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Multiple Use Assessment of the Madrid Basin (Spain) Geothermal Potential

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ABSTRACT

The Madrid Basin enjoys one of the most favorable geothermal environments identified in Spain to date. The "Grand Madrid" area (ca 1500 km^2) at the northern edge of the Tajo sedimentary basin consists of a thick multilayered sequence of tertiary detritic sandstone overlying a Mesozoic crystalline basement.

Based on available geophysical and deep drilling data and present and future demand patterns, the geothermal potential of the area has been assessed to a depth of 5000 m. This study was based on the volumetric assessment method currently practiced by the oil and mineral industries and addressed four resource and utilization classes:

i. Shallow depth (0-200 m, 20-25°C) applications of ground coupled – ground water heat pumps (GCHP-GWHP),
ii. Medium depth (500-1000; 30-35°C) heat pump assisted applications,
iii. Deep (1500-2500m, 70-90°C) applications for geothermal district heating and cooling (GDHC) systems,
iv. Frontier, ultra-deep (3500-5000 m), applications for combined heat and power (CHP) enhanced geothermal systems (EGS).

The amount of exploitable energy was estimated to be ca. 7.3 10^{17} J (730 PJ) over a 75 year lifespan according to existing and foreseeable technology standards and market demand, which represents less than 5% of the recoverable heat potential.

1. INTRODUCTION

Hydrocarbon exploration geophysics and drilling carried out North of Madrid in the late 1970s and early 1980s, followed by the drilling and testing of three geothermal wells from 1985-1990, provided evidence of a dependable reservoir in tertiary clastic host rocks at ca 1500-2000 m depths. Hence, the Madrid area could be a high priority target for geothermal development.

Nonetheless, since the drilling of the Geomadrid 1 well in 1990 (a project with the initial goal of completing a geothermal district heating (GDH) doublet, which was later abandoned) no noticeable geothermal development occurred until 2006, when Petratherm, an Australian based operator, expressed interest in Spanish geothermal energy development in metropolitan Spain and the Canaria Islands. As a result, Petratherm Espana was awarded an exploration lease for an area North of Madrid which includes the previously identified geothermal sites. The location of this area is illustrated in Figure 1.

Due to the energy demand of the rapidly growing metropolis of Madrid, rising fossil fuel price trends, and clean air concerns, it was deemed timely to assess the local resource potential and determine eligible development sites using a resource to market adequacy rationale.

The following are presented in this paper:

i. An outline of the regional and local geothermal environments,
ii. A review of the resource utilization spectrum to a depth of 5000 m,
iii. An evaluation of the resource base, recoverable heat, and ultimately, the exploitable reserve in compliance with the oil and mineral industry assessment standards, customized to the geothermal energy field by Mufler and Cataldi (1979).

2. GEOTHERMAL ENVIRONMENTS

2.1 Geological and structural settings

The Madrid area extends over the north central edge of the Tajo sedimentary basin. Its main aquifer unit consists of a thick multilayered sequence of tertiary consolidated sandstone overlying a Mesozoic crystalline basement. The aquifer is bound to the north by crystalline basement rocks (radiogenic granite) delineating the North Madrid Sierras via deep parallel trending SSW-NNE faults. Elsewhere, its boundaries correspond with the thinning of the sandstone reservoir (Ungemach et al, 2008).

Within the area of concern, a specific area has been selected northeast of the capital city, which includes the exploratory well locations and densely urbanized suburban districts. A map of both areas is shown in Figure 1 along with their salient reservoir features (thickness, formation temperatures, and transmissivities). Sketches of their regional and local structures with NW-SE trending cross-sectional views are provided in Figures 2 and 3, respectively. Their areas extend over 1400 and 150 km^2, respectively, as shown in Table 1.

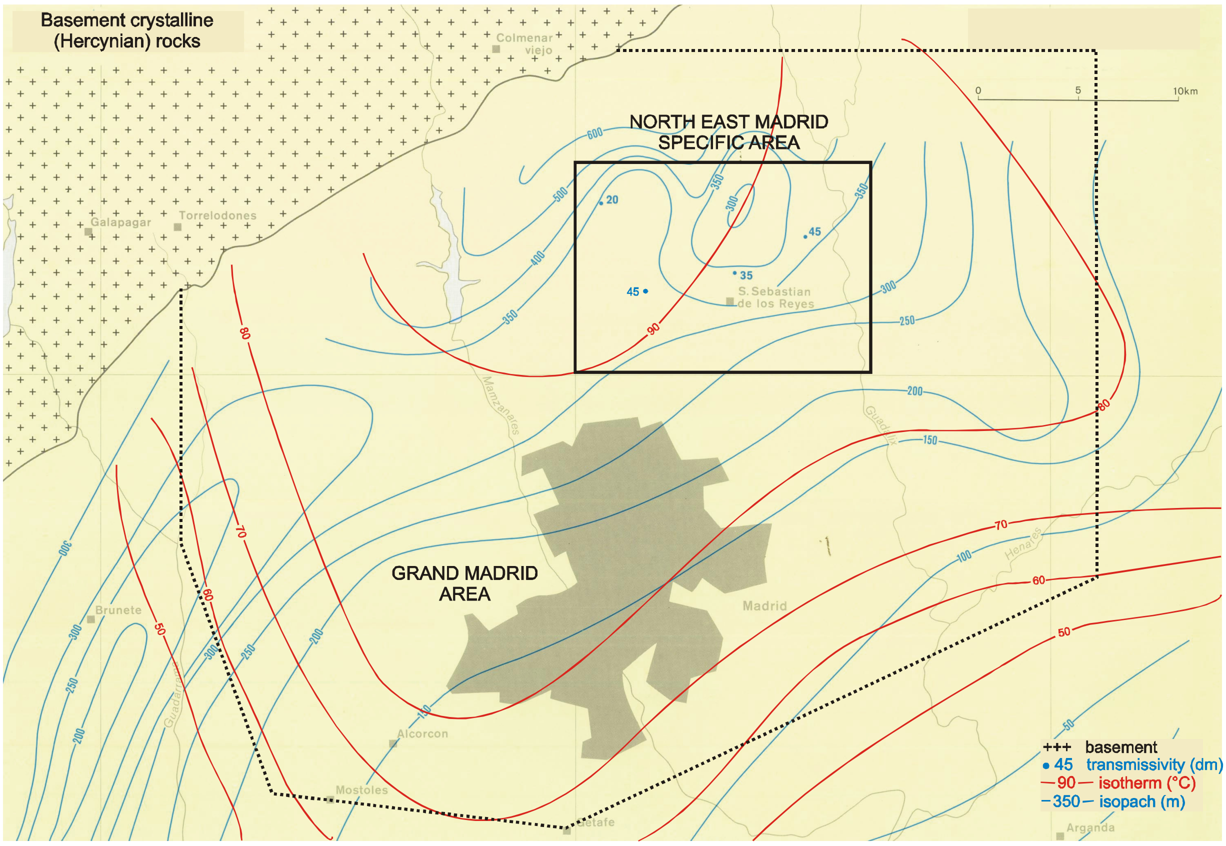


Figure 1. Map of Madrid's geothermal resources Showing the locations of target assessment areas and the Detritic Tertiary Sandstone Aquifer. (Adapted from : European Geothermal Atlas).

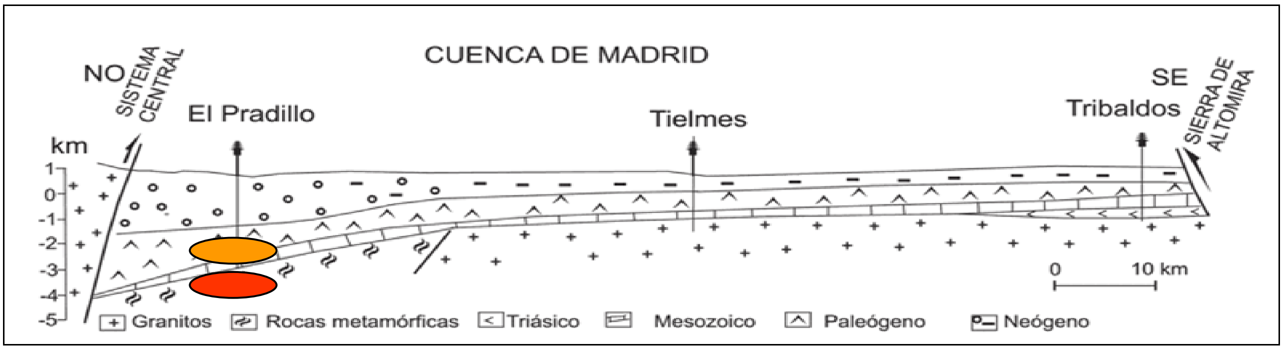


Figure 2. Cross-sectional sketch of the Madrid Basin.

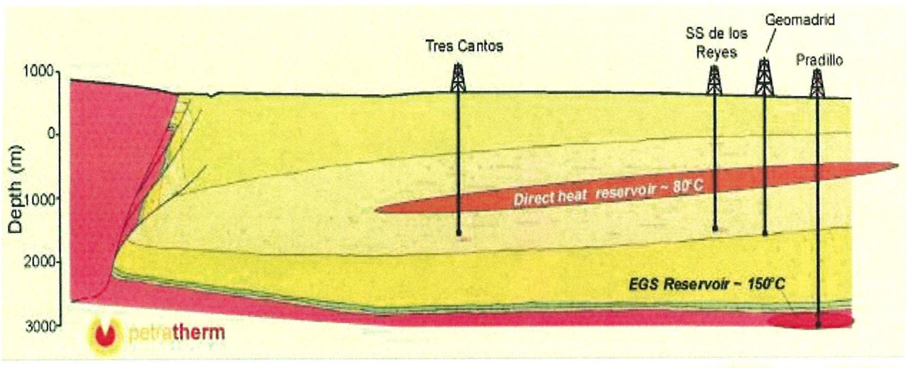


Figure 3. Cross-sectional sketch of the North Madrid Basin including oil and geothermal wells (adapted from IGME).

Table 1: North Madrid well summary sheet (source IGME, PETRATHERM ESP.)

WELL NAME	TVD (mbgl)	Tested/sampled depths and intervals (mbgl)	Transmissivity (dm)	Bottomhole temperature (°C)	Equivalent salinity @ TDS (g/l)	Well productivity (m^3/h)
Pradillo 1	1800	1600-1800	47	70-80	20-30	150
Pradillo 2	3100	@ 2400	10 md	150	-	
Tres Cantos	2400	1600-2400	20	70-90	12-90	150
San Sebastian de los Reyes	2100	1600-2100	35	75-90	12-30	250
Geomadrid 1	2000	1550-2000	44	70-78	20-25	200-250

2.2 Reservoir features

The summary sheet in Table 1 lists the data compiled on Pradillo (1 & 2) oil exploration wells and Tres Cantos, San Sebastian de los Reyes and Geomadrid geothermal step out wells, which were drilled between 1980 and 1990.

3. RESOURCE AND RESERVE ASSESSMENT METHODOLOGY

This study addresses the geological sequence (up to depths of 5 km), resource utilizations, and (heat/power) power ratios (displayed in Figure 4) and heat extraction systems (sketched in Figure 5). It is based on the so called volumetric deterministic method and definitions formulated by Mufler and Cataldi (1978).

The selected horizons with respect to depths and candidate uses are outlined below.

0-200 m. This shallow geothermal field concerns chiefly ground source heat pump applications, which may be subdivided into ground coupled heat pumps (GCHP) and groundwater heat pumps (GWHP) and the related borehole heat exchanger (BHE) and hydrothermal groundwater doublet (GWD) heat extraction technologies, respectively.

500-1000 m. This medium-depth seated reservoir is considered for ground water heat pump assisted hydrothermal doublet/multiplet extraction systems utilized for heating/cooling purposes that generally have small to medium sized loads.

1500-2500 m. This interval covers the entire well surveyed (particularly in its Northern/North Eastern sectors), multilayered detritic sandstone aquifer of tertiary age, which stretches over Madrid and the surrounding areas. The characteristics of this aquifer are summarized in Table 1.

Hot water utilization deals here with large geothermal district heating and cooling (GDHC) applications.

3500-5000 m. Ultra-deep geothermal horizons hosted in tight, low permeability, basement rocks are of interest for the application of EGS (Enhanced Geothermal Systems) technology aimed at engineering geothermal reservoirs. At the present stage of the technology EGS power ratings may be assessed from the following design figures:

- Source temperature: 160°C
- Condensing temperature: 65°C
- Flow rate: 270 m^3/h
- Heat to power conversion efficiency (ORC): 0,10
- Power output: # 3 MWe

Would the (waste) return flow temperature be depleted from 65°C to 35°C a ca 10 MWt heat output could be added to a fully operating CHP plant.

Unit densities can be assigned to each application field. For instance, a borehole heat exchanger exhibits a capacity of ca 50 W/m under normal condition (e.g. a 10 kWt thermal power at a 200 m depth). Similarly, a groundwater doublet would display a 1.16 kW/m^3/h/°C unit capacity (e.g. a 7 MWt installed capacity assuming a 200 m^3/h flow rate and a 30°C temperature depletion in the well). In the case of power generation from an EGS compressed water system and a binary (ORC) conversion cycle, the unit energy density is expressed as:

$$E_w = \phi\left[\frac{h_w(p_i,\theta_i)}{v_w(\theta_i)} - \frac{h_w(p_f,\theta_f)}{v_w(\theta_f)}\right] = \left(\frac{h_{wi}}{v_{wi}} - \frac{h_{wf}}{v_{wf}}\right) \qquad (1)$$

with:

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

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

p_i, p_f = initial and final reservoir pressures (bar)

θ_i, θ_f = initial and final temperatures (°C)

ϕ = porosity

However, for the sake of simplicity, it is recommended to derive EGS power figures from the heat potential, based on a given conversion cycle efficiency.

4. RESOURCE AND RESERVE CALCULATIONS

Relevant figures have been derived from the definitions shown in Figure 6 and applied to the regional (Grand Madrid, 1400 km^2) and local (NE Madrid, 150 km^2) areas.

An exploitable reserve heading has been added. It addresses the fraction of the recoverable heat which can be reliably extracted via available technology, while accounting for end user densities, economic viability and both logistic and environmental constraints.

Exploitation periods extend over 75 year system lives according to the sustainable heat mining concept developed by Ungemach et al (2007) and illustrated in Figure 7.

The following conditions have been assumed regarding resource and reserve appraisals and the related extractable heat and power production issues.

4.1 Recoverable heat

4.1.1 Shallow geothermal

Here HIP = ARB to a 200 m depth. Borehole heat exchangers (BHEs) and groundwater doublets (GWDs) were considered as candidate heat extraction systems, with capacities and densities assessed as follows:

- Capacities: 10 kWt (BHE); 290 kWt (GWD)
- Densities: 1 BHE/ha; 1 GWD/25 km^2

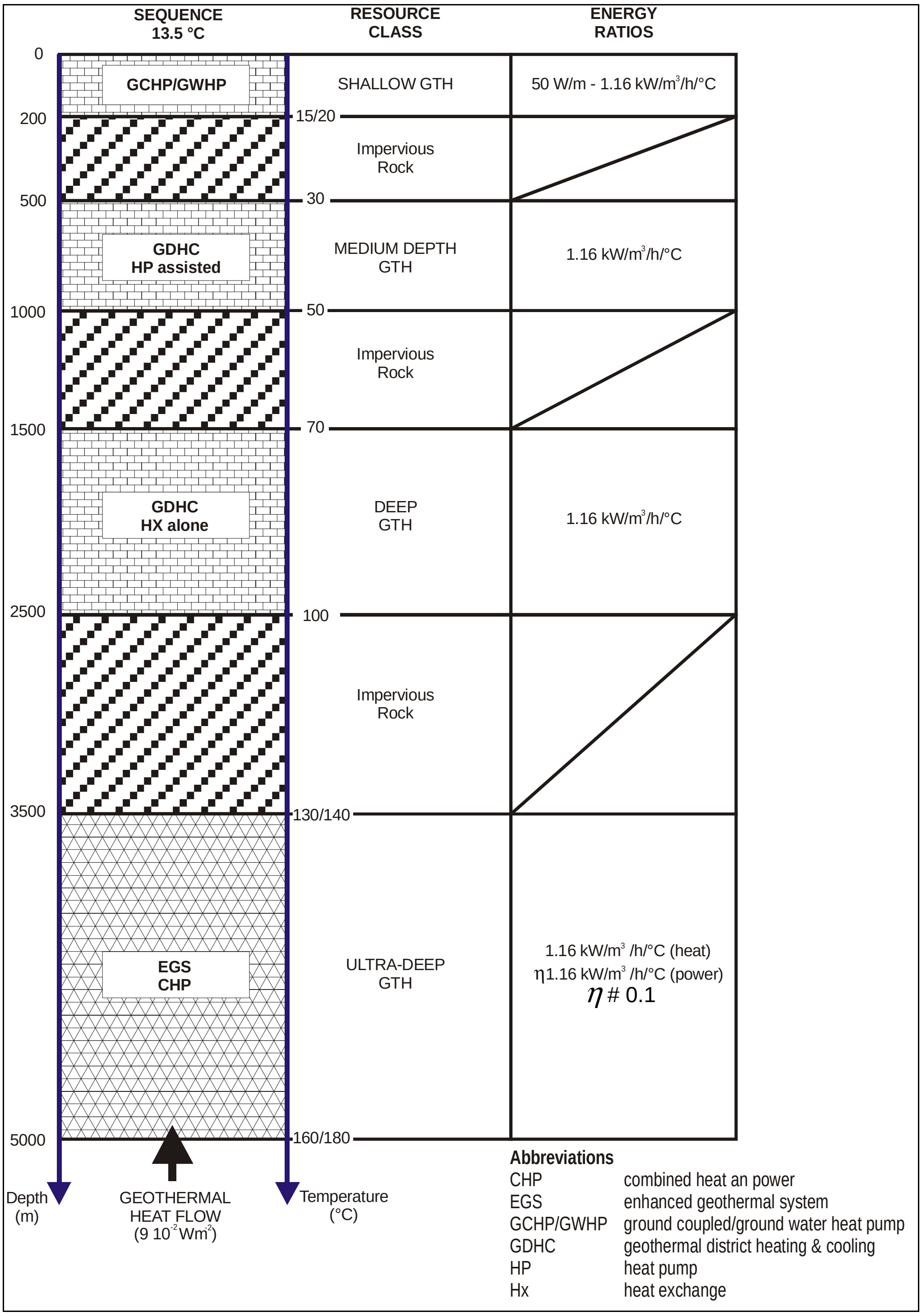
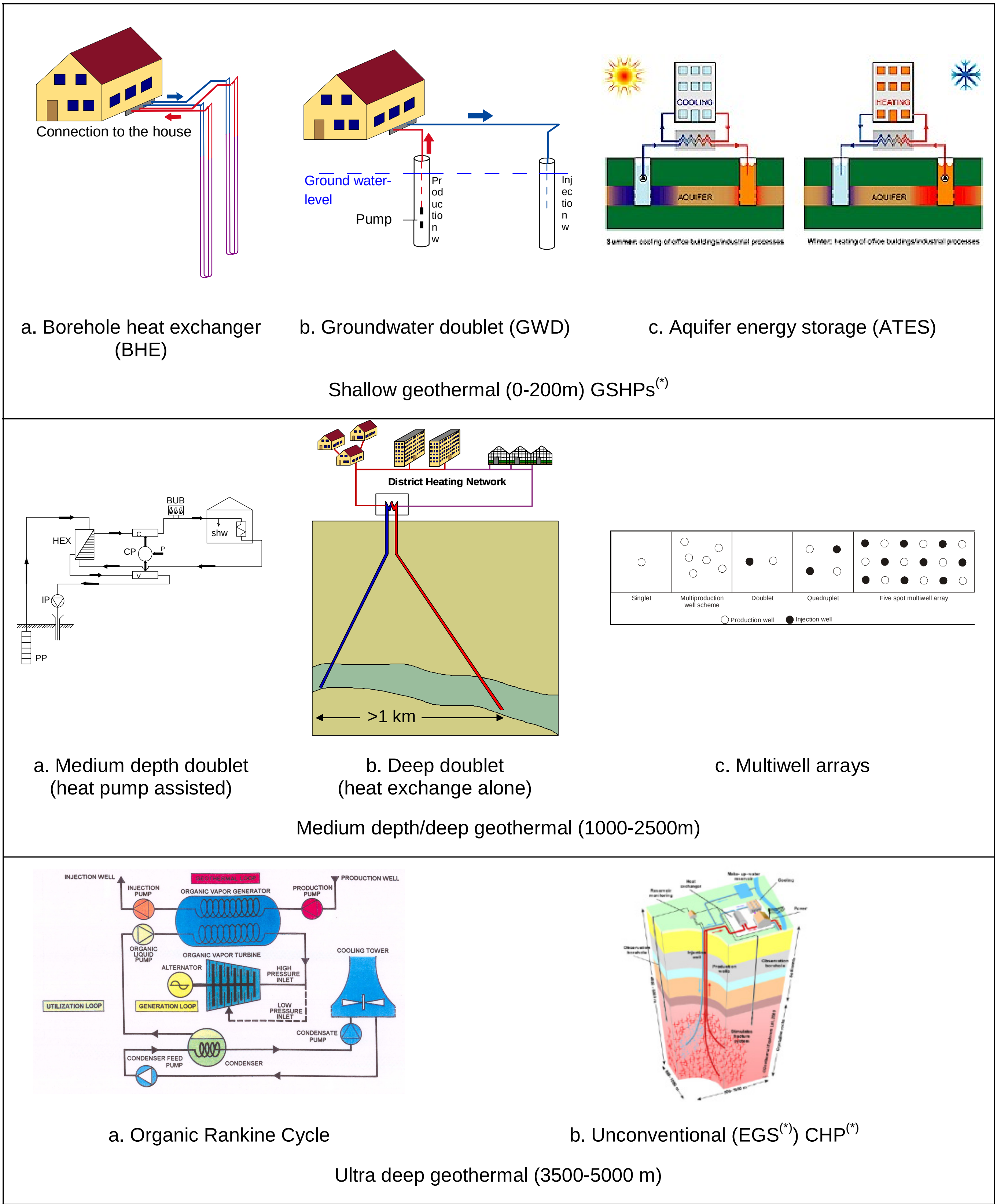


Figure 4. Resource classification vs. depth, temperature, and aquifer occurrence.



(*)GHSP: ground source heat pump
CHP: combined heat and power
EGS: enhanced geothermal system

Figure 5. Eligible heat extraction and power generation schemes in the Madrid area.

DEFINITIONS

- Accessible resource base ARB

  ARB = A*z* $\gamma_t * (\theta_z - \theta_0)$

- Heat in place HIP

  HIP = γ_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

  η = *(q/Ah)** (γ_w / γ_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
$\gamma_t = \phi\gamma_w + (1-\phi)\gamma_r =$ total (fluid+rock) heat capacity ($kJm^{-3}K^{-1}$)
$\gamma_t, \gamma_r =$ rock and water heat capacity ($kJm^{-3}K^{-1}$)
$\theta_i, \theta_0, \theta_r, \theta_c, \theta_z =$ reservoir, mean ground, rejection, condensing and at depth temperatures (°K)
η, η' = efficiencies
ϕ = porosity

NUMERICAL APPLICATIONS

- *Heat (deep hydrothermal)*

  q = 200 (m^3/h); t^* = 25 yrs; γ_w *= 4,180 $kJm^{-3}K^{-1}$;* γ_r = 2,700 *$kJm^{-3}K^{-1}$;* θ_i *= 75 °C;* θ_0 = 15 °C; θ_r = 35 °C

  Values of η and *r* vs *A* (km^2) and *h* (m)

η =

h \ *A*	5	10	20
20	0.61	0.31	0.15
50	0.24	0.12	0.06
100	0.12	0.06	0.03

r =

h \ *A*	5	10	20
5	0.41	0.21	0.10
10	0.16	0.08	0.04
20	0.08	0.04	0.02

- *Power (ultra deep EGS)*

  q' = 180 m^3/h (50 l/s); γ_w *= 4,180 $kJm^{-3}K^{-1}$;* θ_i *= 170 °C;* θ_c *= 50 °C;*

  η' *= 0.12; t'^* = 25 yrs*

  W # 3,000 kWe; E # 657 GWhe
  q' = 300 m^3/h (83 l/s)
  W # 5,000 kWe; E # 1.1 TWhe

Figure 6. Geothermal reservoir heat and power assessment summary sheet.

4.1.2 Medium depth geothermal

Eligible aquifers are likely to be located between the surface and tertiary sandstone reservoirs, and their occurrence is reported in several instances of deep well drilling records. Nevertheless, they should be regarded as relatively site specific, if not erratic. As a result, they will be regarded as dependable over 30% of the Grand Madrid area and 60% of the better documented NE Madrid area. Their lithology is dominantly sandy and clayey, with an effective thickness of about 50 m. Both have porosities of about 20%, and the water and fluid heat capacities are set at 4180 and 3000 $kJm^{-3}°C^{-1}$, respectively (density = 2; specific heat = 1.5 kJ/kg°C). These assumptions led to the HIP figures listed in Table 1.

Given identical heat extraction schemes and sustainability issues, the system recovery and efficiency factors were determined to be 35% and 54%, respectively, by extending the values calculated for deep aquifer cases to medium depth applications.

4.1.3 Deep geothermal

Based on the following figures:

q = 200 m^3/h
γ_w = 4180 $kJm^{-3}K^{-1}$
γ_r = 2700 $kJm^{-3}K^{-1}$
ϕ = 0.15
γ_t # 2920 $kJm^{-3}K^{-1}$
A = 3.5 km^2
h = 100 m
t^* = 75 yrs

The efficiency and recovery coefficients are as follows:

η = 0.54
r = 0.35

4.1.4 Ultra-deep geothermal

It is quite clear that, at the present stage of EGS undertakings, any related resource/reserve assessment remains a highly speculative exercise.

Resource estimates are based on a rock stimulated porosity of 5%, a rock density of 2700 kgm^{-3}, a rock specific heat of 0.95 kJ m^3K^{-1} , a 200 m man made reservoir thickness, and a bottom hole temperature near 170°C. The heat recovery factor has been set, somewhat arbitrarily, at 5%. More information on thermal properties of various rock types and their variations with depth, water content, and temperature may be found in works by Schon (2004) and Economides & Ungemach (1987).

4.2 Exploitable heat

However speculative these assessments may be, the figures shown in Table 2 follow realistic market appraisals and scores.

4.2.1 Shallow geothermal

It has been estimated that 18,000 BHEs could be implemented over the Grand Madrid area, assuming the following split:

- 15,000 family houses (1 BHE/home): 15,000
- 100 collective dwellings (20 BHEs/building): 2,000
- 10 large office buildings/industrial (100 BHEs/building): 1,000
- 28 GWD units were selected, corresponding to a density of 1/50 km^2 and 50% of the estimated potential.

Unit energy demands have been set at 7.5 and 850 MW_th/yr for BHEs and GWDs, respectively.

The areal ratio adopted for recoverable heat assessments was applied again here.

The individual doublet installed capacity and yearly heating and cooling loads were estimated at 3.5 MWt (150 m^3/h, 40-20°C) and 15,000 MWh_t/yr, respectively (assuming a 90% utilisation factor). Bearing in mind that the specific area should allow for twice more doublets regardless of the cascading opportunities offered by deeper drilled doublets, and given the higher medium depth aquifer occurrence in the specific area, the exploitable heat of the Grand Madrid and Northeast Madrid areas were estimated at $1.3 \cdot 10^{17}$ and $2.84 \cdot 10^{16}$ J over a 75 year life, respectively.

4.2.2 Deep geothermal

A realistic projection for the specific northeast Madrid area would estimate at ten times the number of GDHC doublets which could effectively be operated locally (Geomadrid: 2; San Sebastian de los Reyes: 3; Tres Cantos: 2-3; other locations: 2-3). Assuming a unit doublet production of 40,000 MWh_t/yr (i.e. 144,000 GJ/yr), the total heat withdrawn from the tertiary sandstone aquifer over 75 years would amount to 30 TWh_t (i.e 110 PJ) for the specific area alone.

This figure corresponds to 120 TWh_t (i.e. 440 PJ) for the overall area, assuming 40 online GDHC doublets.

4.2.3 Ultra deep geothermal

At the present stage of the EGS technology, any forecast of future development is a risky exercise.

Nevertheless, the following projections can be contemplated, bearing in mind that the most promising prospects should trend along the Mesozoic basement/tertiary sandstone contact and associated border faults likely to favor deeply enhanced hydrothermal convection (as sketched in the cross-section in Figure 3):

- unit installed power: 30 MW_t/3 MWe (10% heat to power conversion cycle efficiency)
- power plant utilization factor: 0.85
- heat demand: 15,000 MWh_t/yr
- system lifetime: 25 yrs (completion of three successive EGSs required over 75 years)
- number of EGS plants
  - overall area: 12
  - specific area: 3

The foregoing lead to the projected heat and power figures listed in table 2:

Table 2: EGS projections

Zone Supply (PJ/TWh(*))	Overall (Grand Madrid)	Specific (NE Madrid)
Power	72/20	18/5
Heat	50/13.5	12/3.4
Total	**122 PJ/13.5 TWh**	**30 PJ/8.4 TWh**

(*)1TWh=3.65 PJ

Note that the 0.1 heat to power conversion efficiency could be regarded as conservative given the fairly high inlet temperature (170°C) and the performance expected from upgraded binary cycles (ORC, Kalina).

4.3 Results

The previous assessments and driving assumptions led to the results listed in Table 3.

Table 3. Summary of Resource/Reserve Assessments

ZONE	OVERALL (Grand Madrid)	SPECIFIC (NE Madrid)
AREA (km^2)	**1400**	**150**
VOLUME 5 km depth (km^3)	**7000**	**750**
HEAT FLOW DENSITY (Wm^{-2})	**9 10^{-2}**	**9 10^{-2}**
SUBSURFACE TEMPERATURES (°C)		
500 m	35	35
1500 m	60-70	60-70
2500 m	80-100	80-100
5000 m	160-180	160-180
ACCESSIBLE RESOURCE BASE (ARB) 5 km 10^{19} J	**560**	**6.2**
HEAT RESUPPLY		
Power (MWt)	126	13.5
Energy (GWht/yr)	**1130**	**104**
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**

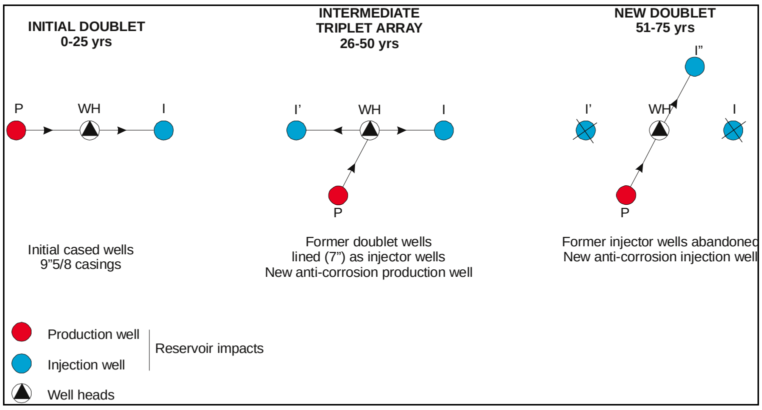


Figure 7. Production/Injection well array configurations (75 years life).

5. CONCLUSIONS

An assessment of the recoverable geothermal potential for shallow, medium-depth, deep and ultra-deep seated geothermal environments within the Madrid metropolitan area was performed.

The exploitable heat and power potential over the Grand Madrid (1400 km^2) and Northrast Madrid (150 km^2) areas amounts to ca 730 and 170 PJ, respectively, assuming a 75 year sustained life. These figures correspond to 3% and 5% of recoverable heat of the Grand Madrid and NE Madrid areas, calculated according to current evaluation criteria practiced by the mineral and geothermal industry.

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