be created and a geothermal industry structured accordingly.

1. INTRODUCTION

Europe at large (i.e. continental/political Europe extended to Iceland and Turkey) encompasses the whole geothermal energy spectrum and related geodynamic attributes. It pioneered outstanding achievements, among which worth mentioning are (i) the first geopower turbine driven by a superheated (“dry”) steam source (Larderello, Central Tuscany, 1904), (ii) the large geothermal district heating (GDH) grids serviced in the City of Reykjavik (since the 1940-1950s) and the Paris suburban areas (since the 1970s) and, last but not least, (iii) the first electricity ever powered from a 5,000 m deep enhanced geothermal system (EGS) completed at Soultz-sous-Forêts (Rhine Graben, 2008).

Although geothermal accomplishments scored well, thanks to extraction and conversion technologies mastered to mature stages, geothermal energy development in Europe is at a crossroads.

Actually, the ambitious (and disputed) targets set forth by the European Geothermal Energy Council (EGEC), as of year 2020, for geopower and geoheat installed capacities/yearly energy supplies, 5,000 MW_e/ 35 TWh_e and 25,000 MW_t/ 80 TWh_t respectively, represent a true qualitative jump if not a challenge compared to existing figures, 1,300 MW_e/ 8.5 TWh_e and 10,000 MW_e/ 30 TWh_t respectively.

This, bearing in mind that although a renewable energy source, as an evidence of the terrestrial heat flow, in no way is geothermal heat inexhaustible. Its resupply is conductive and its extraction convective, one order of magnitude higher.

Hence, bridging this gap requires that resources/reserves and eligible uses be thoroughly assessed and sustainable heat mining schemes designed accordingly. Regarding geopower and combined heat and power (CHP) issues, selection of relevant candidate, EGS demonstration sites should be assigned the highest priority.

These key issues are illustrated in fig. 1 and 2. Fig. 1 displays the resource utilisation spectrum by highlighting (i) the emergence of supercriticial fluids in selected volcano-tectonic environments, (ii) the dominant role expected in the near future from, long overlooked, medium enthalpy sources thanks to conventional and enhanced organic Rankine cycle (ORC) geopower production, and (iii) the widespread low enthalpy geoheat utilisation field, particularly low temperature shallow seated sources likely to be boosted by the blossoming development of water driven ground source and ground water heat pump systems. Fig. 2 addresses the ultimate EGS challenge in extending the presently “usable” geothermal domain from high/mid/low grade – high porosity (> 0.10)/permeability (> 100 md) hydrothermal boundary to the vast unexplored/unexploited high/mid/low grade poorly porous and permeable, conduction dominated, EGS frontier. This implies creating interfracture connectivity where there was initially none.

As a result, the present paper will defend and illustrate the aforementioned key issues through selected case studies addressing resource/reserve assessments, heating and cooling applications and EGS problematics

Ungemach and Antics.

Economic, environmental and legal/institutional impacts, alongside risk mitigation, are discussed *in-fine*.

2. RESOURCE ENVIRONMENTS

Europe exhibits a variety of geothermal resource settings, displayed in fig. 4 sketch map, which relate to distinctive geodynamic environments namely:

- Large sedimentary units subdivided into (i) intracratonic (Paris – Hampshire, Aquitaine, Tajo, Castillan, Rhone – Languedoc, West Yorkshire – Netherland, North German, Danish, Warsaw, Thracean), (ii) orogenic belt (Pyrenean, Ebro, Caltanisetta, Alpine, Po Valley, Appenninic, Carpathian) foredeep, and (iii) marginal/back arc basins (Pannonian, Transylvanian, Aegean) hosting, generally multiple, aquifer systems with normal, low and high geothermal gradients respectively, favouring direct uses, among which geothermal district heating (GDH) holds a prevailing share.

- Tertiary-quaternary continental rifts (Rhine Graben, Limagne, Rhone – Bresse, Campidano, Pantelleria) eligible to medium enthalpy/CHP prospects and, ultimately, to EGS developments of which two are online (Soultz, Landau) and one (Basel) temporarily abandoned.

- Orogenic folded belts and foreland platforms, often associated with deep faulted – upwelling hydrothermalism and medium enthalpy reservoirs.

- Crystalline massifs (Iberic Meseta, Armorican, Central France, Bohemian, Rhodope) with hot springs and hydrothermal faulted systems.

- Recent “in plate” Pliocene/quaternary volcanism (Catalunya, Puy Chain, Effel, Campidano, Susaki), regarded as candidate medium enthalpy, if not EGS, projects.

- Last but not least, active subduction, volcanic island arcs, active magmatic and recent/active “pull a part” extensional horst and graben structures, the field of excellence of high enthalpy geopower present and future achievements.

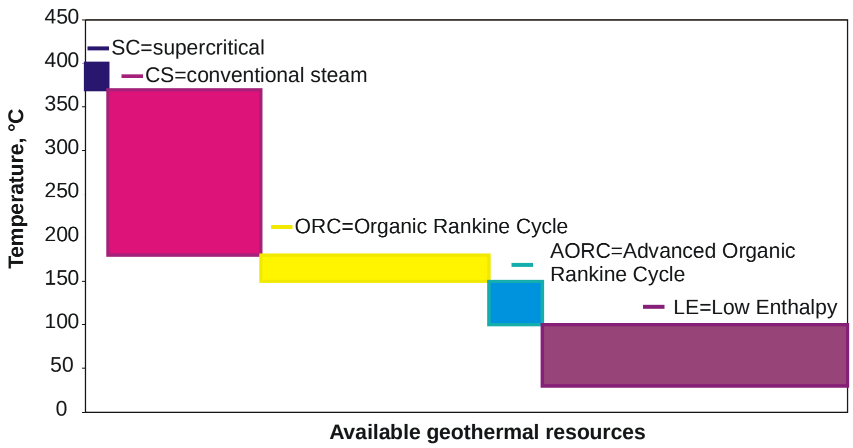


Figure 1: Geothermal resource utilisation potential. A tentative assessment

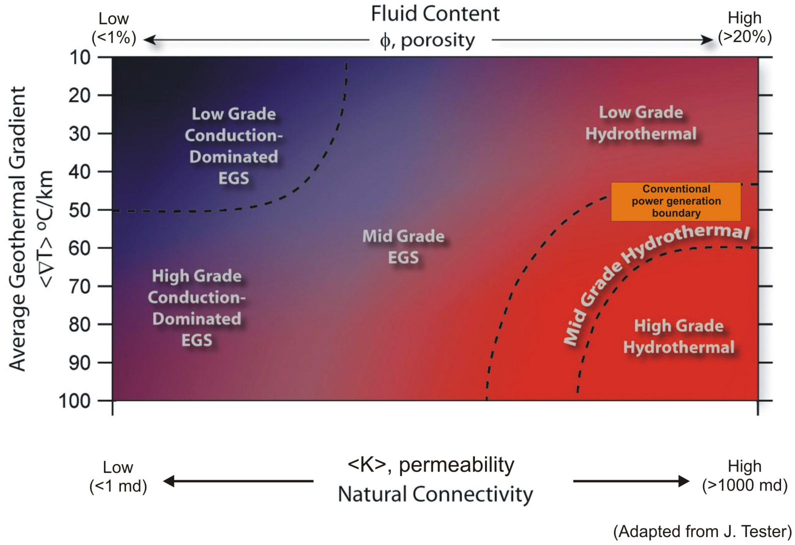


Figure 2: Geothermal continuum – The EGS issue

Figure 3: European geothermal resource environments

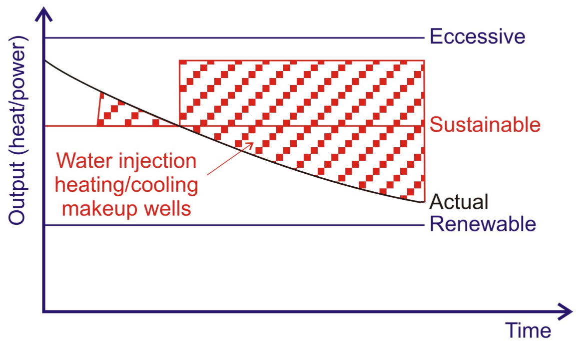


Figure 4: Renewable, excessive and sustainable exploitation strategies

3. RESOURCE DEVELOPMENT

As far as high enthalpy geopower is concerned, subduction zones and double flash condensing cycles are the dominant attributes of presently exploited high enthalpy fields worldwide. Although much remains to be reclaimed in those areas, given the geodynamics of the European plate and boundaries, high grade hydrothermal occurrence is limited to the Icelandic rift, the Central Tuscany/Northern Latinum magmato/tectonic province, the West Anatolian distensive grabens and Aeolian & Aegean volcanic island arcs.

The governing rationale is to extend the geopower potential to candidate medium to high temperature, tight rock, bodies including high grade EGSs.

Exploration methods should therefore focus on detecting, preferably fluid filled, fracture zones nearby dry holes and on relating past tectonic episodes to fractures and stress fields, whenever new drillings are anticipated, in order to significantly reduce mining risks.

Regarding medium enthalpy reclamation issues, above 100°C temperatures – below 5000 m depths resources, as portrayed in fig. 3, are widespread throughout Europe and eligible to ORC and combined heat and power (CHP) utilisation, as already confirmed on several Austrian and German prospects, in Altheim, Neustadt-Glewe, Bad Blumau, Unterhaching and Landau sites. The latter actually, although belonging to a prevailing sedimentary environment, is illustrative of the Soultz EGS rock stimulation technology transfer in bringing to production an initially dry well and securing commercial heat and power exploitation.

Clearly, this resource segment and its CHP corollary represent the major development perspective, whose success requires thorough resource/reserve and market opening assessments and a feasible/sustainable outcome of ongoing and future EGS undertakings.

The low enthalpy/direct uses sector benefits from an important, fast growing, contribution of the ground source heat pump (GSHP) and, at a lesser extent though, of the ground water heat pump (GWHP), the so called shallow geothermal, concepts.

The GSHP potential development is enormous since it can be implemented anywhere/anytime, provided there exists locally a user and a power source, i.e. it by-passes the mining rationale inherent to the search of geothermal shows and reservoirs.

Heat pump technology would significantly impact deeper seated GDH systems by boosting source temperatures, best depleting the rejection temperatures and, most important, adding a district cooling partition, thus upgrading the presently prevailing development trend.

4. RENEWABILITY VS SUSTAINABILITY

Among renewable energy sources, geothermal energy exhibits a singularity. Whereas a wind turbine or a photovoltaic cell cannot extract more energy than carried by the wind or radiated by the sun, geothermal exploitation does, in most if not all instances, extract more energy than the natural terrestrial heat supply, which flows at a 0.065 Wm^{-2} (continental average) density.

However, an objective assessment of the geothermal exploitation problematic can be biased by misleading statements regarding the natural intake of geothermal reservoirs and estimates of the potential resource base.

At a stage, when the meteoric origin of geothermal fluids was evidenced and geothermal systems therefore subject to transfer and recharge "*a popular theory was that a geothermal system at the natural recharge rate would lead to an inexhaustible source of energy. This idea appeared often, and since unchallenged, was eventually accepted as a fact*" (Ramey, 1987).

An estimate of the heat stored in the uppermost 1 000 m of the continental crust (area # 210^{14} m^2), i.e. ca 3.9 10^8 EJ (Rybach, 2003) indeed a huge potential, would, at the present world energy consumption rate (ca 450 EJ/yr), secure a 870 000 year life, and, when exhausted, require a 1030 years recovery time.

There is factual field evidence, from pressure and temperature depletion among others, this was merely wishful thinking. Actually, geothermal heat is exhaustible given that its (re)supply is structurally diffuse (conductive) and its exploitation necessarily concentrated (convective) to meet, via a heat carrier fluid, end users' demand according to technically relevant, economically viable and environmentally safe standards. Hence, reclamation of geothermal resources complies with an exploration/production mining rationale addressing the search of anomalies, i.e. occurrence of geothermal reservoirs and higher than normal heat flows in selected geodynamic and hydrogeological environments.

The foregoing pose the problematic of reservoir life and of sustainable resource extraction and management, which ambition at mining geothermal heat over significantly long, say 100 years or more times (Rybach, L. 2003a and 2003b).

However, as stressed by Sanyal (2005a), some ambiguity remains between the various definitions of renewability and sustainability suggested by the Swiss (Rybach et al., 1999, Rybach 2003a and 2003b) and Icelandic (Orkustofnun, 2001, and Axelsson et al, 2004) schools, since the first deals with the resource proper and the second with its utilisation.

Worth recalling is that the renewability issue has been recently challenged by the massive implementation of GSHP systems which have added a huge reserve, stored at shallow 100 to 400 m depths which, operated under heating/cooling mode, extract shallow terrestrial heat at near to equilibrium conditions.

4.1 Definitions

What makes the definitions of renewability somewhat mutually ambiguous are less the definitions proper than the confusion induced between them instead.

Renewability clearly means that the extracted heat is balanced by the natural recharge influx during the exploitation life span. Therefore exploitation occurs at equilibrium conditions.

Quoting Rybach (2003a), sustainable heat extraction means "*practically the ability of the system to sustain production over long times*".

More precisely, according to Axelsson et al (2004) "*for each geothermal system and for each mode of production there exists a certain level of maximum energy production, below which it will be possible to maintain a constant energy production from the system for a very long time (100 – 300 years)…*". This level is termed **sustainable production** whereas the previous one is termed **excessive production**.

These three, namely renewable, sustainable and excessive production thresholds and levels, extensively commented by Sanyal (2005a), are illustrated in fig. 4 sketch.

It is quite clear that a precise assessment of renewable and sustainable thresholds requires thorough natural steady state and predictive reservoir simulation studies to be exercised.

Sanyal (2005a), further to the compilation of some 37 liquid dominated fields, with an overall installed capacity nearing 2020 MW_e, reached the conclusion that the sustainable generating capacity was, in average, close to one order of magnitude higher than its renewable counterpart which makes sense. For instance, the renewable capacities of the Cerro Prieto, Miravalles and Nesjavellir fields stand at 73, 16 and 17 MW_e respectively and their sustainable capacities ten times higher. The renewable component estimate includes both conductive and convective heat transfers. Furthermore, it is stressed that, at the ca 10 MWe renewability threshold, hardly 11 of the reviewed fields would qualify for commercial production.

It may occur (fig. 4) that initial power generation exceeds the sustainable capacity, in which case production drops drastically until it gets sustained thanks to the drilling of make up wells (Sanyal, 2005b) to compensate the decline in production of earlier completed wells. Curiously, no mention is made whatsoever of water injection, which has elsewhere proved to be a decisive stimulus in sustaining depleted superheated (dry) steam fields.

Renewability assessments, indeed a thought provoking exercise, have been the subject of a number of contributions. Worth mentioning in this respect are those of Economides (1987), Ungemach (1988), Pritchett (1998), Rybach et al (1999), Stefansson (2000), Sanyal (2005a) and Rybach and Mongillo (2006). Summing up, three assessment approaches have been contemplated, namely (i) volumetric replenishment, (ii) post-production temperature build-up, and (iii) natural state heat flow simulation, which are reviewed by Ungemach et al. (2007). Cursory calculations by Economides (1987) and Ungemach (1988) have estimated the times required to resupply the amounts withdrawn during exploitation in the Geysers steam field and Paris Basin hot water reservoir to ca 9,000 and 80,000 years respectively. These figures are not to be taken at face values, but viewed instead as orders of magnitude, which echo the many thousand years involved in the geoheat accumulation process.

4.2 Sustainability issues

Sustainability aims basically at prolonging reservoir life ahead from the thirty year standard, seeking preferably a three and even four fold increase.

The starting points of the exercise are the energy densities and heat in place hosted by high and low enthalpy geothermal reservoirs.

Following Horne (1988) and equations listed in Appendix, the energy densities of high enthalpy geothermal reservoirs under various fluid states, compressed water, two phase and superheated steam respectively, may be calculated assuming initial reservoirs conditions set at 250 °C, 40 bars.

It can be seen that for the single liquid and vapour phases most (85 to 90 %) of the energy is provided by the rock as opposed to the two phase water/vapour mixture where the fluid supplies almost 90 % of the energy. Reservoir volumes required to sustain a 50 MW_e power production over thirty years clearly reflect this status. So does the number of geothermal flashed steam fields operated to date, which largely exceeds the occurence of single phase settings.

The stimulii to enhanced sustainable production consist of either water injection (superheated steam) or makeup wells (two phase) although both alternatives should be implemented to sustain the production objective.

Water injection and multi (production/injection) well arrays represent here the key issue in achieving high heat recovery.

4.2.1 Water injection

The Geysers dry steam field had long undergone anarchic over-production, resulting in sharp pressure decline and generated power losses alike, a trend illustrated in fig. 5, until water injection came into play. In a dry, superheated, steam field, injection of the steam condensate, recovered downstream from the turbine outlet, is of limited interest. Therefore, an exogenous water source is required which, in the case of the Geysers field, is partly supplied by a distant (Lakeside) city processed waste water, piped to selected peripheral wells. The impact of water injection can be visualised in fig. 5. The fast depleting pressure trend has been countered and significant power gains achieved, restoring up to 88 % of the electricity generation level recorded prior to water injection. Identical trends have been noticed in the Larderello field since similar practices were implemented (Capetti, 2004).

In the Geysers and Larderello, neither were make up wells of any help whatsoever, as they had already been completed, contributing thus far to over-production, excessive pressure depletion and incurred power generation losses.

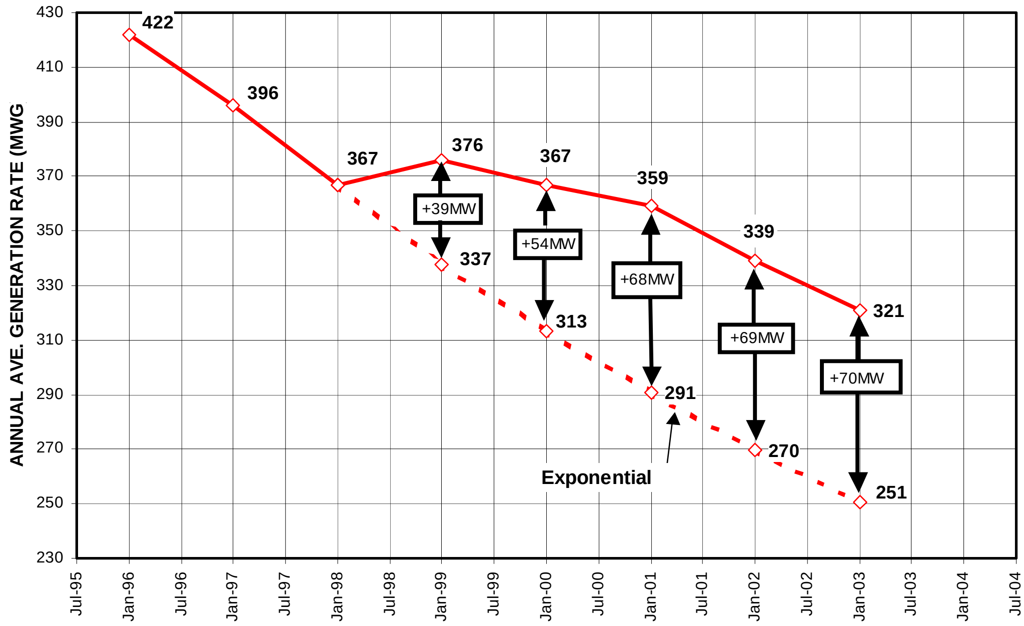


Figure 5: Effect of SEGEP injection on SE geysers generation Calpine Power Plant Units 13, 16, 18, and NCPA Plants 1 & 2 (Source: IGA, Calpine and NCPA)

As far as flashed steam, liquid dominated, fields are concerned, water injection, although raising wider interest from operators, still remains a largely unexplored route. This attitude is likely due to well short-circuiting/premature cooling, injection well plugging and, last but not least, to induced seismicity fears among others. It somewhat persists in spite of the positive impacts reported in the Imperial Valley of Southern California, despite a locally hostile thermochemical environment, to defeat subsidence of an extensively irrigated farmland, and in the Kizildere and Balcova fields of Western Anatolia (Serpen and Aksoy, 2005).

Water injection, though, requires special care while pumping cooled brines into fine grained, clastic, sedimentary environments, combining alternating sand, sandstone and clay sequences, a matter reviewed by Ungemach (2003) who emphasized custom designed brine processing/filtering and well completion issues.

Nevertheless, the benefits of water injection in low enthalpy environments have been evidenced from Gringarten (1978) investigations, which exemplify the dramatic improvements in heat recovery achieved by the doublet and, moreover, multi-doublet, "five spot", production/injection, well arrays.

4.2.2 Prolonged geothermal district heating life span

1985-2010, is there a life after? That was the geothermal existential dilemma arisen further to the completion of geothermal district heating doublets in the Paris Basin, a 25 year life span consistent with both the reservoir (appraised through the thermal breakthrough time initiating the cooling of the production well) and system physical (well casing weir) lives.

The response was positive. There is a life after, provided the heat mining system is redesigned every twenty-five years following the initial system completion, according to the well arrays and exploitation scenarios depicted in fig. 6.

Simulation results (Ungemach and Antics, 2003, and Ungemach, et al, 2005) confirmed the validity of the system design features, in that no production well cooling was noticed so far.

Furthermore, the reservoir simulation showed that this natural steady state would be re-established after several hundred thousand years for both constant pressure and impervious lateral boundary conditions (fig. 6).

4.3 Development potential. A case study

The foregoing logically lead to the assessment of the geothermal development potential of any area of interest, an exercise which has been applied by Ungemach et al (2008b) to the Madrid region (Grand Madrid and NE Madrid). The area, which enjoys one of the most favourable geothermal environment identified to date in Spain, belongs to the Tajo sedimentary basin of which it occupies its uppermost northern part. The area is bound to the North by crystalline basement rocks (a radiogenic granite) delineating the North Madrid Sierras, via a system of deep parallel faults trending SSW-NNE. The sedimentary cover, ca 3.6 km thick, includes several medium depth layers exhibiting aquifer properties and a main hot geothermal reservoir, a thick multilayered sequence of tertiary detritic, consolidated, sandstone overlying a Mesozoic basement. The area benefits from a reliable data base – a dense seismic line coverage and well control, the deepest, drilled to a depth of 3,000 m, having hit a hot (#150°C) and tight (#10 milli darcy permeability) indurated bed rock.

Period	1985-2010	2011-2035	2036-2060
Mining Scheme	doublet	triplet	doublet
Flow rate (m3/h)	170	130	120
Injection temp. (°C)	48	40	30
Recovery time (yrs) constant pressure	57500	316000	1158000
closed reservoir	230000	558000	380000

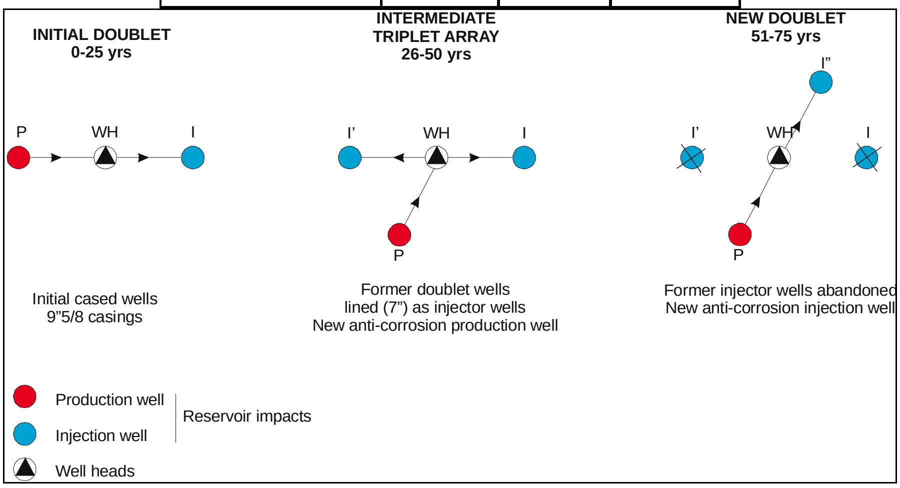


Figure 6: A 75 year sustainable geothermal district heating scenario, Paris basin, Dogger reservoir (source: Ungemach, 2007)

The resource/reserve assessment rationale addressed:

(i) two selected areas, Grand Madrid (1,400 km^2) and NE Madrid(150 km^2), the latter matching the perimeter investigated by four(one hydrocarbon, three geothermal) deep exploration wells;

(ii) a 5,000 m depth, i.e. rock volumes amounting to 7,000(Grand Madrid) and 750 km^3(NE Madrid);

(iii) a multiple aquifer interbedded sequence, split into four resource classes and uses, namely shallow depth/ground source-groundwater heat pump(GSHP/GWHP), medium depth(heat pump assisted) and deep(heat exchange alone)/geothermal district heating and cooling(GDHC) systems, and, last but not least, frontier, ultra-deep/combined heat and power(CHP) enhanced geothermal schemes(EGS);

(iv) a sustainable reservoir management approach, aimed at a 75 year reservoir thermal life via adequate heat extraction designs;

(v) the evaluation criteria practiced by the mineral and geothermal industry in assessing recoverable heat and power quantities which are summarised in Appendix.

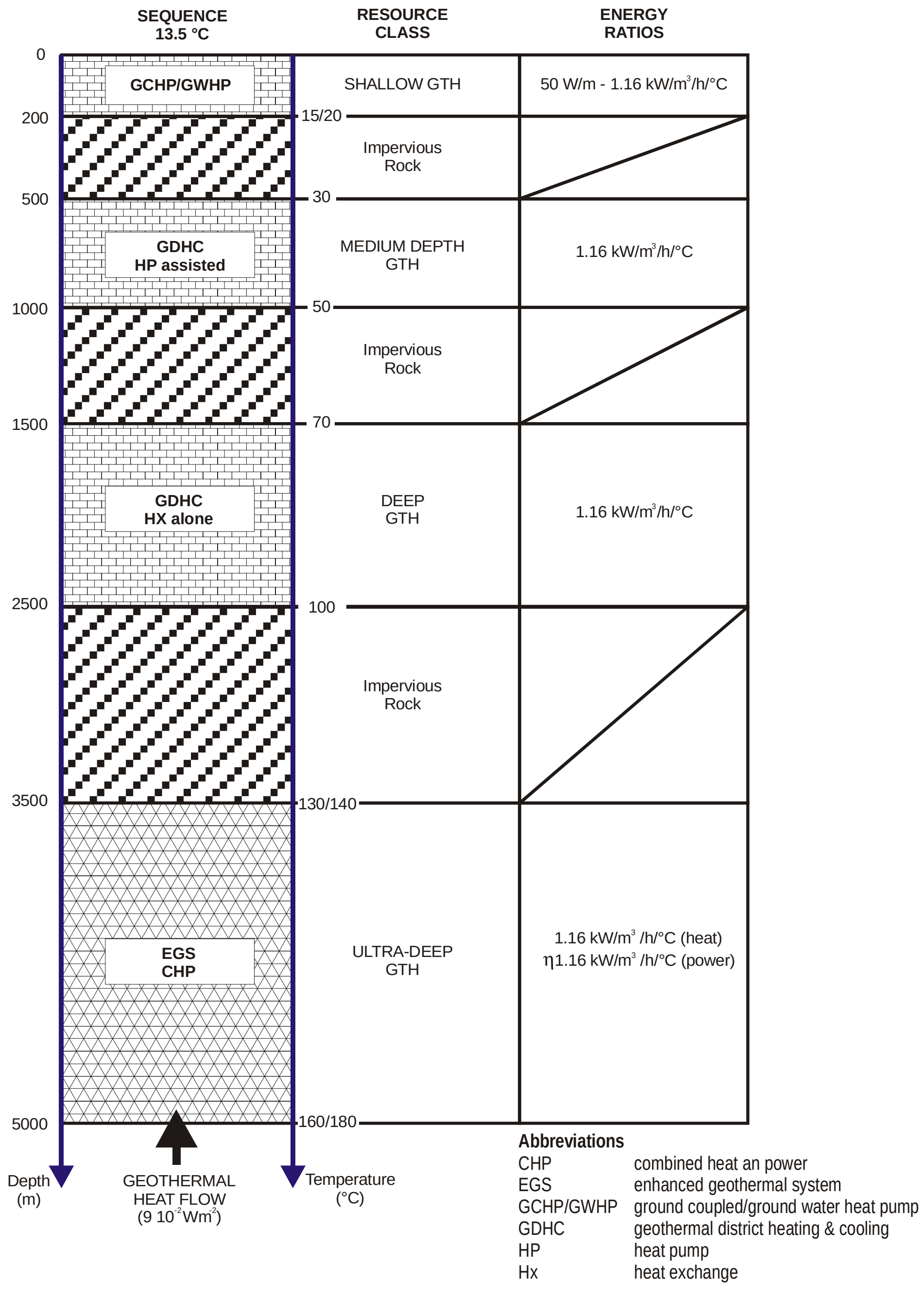


Figure 7: Resource classification vs. depth, temperature and aquifer occurrence (source Ungemach et al, 2008)

Table 1: Summary of Resource/Reserve Assessments

ZONE	OVERALL (Grand Madrid)	SPECIFIC (NE Madrid)
AREA (km^2)	**1400**	**150**
HEAT IN PLACE (HIP) (10^{18} J)		
Shallow GTH	21	2.2
Medium depth GTH	18	3.9
Deep GTH	27	3.1
Ultra-deep GTH	115	13.1
TOTAL	**181 10^{18} J**	**22.3 10^{18} J**
RECOVERABLE HEAT (RCH) OVER 75 yrs		
Shallow GTH (BHE/GWD) (10^{18} J)	3.3/1	0.35/0.1
Medium depth GTH (10^{18} J)	6.3	1.4
Deep GTH (10^{18} J)	9.5	1.1
Ultra-deep GTH (10^{18} J)	5.8	0.7
TOTAL	**24.9/22.6 10^{18} J**	**3.6/3.3 10^{18} J**
EXPLOITABLE HEAT (AND POWER) OVER 75 yrs		
Shallow GHT (BHE/GWD) (10^{17} J)	0.36/0.07	0.04/0.007
Medium depth GTH (10^{17} J)	1.3	0.3
Deep GTH (10^{17} J)	4.4	1.1
Ultra-deep GTH CHP (10^{17} J)	1.2	0.3
TOTAL	**7.3/7 10^{17} J**	**1.7/1.7 10^{17} J**
HEAT RESUPPLY (10^{17} J)	**3.09**	**0.33**

The exercise, displayed in fig. 7 and table 1 summary sheet leads to the overall projections listed herein after:

Item	Grand Madrid	NE Madrid
Heat in place (HIP) 10^{18} J	181	22
Recoverable heat (RCH) 75 yrs 10^{18} J	25	3.5
Exploitable heat(and power) (EXH) 75 yrs 10^{17} J	7.3	1.7
Heat resupply (assuming $90mWm^{-2}$ heat flow density) 10^{17} J	3.09	0.33
EXH/RCH ratio (%)	3	5

Noteworthy is that, in this well documented, fast developing, area enjoying an optimum geoheat & cold power to demand adequacy, only a few percents of the available geothermal heat is mined at a 75 year time scale.

A similar rationale applied to the main European metropolitan areas, most of them overlying thick sedimentary sequences and crystalline basement rocks, would support an ambitious geothermal development vision and projected geoheat and power for the future.

However, such predictions arise several important concerns regarding heat pump, cooling and EGS issues.

It became quite clear that, in the shallow geothermal field, the ground source (BHE) and, at a lesser extent though, the groundwater (doublets) heat pump (GSHP and GWHP) systems would definitely take the lead in future geothermal heat pump developments, a statement based on recorded market sales. However, either heating or cooling single uses will ultimately either cool down or heat up the soil, an impact particularly acute in dense, individual home and building concentrations not to mention GSHP fields or piles, thus defeating a development trend deemed (and claimed) environmentally friendly and sustainable.

Cooling, as an alternative or a complement to heating, may also be regarded as an asset when designing and implementing deep GDH (and GDH&C) systems. Not only would it add summer production and subsequent revenues but simultaneously sustain longer thermal lives. These issues are further commented in section 5.3.

EGS could obviously meet most of the geopower development targets, would such systems be operated at depths of say 10,000 m, where temperatures above 200/250°C are likely be encountered almost anywhere, at technologically mature, environmentally safe and economically viable conditions. This implies that drilling costs be cut down significantly, which requires dramatic technological breakthroughs and less market dependant rig costs along with feasible rock stimulation procedures in building up the required reservoir performance, all issues discussed in section 5.4.

5. THE ROAD AHEAD

5.1 Targets

It was already stressed that the year 2020 objectives set for geopower and geoheat capacities shaped quite ambitious. In fact, the figures projected for Europe at large, from year 2010 until 2030, represent a three (geopower) and two fold (geoheat) increase per decade respectively (fig. 8).

Clearly the geoheat increment will strongly depend, as noticed in the past years, on the fast growing shallow geothermal sector and related ground source and groundwater heat pump (GSHP and GWHP) technologies. A 50% contribution, during the 2010-2020 decade, would result in a 1,000 MW_t yearly incremental power increase i.e. ca 100,000 individual home equivalents and 5,000 tertiary/residential building equipped with borehole heat exchangers (BHEs) and hydroenergy doublets (HED), each rated 5 (GSHP) and 100 kWt (GWHP) respectively.

Other, deep geothermal geoheat developments should rely on agricultural, process heat, district heating/cooling, recreational uses, most of them eligible to medium enthalpy combined heat and power undertakings, which could likely stand as an important contributor, would low temperature CHP gain adequate financial and public support.

As far as geopower is concerned, the future is definitely dependant on the EGS outlook, although power generation from (i) widespread low to medium enthalpy deposits and, (ii) supercritical fluids, restricted to selected volcanic and tectonic (Iceland and Italy) localities, which would theoretically exhibit enthalpies three to five times higher than for a standard pressurised hot liquid, should not be overlooked and prospects developed accordingly.

5.2 Impacts and constraints

5.2.1 Drilling costs

The deeper the source the higher the capital investment, a sensitive issue when contemplating the ultimate 10,000 m target depth set for EGS. Conventional deep geothermal projects, such as a 2,000 m deep GDH doublet, rated 8 MW_t/35,000 MWh_t/yr, currently mobilise 50% of total capital expenditure.

A survey undertaken by MIT (2006), summarised in fig. 9, estimated the costs of 5,000 and 10,000 m deep wells at ca 7 and 20 mio USD (as of year 2004), respectively the latter figure deemed more or less speculative at present assessment stages. Since then, the cost escalation shown in fig. 10 took place, highlighting a strong dependence to steep rises in crude oil prices, particularly acute for land rigs. In late 2008, the unit cost for drilling/completing a 2,000 to 3,000 m deep well amounted to ca 2,000 €/m (i.e. 2,800 USD/m). This means that, under presently prevailing technical standards (hydromechanical stem rotary drilling) and (oil and gas dominated) market trends, the previous 5,000/10,000 m well costs would stand at ca 15 and 40 mio USD (10.7 and 28.6 mio €) respectively, indeed dissuasive figures for any investor whatsoever.

Hence, novel innovative breakthrough drilling and associated "intelligent" measuring while drilling/steering/driving concepts are needed, along the build-up of a geothermal industry core, in order to significantly reduce costs and oil market dependence.

It remains a far sighted perspective since revolutionary drilling-spallation, fusion, laser, robotic-technologies quoted by MIT (2006) are still in the pre-design phase and far from any commercial development yet.

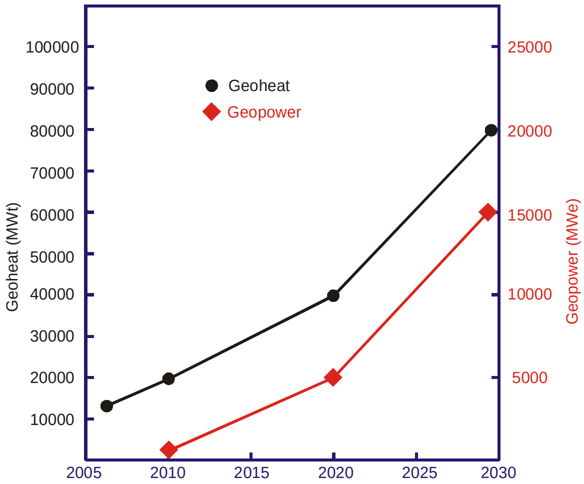


Figure 8: Future projections for Geoheat and Geopower installed capacities. Overall Europe (source: EGEC/EREC)

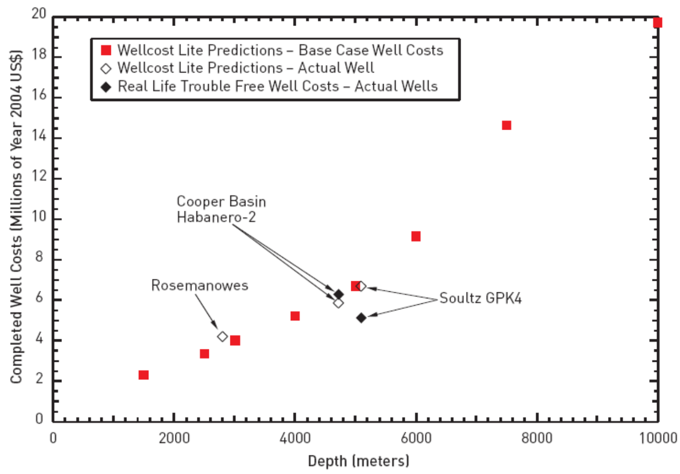


Figure 9: EGS MIT modelled EGS well cost predictions compared to actual EGS well costs (source: MIT, 2006)

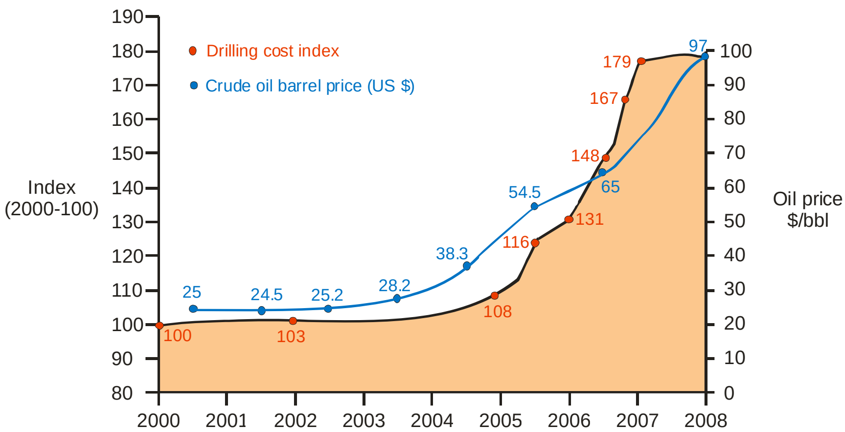


Figure 10: Drilling costs vs crude oil prices (2000-2008) (source: Ungemach, 2008)

5.2.2 Induced seismicity

A heightened awareness of the Public to geothermally induced seismic hazards focused essentially on the sole EGC and, occasionally, conventional water injection issues. Actually, many geothermal sites are located in seismically active areas, a fact which may introduce some confusion, would the induced seismic impacts not be clearly identified and the risk assessed and mitigated accordingly.

The Rhine Graben is a geothermal province of known seismic activity. It hosts two EGS sites, the ongoing Soultz pilot plant operation and the Basel project presently on standby. Earthquakes of magnitues 5 and 6.4 have been recorded at Soultz (1970) and Basel (1956), the latter reported the worst damaging in Central Europe seismic history. Microseisms of magnitudes 2.9 (Soultz) and 3.4 (Basel) were recorded lately, further to hydraulic fracturing rock stimulation sequences, i.e. two to three orders of magnitude lower, but perceived and reported by the local population.

The Basel case, extensively described by Häring et al (2008), deserves a comment. After completing the first, 5,000 m deep, well, massive hydrofracturing was carried out over the lower 371 m openhole section. A 12,000 m^3 of water volume was injected during six days with flowrates and well head pressures peaking at 3300 l/min (# 200 m^3/h) and 296 bar respectively, accompanied by a quasi simultaneous microseismic activity of 185 events/h, maximum magnitudes nearing 3 (the maximum tolerance threshold borrowed to the Soultz microseismic monitoring), a response deemed unacceptable respective to the agreed protocol, which led the operator to reduce the injection rate and, due to a persistent microseismic activity, finally shut in and bleed off the well. A 3.4 magnitude event occurred before bleed off, then microseismicity decreased with well head pressures and venting. Surprisingly, three main aftershocks with magnitudes exceeding 3 occurred during the 56 days following well shut in/bleed off. The foregoing suggested a hydromechanical shearing process, triggering a cascading (in time and space) process in a very low permeability rock environment intersected by poorly conductive subvertical fracture zones (Häring et al, 2008).

These events, although non damaging to the nearby urbanised neighbourhood, were perceived emotionally (and negatively) by the population, actually highly sensitive to environmental hazards and disasters, and widely echoed by the media, resulted in the postponement "*sine die*" of the Basel EGS project.

The project outlook is however rewarding in the light of the following guidelines:

(i) avoid the near vicinity of populated areas and districts while siting the well(s);
(ii) install and operate a thorough microseismic monitoring network and protocol aimed at reliably assessing the seismic signature and background noise prior to drilling, a prerequisite particularily relevant in the Basel area subject to accumulated tectonic stresses at the Southern Rhine Graben edge, at the Jura/Bresse transition;
(iii) measure straight forwardly "*in situ*" stresses via standard packer hydrofrac tests;
(iv) carefully (re)design the rock stimulation strategy in order to secure a progressive build up of the EGS reservoir avoiding excessive and rapid volume/pressure increases and related poro-elastic stress accumulation/release, thus mitigating the seismic impact;
(v) thoroughly investigate the microseismic impact during "routine" plant operation in order to assess (and mitigate) the exploitation induced seismic risk if any;
(vi) last but not least, dedicate efforts to communicating with the public by clearly informing him on the real magnitude of geothermally induced seismic hazards.

Incidentally, several misleading "*a priori*" should be dissipated with respect to EGS seismic impacts.

EGS induced microseismic event signatures, in terms of epicentre depths and focal mechanisms, are often opposed to their natural earthquakes counterparts. As to epicentral depths there is evidence of a number of shallow natural earthquakes, at depths and magnitudes in the (2-4 km)/(4-5) ranges, recorded in the near Alpine and Jura regions (Deichmann, 2009). Similar fault plane analysis may equally be applied as was the case in Basel (Deichmann et al, 2007).

The fact EGS induced seismicity may be turned into an asset owing to, deemed benefical, release of long accumulated stresses, thus avoiding the advent of devastating earthquakes is illusory. Actually, there is at least a two orders of magnitude difference between EGS provoked and naturally occurring seisms.

5.2.3 Heat pumps

Shallow geothermal, calling on ground source and groundwater heat pump technology, is by far the fastest growing link of the whole geothermal chain, with a ca several thousand MW_t increments in installed capacities of geothermal heat. The fact the sector could develop almost indefinitely wherever there are users and a nearby power source became soon popular. This belief ought to be challenged since it is quite clear a mono use, either heating or cooling alone, of the resource will ultimately mine it, and at faster rate in densely populated areas. Here, the accumulation of single home BHEs could be assimilated to a GSHP field.

Hence careful system design and resource management are required. Combined heating and cooling should be the rule and amounts of heat and cold withdrawn from the ground and aquifer balanced accordingly as depicted in fig. 11 (GSHP BHE field). Note that the subsidiary source could consist locally of either a district heating grid, air cooler or absorption chiller facilities, or a surface stream.

5.2.4 Mining risk

Whereas it seems premature at present stage of EGS technlology, still in its infancy, mining or geologic risk mitigation for current hydrothermal geopower/geoheat drilling ventures is becoming a routine procedure practiced by several institutions and insurance networks (Antics and Ungemach, 2009). An example of quantified risk occurrence and coverage criteria for a GDH deep drilling application, is illustrated in fig. 12. Here, the success/failure zones are delineated by two hyperbola Q(To-Ti)=C, with Q well discharge, To and Ti well head formation and grid rejection temperatures and C a constant defined by a given internal rate of return (success criteria) and zero net present value (failure threshold).

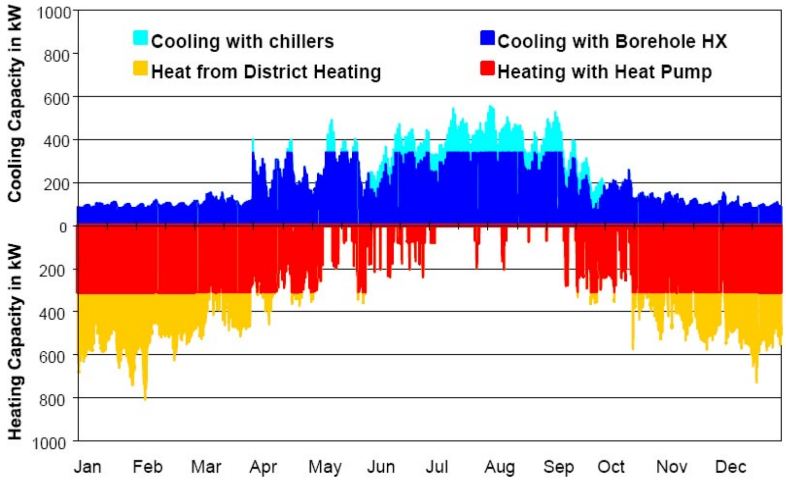
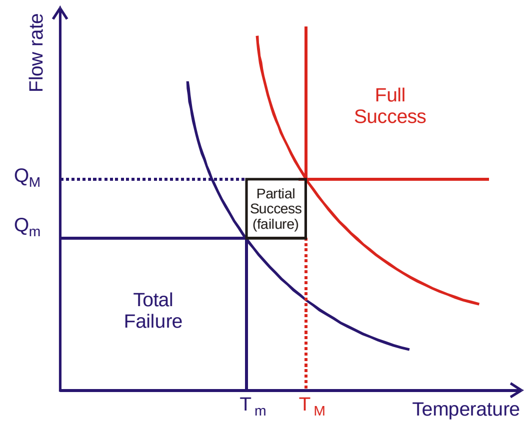


Figure 11: Heating and cold patterns and supply sources. German Air Traffic Control (DFS) (source: Mands and Sanner, 2005)



Full success:

$$Q\left(T_{wh}-T_i\right)=\frac{1}{1.161\cdot nh\cdot c}\left[A\cdot INV+OMC+\frac{INV}{n}\right]$$

Total failure:

$$Q'\left(T_{wh}-T_i\right)=\frac{1}{1.161\cdot nh\cdot c}\left[A'\cdot INV+OMC+\frac{INV}{n}\right]$$

Where:
Q, Q’ = flowrate (yearly average) (m^3/h)
T_{wh} = production wellhead temperature (°C)
T_i = injection temperature (yearly average) (°C)

$$A=\frac{r(1+r)^n}{(1+r)^n-1}$$

$$A'=\frac{r'(1+r')^n}{(1+r')^n-1}$$

INV = capital investment (€)
OMC = operation and maintenance costs (€/yr)
c=heat selling price (€/MWh_t)
n = project lifetime (years)
nh = number of operating hours per year
r, r’ = discount rates

Figure 12: Mining risk. Success vs. failure criteria

5.3 District heating and cooling

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

For instance, shallow cold/tiepid (14 to 25 °C) aquifers can be harnessed for district heating and cooling purposes as exemplified by the Milano Canavese project (Piemonte, 2008), which incidentally reconciles energy, water management and land conservation concerns. Here, the near overflowing Po valley watertable aquifer is exploited to heat and cool a suburban district by large (10 MW_t) thermocentrifugal heat pump units operating in the 12-90°C and 5-30°C temperature ranges respectively. The spent water (re)injection is stopped whenever required by ground water (overflowing) levels. The use of a natural gas (combined cycle) cogenerating outfit utilised in self consuming mode, with recovery of the waste heat from the cooling of the generating units and condensed smokes, adds 25% to overall system efficiency (Piemonte, 2008).

Downstream from Milano, the Ferrara city, contrary to most other Po valley locations addressing poorly permeable and lower to normal deep subsurface temperatures, enjoys a hot and dependable resource (120 °C, 300 m^3/h) favoured by a fractured carbonate convective horst system. The capacity of the city GDH grid will be increased by 40% by depleting the rejection temperatures down to 30°C via a 10 MWt rated heat pump.

GDHC grids combining (i) two, one shallow (cold), one deep (hot), aquifers, and (ii) topping/bottoming, i.e. boosting production and depleting injection temperatures respectively, operating simultaneously in heating and cooling (thermorefrigerating) modes have been designed as illustrated in fig. 13 layout.

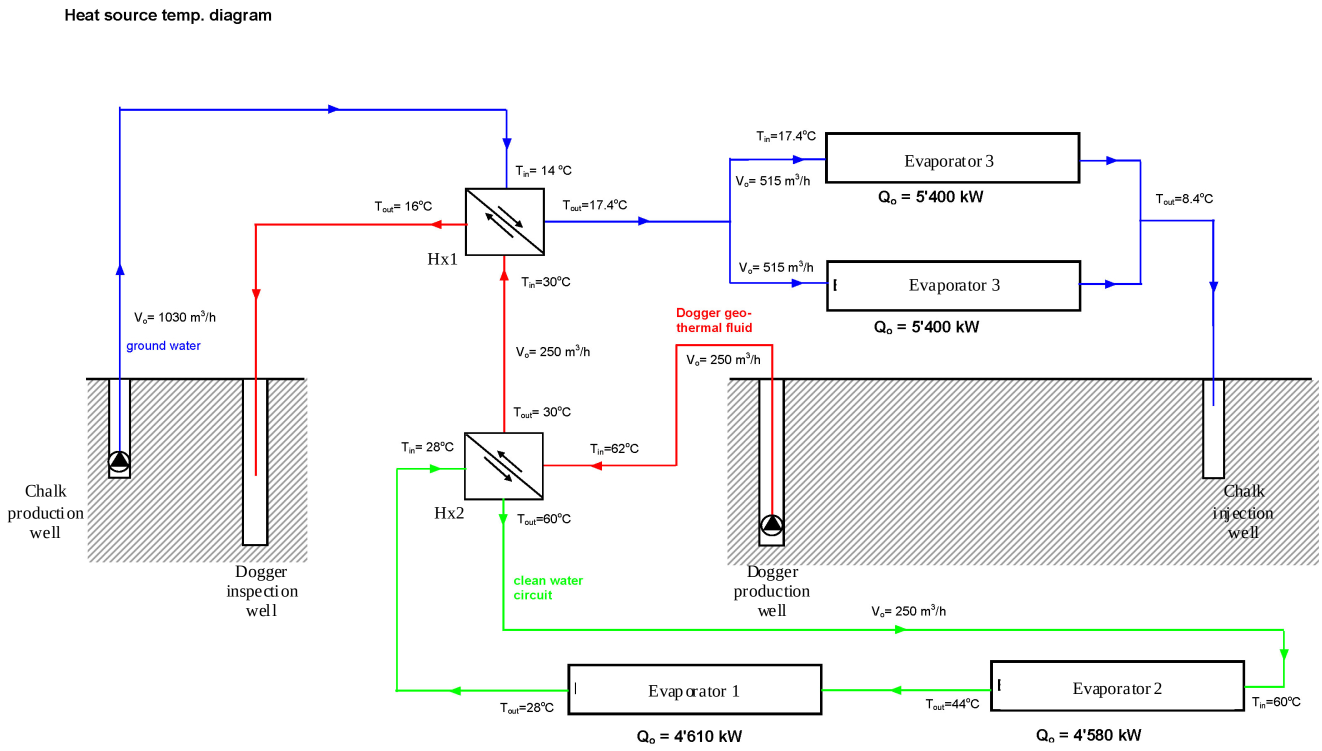


Figure 13: Preheating of shallow ground water (from 14 to 17,4°C) via direct heat exchange with deep geothermal water (Dogger reservoir) (Source: Friotherm, 2009)

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

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

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

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

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

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

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

Summing up, an increase of 2000 MW_t of the GDHC installed capacity may be expected in the next decade.

5.4 EGS issues

Most of the resource base addresses the heat stored in deep seated, conductive/radiogenic dominated, tight sediments and hard crystalline basement rocks. The essence of EGS technology is the engineering of man made geothermal reservoirs by stimulating these low permeability/low connectivity rock environments to recover a fraction of this vast dormant energy. It may therefore be regarded as the ultimate challenge of the geothermal community, bearing in mind that the recovery of say 1% of the heat stored within the 5 to 10 km depth over continental Europe, i.e. 10^{23} J (100,000 EJ) could cover European primary energy demand for centuries ahead.

Recent EGS designs have replaced the former HDR (hot dry rock) concept of heat mining, which aimed initially at connecting two wells, via a set of hydrofracked parallel (sub)vertical fractures, by stimulating instead (pre)existing natural fractures and have them connected to production and injection wells.

The primary objective of a commercial EGS plant is to sustain minimum 5-6 MW_e/10-15 MW_t installed capacities of power and heat, over a minimum 20 years lifetime, according to the specifications outlined in table 2.

A distinction ought to be made at this stage between the high grade and low grade EGS source settings. High grade EGS would normally address tight sedimentary formations exhibiting some matrix (low permeability, in the milidarcy range) properties, generally overlying radiogenic granite basement rocks displaying no flow performance whatsoever, unless conductive fractures be accessed via stimulated flow paths.

These two setting coexist in the earlier assessed, non developed yet, North Madrid Tajo Basin location and the upper Rhine Graben continental rift where two such EGS undertakings have been completed at the Landau and Soultz sites.

The Landau site can be characterised as high grade EGS. Here, the second well of a planned CHP doublet scheme, initially dry, could be successfully stimulated, thanks to fracturing techniques previously designed on the Soultz European EGS pilot test site, and the 5 MWe/10 MWt plant start up commercial operation. In Soultz, year 2008 concluded 22 years of a research stream materialised by the completion of a 5000 m deep well triplet array rooted in a crystalline basement and of a 1.9 MWe rated ORC plant, the first EGS ever achieved to date. Continuous plant operation and reservoir microseismic monitoring are required to analyse the long term behaviour of a man made geothermal reservoir. The Soultz site is a prototype representative of low grade EGS, by far the most frequently encountered setting.

Still, although promising, the present outlook stands behind expectations as evidenced by table 3 targets vs. best so far accomplished records.

EGS performance may be upgraded by circulating working fluids other than water, such as CO_2, a topic investigated by Brown (2000) and Pruess (2007). Owing to a higher mobility ratio, supercritical CO_2 could secure much higher flowrates and subsequent heat extraction, in spite of a lower heat capacity; contrasted production vs. injection well head pressures would elsewhere boost thermosiphon circulation (buoyant drive), possibly saving the use of a submersible pump. Among the negative impacts are the faster cooling kinetics and more severe density segregation effects causing, if not carefully controlled at the production well, premature thermal breakthrough (Pruess, 2007). Thermochemical interactions with respect to sensitive mineral species and related supersaturation/precipitation shortcomings studied by André et al (2007), in the framework of a CO_2 aquifer storage project, require in depth appraisals for candidate EGS rock petrographic settings. EGS/CO_2 can be turned into an advantage if combined to a carbon sequestration scheme, a synergy discussed by Pruess (2006), in which case, incidentally, fluid losses would be less a problem.

Present EGS know how and findings may be summarised as follows:

- fracture initiation and growth are governed by the natural fracture network and in situ stress field;
- low pressure shearing is the driving rock stimulation mechanism;
- low hydraulic impedance and large heat exchange areas, the so-called HDR paradox, are the key factors governing system efficiency;
- limited reservoir performance (≤2MWe capacity) recorded so far;
- system reliability merely site specific;
- social acceptance occasionally clouded by microseisms induced during hydraulic fracturing.

In this respect, the striking differences noticed between the Soultz (distensive graben stress field, sub-vertical fracture pattern, low pressure system) and the Australian Cooper Basin (compressive stress field, horizontal fracture propagation, overpressured reservoir) EGS sites ought to be mentioned, thus emphasising the need for widening the scope of EGS field assessments.

Ongoing and future research priorities should concentrate on:

- upgrading hydraulic conductivity/connectivity and relevant EGS reservoir performance;
- identifying active heat exchange area and stimulated rock volume respective to the in situ stress field;
- securing reservoir life and sustainability issues;
- last but not least, mastering induced seismicity according to stimulated reservoir growth, recorded natural background (micro)seismicity and (long) accumulated stress release

Table 2: Man made/engineered geothermal reservoir issues (source: Ungemach, 2008a)

DRIVEN BY ECONOMICS: **Target 5-6 MWe /module**

LIFE OF THE SYSTEM:	~20 Years
TEMP/DEPTH OF THE WELLS:	~ 200°C
SEPARATION BETWEEN WELLS:	~600 m
PRODUCTION FLOW RATE:	~75 Kg/s
FLOW IMPEDANCE:	~ 0.1MPa/l/s
WATER LOSS:	~ 10% MAX
THERMAL DRAWDOWN	~ 10%
CONTACT SURFACE AREA:	~ 10 million m^2
RESERVOIR ROCK VOLUME	~ 300 million m^3
INTEREST RATE FOR THE CAPITAL:	~ 5%
SUPPORT :	No CO2 levy support etc

Table 3: EGS targets vs. achievements. 2008 status. (source: Baria, 2008).

TOPIC	Econ. TARGETS	BEST SO FAR
System life	20 years	5 years Rosemanowes
Drilling cost	10m €for 6km well	5 m €for 5 km (GPK3)
Temperature	200°C+	270°C @ 2.2km Hijiori
Separation between wells	600m	600 m @ Soultz
Flow-rate	~ 75 l/s	26 l/s @ Soultz
Flow Impedance	0.1 MPa/l/s	0.29 @ Soultz
Water loss	10 %	0 % @ Soultz
Thermal drawdown	10 % after 20 years	
Contact surface area	10 million m2	
Reservoir rock volume	300 million m3	
Interest rate	~ 5%	

6. CONCLUSIONS

European (at large) present geothermal exploitation status and projected development targets have been reviewed with respect to its geothermal/geodynamic environments and prospective resource reclamation trends.

Although geothermal utilisation scored well so far, thanks to mature extraction and conversion technologies earlier pioneered in the areas of power generation, district heating and EGS, geothermal energy development in Europe is at a crossroads.

Actually, the objectives ambitioned by the geothermal community are targeted at 5,000/15,000 MWe and 25,000/75,000 MWt for years 2020/2030 installed capacities respective to geopower and geoheat, indeed a huge challenge given the late 2008, 1,300 MWe and 12,000 MWt development status.

Hence, based on reliably assessed recoverable reserve estimates and sustainable heat mining technologies, development efforts should focus on the following priorities.

(i) shallow geothermal (≤ 400 m)
- intensification of the fast growing heat pump - individual home borehole heat exchangers and building groundwater doublet/multiplet well arrays-load;

(ii) deep geothermal (≤ 4,000 m)
- extension to eligible heat and cold markets of geothermal district heating and cooling grids, including heat pump assisted and combined heat and power supply systems;
- harnessing heat and power from medium grade sources via performant binary conversion cycles, which should add a significant increment to existing capacities;
- achievement of a two to three fold increase of geopower capacities from identified conventional high enthalpy volcano-tectonic deposits and flashed (and direct expansion) steam cycles, to which could be added a power segment from supercritical fluids in selected volcano/magmatic settings;

(iii) ultra deep geothermal (≥ 5,000 m)
- it addresses EGSs, the new geothermal frontier, to which the Soultz project, concluded by a 2 MWe rated pilot plant, provided invaluable clues. Given the huge amount of heat stored in the 4,000 to 10,000 m depth range, accessible to current drilling technology, a considerable geopower/geoheat potential is waiting to be mined.

Achieving this goal requires a far sighted R, D & D supporting stream, coupled to at least ten pilot test sites, equally shared between low grade and high grade EGS, representative of the diversity of candidate rock petrographic and tectonic environments. This phase aims at bridging the gap between EGS current status and target expectations. It should ultimately enable to design, build and operate feasible and sustainable man made EGS reservoirs at low induced seismic risk and reduced well drilling/completion costs.

Would this trial period prove rewarding, then the 2030, 15,000 MWe target geopower capacity could become a reality.

Not to be overlooked are the accompanying measures in the areas of financial support, fiscal incentives, tax credits, feed in tariffs, risk mitigation, quality standards and regulatory frameworks enforced at European levels.

Last but not least, the foregoing require urgently that the geothermal community be structured as an **industry,** which in turn requires a relevant **market** to be created at European scale, otherwise the commitment to development will remain *"lettre morte"*.

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APPENDIX

Rock and fluid energy densities and energy outputs (source: Ungemach et al, 2007)

Energy densities

- *Rock*

$$E_r = (I-\phi)\rho_r c_r(\theta_o - \theta_f) \quad (1)$$

with:

ϕ = porosity

ρ_r = rock density (kg/m^3)

c_r = rock specific heat (kJ/kg °K)

θ_o = initial rock temperature (°C, °K)

θ_f = final rock temperature (°C, °K)

- *Fluid*
    - Single phase liquid (compressed water)

$$E_w = \phi\left[\frac{h_w(p_i,\theta_i)}{\nu_w(\theta_i)} - \frac{h_w(p_f,\theta_f)}{\nu_w(\theta_f)}\right] = \phi\left(\frac{h_{wi}}{\nu_{wi}} - \frac{h_{wf}}{\nu_{wf}}\right) \quad (2)$$

with:

h_{wi}, h_{wf} = liquid (water) enthalpies at initial and final reservoir conditions (kJ/kg)

ν_{wi}, ν_{wf} = liquid (water) specific volume at initial and final reservoir conditions (m^3/kg)

p_i, p_f = fluid (water) pressure at initial and final reservoir conditions (Pa)

- Two phase (liquid water/steam)

$$E_{2\varphi} = E_{wi} - E_{sf} = \phi\left(\frac{h_{wi}}{\nu_{wi}} - \frac{h_{sf}}{\nu_{sf}}\right) \quad (3)$$

with:

h_{sf} = saturated steam enthalpy at final state

ν_{wf} = saturated steam specific volume at final state

- Single phase vapor (superheated steam)

$$E_s = \phi\left[\frac{h_s(p_i,\theta_i)}{\nu_s(\theta_i)} - \frac{h_s(p_f,\theta_f)}{\nu_s(\theta_f)}\right] = \phi\left(\frac{h_{si}}{\nu_{si}} - \frac{h_{sf}}{\nu_{sf}}\right) \quad (4)$$

with:

h_{si}, h_{sf} = superheated steam enthalpies at initial and final reservoir conditions

ν_{si}, ν_{sf} = superheated steam specific volumes at initial and final reservoir conditions

p_i, p_f = superheated steam pressures at initial and final reservoir conditions (Pa)

- *Total reservoir energy densities*
    - Single phase liquid

$$E_{wt} = E_w + E_r$$

- Two phase

$$E_{2\varphi t} = E_{2\varphi} + E_r \quad (5)$$

Geothermal reservoir heat and power assessments. Summary sheet

- Single phase vapor

$$E_{st} = E_{st} + E_r$$

- *Reservoir volumes required to sustain a thirty year geoelectric power plant life*

$$W_{el} = P_{el}\Delta t \quad (6)$$

$$W_{th} = W_{el}/\eta$$

with:

W_{el} = electrical energy (kWhe)

P_{el} = installed electrical power (kWe)

Δt = plant life (hrs)

W_{th} = thermal energy (kWh$_{th}$)

η = conversion efficiency

- *Volume requirements*
    - Single phase liquid

$$V_w = W_{th}/E_{wt}$$

- Two phase (7)

$$V_{2\varphi} = W_{th}/E_{2\varphi t}$$

- Single phase vapor

$$V_s = W_{th}/E_{st}$$

Energy outputs

- *Superheated steam (reserver and turbine inlet)*

$$W_s = \phi\, h_s/\nu_s \quad (8)$$

with:

W_s = recoverable energy per unit reservoir volume (kJ/m^3)

h_s = steam enthalpy at reservoir conditions

ν_s = steam specific volume at reservoir conditions

- *Compressed water (reservoir)/two phase (separator outlet)*

$$W_l = \phi\ x\ h_l \nu_l \quad (9)$$

with:

W_l = recoverable energy per unit reservoir volume (kJ/m^3)

x = steam quality = $\dfrac{h_l - h_w}{h_s - h_w}$

h_l = compressed liquid enthalpy at reservoir conditions

h_w = water enthalpy at turbine inlet pressure

h_s = separated (flashed) steam at turbine inlet pressure

ν_l = water specific volume at reservoir conditions

DEFINITIONS

- Heat in place HIP
  $HIP = \gamma_t * Ah(\theta_i - \theta_0)$
- Recoverable heat RCH
  $RCH = \eta\gamma_t * Ah(\theta_i - \theta_r) = r * HIP$
- Heat recovery factor r
  $r = RCH / HIP = \eta(\theta_i - \theta_r)/(\theta_i - \theta_0)$
- Efficiency of the heat extraction scheme η
  $\eta = (q/Ah)*(\gamma_w/\gamma_t)*t^*$
- EGS power (W) and energy supply (E)
  $W = \eta' q' \gamma_w(\theta_i - \theta_c)/3600$
  $E = W * t'^*$

NOMENCLATURE

A = area (m^2)

h = effective thickness (m)

q, q' = flowrates (m^3/h)

r = recovery factor

t^*, t'^* = system life (hrs)

$\gamma_t = \phi\gamma_w + (1-\phi)\gamma_r$ = total (fluid + rock) heat capacity (kJm^{-3}K^{-1})

γ_t, γ_r = rock and water heat capacities (kJm^{-3}K^{-1})

$\theta_i, \theta_0, \theta_r, \theta_c$ = reservoir, mean ground, rejection and condensing temperatures (°K)

η, η' = efficiencies