Proceedings Indonesia International Geothermal Convention & Exhibition 2014
Jakarta Convention Center, Indonesia 4-6 June 2014

TECHNICAL, ECONOMIC AND FINANCIAL FEASIBILITY STUDY FOR THE DEVELOPMENT OF THE SHALLOW RESERVOIR IN DUBTI (TENDAHO - ETHIOPIA) THROUGH A POWER PLANT OF INSTALLED CAPACITY UP TO 12 MW

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Keywords: Feasibility Study, Exploitation, Shallow Reservoir, Production-Reinjection Wells, Power Plant, Financial Analysis.

ABSTRACT

To assess on behalf of GSE (Geological Survey of Ethiopia) the feasibility of development and exploitation of Dubti geothermal resources (Tendaho Graben, Ethiopia) the available documentation was reviewed by ELC Electroconsult and an updated assessment of the project status was elaborated. Such documentation included the results of numerous geoscientific investigations and of five wells drilled in the area to depths included between 460 and 2,200 m, out of which three are productive.

The evaluation of the geothermal prospect and in particular of the existence of a deep resource and of a commercially exploitable shallow reservoir was conducted through the following steps: *Independent Review of the Scientific Work*, *Program for Drilling of Geothermal Wells* and *Technical, Economic and Financial Streamline Feasibility Study*.

Among the different scenarios, the *immediate exploitation* of the proven resource pertaining to the shallow reservoir was recommended, through the installation of a geothermoelectric power plant with a capacity of up to 12 MW. The liquid dominated shallow reservoir is encountered at depths in the 220-510 m range, with pressure and temperature close to a Boiling Point for Depth distribution.

Different options were analysed as refers to drilling of production wells for the exploitation of the shallow resources. The recommended solution was to make use of the Kremco drilling rig owned by GSE, after an adequate refurbishment. The utilization of the Massarenti drilling rig, owned by GSE too, should be considered as a "*mitigation option*" in case the Kremco rig is not available for any reason.

The level of knowledge of the shallow reservoir is largely sufficient to start the development of the entire project together with the preparation of the procurement process for the power plant and the gathering system. The need of drilling additional production wells closer to the upflow zone, as well as the lack of a numerical model of the reservoir, suggest to postpone the final assessment of the power plant capacity.

The analysis of alternative exploitation technologies allowed to select as most suitable, from the technical and economic viewpoints, a single flash condensing power plant. Following such selection, the basic design of the Fluid Collection and reinjection System and of the power plant has been carried out.

The result of the economic and financial analysis showed that the development of the project by EEP is compatible with sound business practices.

FOREWORD

Within the framework of the program for development of the Ethiopian geothermal resources, ELC Electroconsult, on behalf of the Geological Survey of Ethiopia (GSE), has reviewed all the available documentation on the Tendaho prospect and has elaborated its own assessment of the status of the Project, proposing a strategy for future development in terms of integrative geoscientific investigations and of deep drilling campaign.

As discussed here after, the investigations conducted so far allowed to identify the existence of two separate geothermal systems, namely: (1) a "shallow reservoir", encountered in the wells drilled in the proximity of the Dubti Cotton Plantation, whose thermodynamic and chemical characteristics have been defined with a fair degree of approximation; (2) a "deep reservoir", whose characteristics and potential commercial interest remain to a large degree undefined.

Based on the above, the immediate exploitation of the resources pertaining to the shallow reservoir is recommended and the relevant technical, economic and financial feasibility has been accordingly analyzed, indicating at the same time the opportunity to proceed with the investigations aimed at proving the existence of an exploitable deep reservoir.

GEOSCIENTIFIC FRAMEWORK

Extensive geological, geophysical and geochemical investigations were carried out in the area during the last 35 years (see Figure 1). Moreover, two deep wells (depth of 1,811 and 2,196 m) and three shallow wells (depth of 466-516 m) were drilled in the Dubti prospect and one more (depth of 1,989 m) to the North of Dubti.

The Tendaho area is characterized by the presence of a 50 km wide graben trending NW-SE (Tendaho Graben), dissected on its turn by a series of normal faults forming a sequence of secondary horst and graben. The basement of the graben is composed of fissural basalt of the Afar Stratoid Series, overlain by a 1,200-1,400 m thick sedimentary sequence (siltstone and subordinate sandstone) with basaltic intercalations, which hosts the shallow reservoir.

The horst-graben structure within the Tendaho Graben has been confirmed by the results of the gravimetric and magnetometric surveys. The MT survey identified the presence of an upper conductive unit, some 1,000 m thick around the Dubti prospect, which might reflect the occurrence of hot, saline fluids within the shallow reservoir.

A lower conductive unit, recognized at a depth of 5-10 km, might on its side correspond to a molten magmatic chamber.

The fluids of both deep and shallow reservoirs have very similar chemical characteristics, belonging to the Na-Cl family with a TDS of about 1,800 mg/l. Such similarity would indicate a direct connection between the main upflow zone of the geothermal system and the two geothermal reservoirs.

CONCEPTUAL MODEL OF THE FIELD

The conceptual model of the field, with specific reference to the Dubti prospect, has been elaborated based on the results of the geoscientific investigations and of the exploratory wells.

The **heat source** of the geothermal system/s may be associated with phenomena of continental crust thinning and opening, particular evident along the axial range of the Tendaho Graben. In accordance with the MT findings, the molten magmatic material is deemed to occur at a depth of 5 to 10 km.

The **geometry of the shallow reservoir** has been reconstructed based on the results of drilling and of geophysical, soil temperature and soil gas surveys (see Figure 2). The top and bottom of the reservoir are assumed to occur at depth of 250 m and 550 m, respectively, while the area proven by drilling cover a surface of 1 km^2 and the "probable" area, as indicated by the geoscientific investigations, covers a surface of 3 km^2.

No evidences are at present available on the **geometry of the deep reservoir**, except for the indication derived from the results of the MT survey that its top presumably would occur at a depth ranging between 2,000 and 3,000 m.

As refers to the **hydraulic features**, it can be observed that the basalts of the Afar Stratoid Sequence are characterized by very low permeability, at least wherever intersected by the deep wells. The sedimentary sequence, on the other hand, is associated with feed zones in basaltic lava flows and in coarse grained sandstone layers. Permeability thickness product (kh) is highly variable, ranging between 4 and 100 Dm.

Thermodynamic conditions of both shallow and deep permeable zones are liquid-dominated, with pressure distribution controlled by liquid water density. While deep permeable zones are far from boiling conditions of pure water, the shallow ones are close to boiling point for depth, with temperature reaching 255 °C.

The reconstruction of the **natural fluid flow pattern** indicates that recharge is supplied by a regional aquifer carrying meteoric water infiltrated at the margins of the Tendaho Graben and in the Ethiopian Plateau (see Figure 3). The main upflow of hot fluids is linked to sub-vertical faults penetrating deeply into the Afar Stratoid Series. Moving upwards, these fluids can recharge the permeable layer crossed either in the Afar Stratoid Series or in the sedimentary sequence. In the latter, fluid path flows are very likely linked to sub-horizontal pervious layers represented by coarse grained sediments and by basalt lava flows.

ASSESSMENT OF THE RESOURCES

The assessment of the geothermal resources was carried out only for the shallow reservoir, where the available information is sufficient for estimating, with a fair degree of reliability, the geometric, hydraulic and thermodynamic conditions.

The volumetric method supplemented by the Monte Carlo approach has been accordingly adopted to evaluate the heat stored in the shallow reservoir and the capacity of the power plant. The area of 3 km^2 has been assumed as the most probable value, together with a thickness of 300 m, a reservoir temperature of 240 °C, a porosity of 0.15, a rejection temperature of 165 °C and a power plant life of 30 years.

The results obtained with 10,000 Monte Carlo realizations show that the most frequent power plant value is 9.6 MWe, while the values corresponding to 90, 50 and 10 % probability are 7.4, 9.7 and 13 MWe, respectively. Thus, a power capacity in the order of 7 to 10 MWe can be considered of high probability for the shallow reservoir (see Figures 4a, b). Drilling of additional exploratory and development wells is needed to confirm the above evaluation, although it should be mentioned that higher temperatures and reservoir thickness are likely to be found moving towards the upflow recharging the shallow reservoir, inferred to occur in the SE sector of the Dubti hydrothermal area.

ALTERNATIVE DEVELOPMENT STRATEGIES

According to GSE, two options of development strategy can be envisaged, based on the conceptual model of the Tendaho geothermal resources, namely:

a. To devote further effort to the characterization, development and utilization of the shallow resources.

b. To continue exploring the sector located to the SE of the drilled area, in order to discover the deeper, primary reservoir.

Option a. is subject to two major constraints: (1) the full-scale exploitation of the shallow resources may be limited by the actual extent of the recharge from the deeper source; and (2) such exploitation could also bring about significant subsidence in the environmentally sensitive and economically important land in the Dubti area. GSE recommends therefore to focus the next activities towards the identification of deep targets, to be tested through drilling.

In spite of the above mentioned constraints, it is felt that the proven existence of exploitable shallow resources deserves the immediate implementation of a drilling program, due to be associated with a relatively low mining risk. It is hence recommended to pursue both alternatives in parallel, in the understanding that at this stage it is too early to set targets in terms of global electric power to be installed and of corresponding time schedule.

DEFINITION OF THE DRILLING STRATEGY

The implementation of the above described development strategy (early exploitation of the shallow resources in parallel with integrative exploration of the deep ones) implies obviously the execution of an extensive drilling campaign, associated with significant costs. It is therefore important to define a drilling program, which, taking into account the existing and potential drilling facilities as well as the overall objectives of the campaign, minimizes costs and timing of the campaign itself.

Drilling activities can be carried out through four alternative means:

1. Utilize the Massarenti rig owned by GSE, presently in good operating conditions, but at least partly destined to drill other geothermal fields in Ethiopia, in particular the Aluto one. The rig can drill up to a depth of 3,000 m with a hole section of 81/2"

2. Utilize the Kremco rig owned by GSE, less powerful than the Massarenti one and idle since the year 1986, requiring heavy reconditioning interventions. The rig can drill up to a depth of 2,500 m with a hole section of 81/2"

3. Purchase a new rig

4. Hire a Drilling Contractor, presumably from Kenya

In order to select the most convenient strategy, to be adopted for the next few years drilling program, four options have been analyzed, namely:

A. Drill the shallow wells in Dubti with the Kremco rig, following proper reconditioning actions, whereas the Massarenti rig, once completed drilling operations in Aluto, can move to Tendaho to drill deep exploratory wells.

B. A new rig will be purchased and used to drill the shallow wells in Dubti, whereas, similarly to Option A, the Massarenti rig, once completed drilling operations in Aluto, can move to Tendaho to drill deep exploratory wells.

C. A Drilling Contractor will drill the shallow wells in Dubti, whereas, similarly to Option A, the Massarenti rig, once completed drilling operations in Aluto, can move to Tendaho to drill deep exploratory wells.

D. In case reconditioning of the Kremco rig can not be carried out for any reason, use the Massarenti rig for drilling the Dubti shallow wells.

The economic analysis of the four options indicates that Option C, relevant to hiring of a Drilling Contractor, is clearly the most expensive one and should not be taken into consideration. Options A and B are almost equivalent, in terms of "cost per well", but Option A is associated with a lower Net Present Value of the fixed costs and is therefore preferable. Option D can be classified as a "mitigation option", to be adopted only in case of impossibility of reconditioning the Kremco rig.

It is therefore strongly recommended to proceed immediately with the Kremco reconditioning operations and, at completion, with the utilization of this rig for drilling the production and reinjection wells required for the exploitation of the Dubti shallow resources (see below). The Massarenti rig, on its turn, once completed the Aluto program, should move to Tendaho to investigate the deep targets singled out by the integrative geoscientific investigations.

FEASIBILITY STUDY FOR THE DEVELOPMENT OF THE SHALLOW RESERVOIR

At completion of the resources assessment and of the definition of a development strategy, a feasibility study was elaborated, relevant to the installation of a power plant with a capacity of up to 12 MW, exploiting the shallow resources.

Field Development

On the base of the reservoir properties and deliverability characteristics of the already drilled wells, it is estimated that four production wells, to be drilled SE of the already investigated area, will be needed to guarantee the required steam with an adequate degree of reliability and flexibility. Two reinjection wells are foreseen, located some 2 km NW of the extraction sector in order to limit the risk of an early thermal breakthrough. Finally, to compensate the reservoir depletion caused by fluids extraction, four make-up wells are expected to be required throughout the 30 years plant operation period.

All wells are assumed to be of standard diameter (7" slotted liner) and to be drilled to an average depth of 600 m, with the production casing shoe set at 250 m.

With reference to the Fluid Collection and Reinjection System (FCRS), it is proposed to collect the geothermal fluids coming from each production well into a common separation station, located in a barycentric position among the wells. From there the steam line will go the power plant and the separated water line to the reinjection wells (see Figure 5).

Basic Design of the Power Plant

Four thermal cycles have been considered for the power plant:

A. Cycle with primary steam separated from the geothermal fluid, expanded in the turbine and discharged into the atmosphere (single flash backpressure turbine).

B. Cycle with primary steam separated from the geothermal fluid, expanded in the turbine, condensed and partially reinjected into wells (single flash backpressure turbine).

C. Binary cycle, where the geothermal fluid is flashed in the separator and then the steam and the hot brine feed two different sections of the evaporator. The working fluid is only the organic one (Rankine cycle).

D. Combined cycle, where the steam separated from the geothermal fluid is expanded in the turbine, condensed and reinjected, whereas the hot water from the separator exchanges heat with an organic fluid working in a Rankine cycle.

The comparison among these four alternatives has been carried out taking essentially into account the well production characteristics (enthalpy, WHP, NCG content, etc.) as well as economic factors. The analysis indicates as most suitable the adoption of Cycle B (condensing cycle), associated with a net specific consumption of 8.1 (t/h)/MW of steam.

The main features of the power plant are summarized here below (see Figure 6):

- ✓ **Steam turbine**: capacity of 12 MW, saturated steam at 5-7 bar, speed of 3,000 rpm.

- ✓ **Condensing system**: direct type with condensing pressure of 0.09 bar.

- ✓ **Non Condensable Gas (NCG) Extraction System**: ejector system due to the low NCG content, estimated to be 0.5 % by mass fraction in the separated steam phase.

- ✓ **Cooling system**: mechanical induced type cooling tower.

Cost Estimate

Investment and operation costs of the shallow reservoir development in Dubti were estimated on the basis of updated information and direct experience of the Consultant in other geothermal prospects with similar characteristics and of the market prices for most of the items.

The capital expenditures (see Table 1), referred to drilling of 6 production/reinjection wells, supply and erection of the FCRS and of a 12 MW power plant, construction of a 20 km long 33 kV transmission line connecting the plant to the Semera substation, are summarized here below. These costs make allowance for land acquisition, engineering services, project management and contingencies.

SUMMARY OF CAPITAL EXPENDITURES			
Project Components	US$x1000	Birr (in USx1000)	TOTAL US$x1000
Drilling ad Testing of Prod. & Reinj. Wells	4500	2100	6600
Supply and Erection of FCRS	2570	700	3270
Supply and Erection of Power Plant	17000	4000	21000
Supply and Erection of Transmission Line	1200	300	1500
Total Cost of 12 MW Project	**25270**	**7100**	**32370**

Table 1 - Summary of Capital Expenditures

The Operation and Maintenance (O&M) costs include fixed (staff salaries, routine measurements, insurance, etc.), major plant overhaul and make-up wells drilling costs. The yearly O&M costs range between 1.5 and 3.4 MUS$, for a total of 55.1 MUS$ during 30 years of plant operation time.

Economic Analysis

The economic analysis has been carried out assuming a time of approximately 3 years for the full development of the shallow resources, from the reconditioning of the Kremco drilling rig until the start of the commercial operation. Assuming moreover a yearly generation of 80 GWh (corresponding to a plant capacity of 10 MW and an average plant factor of 0.9) and a 10 % discount rate, the Net Present Value (NPV) would amount to 76.2 MUS$.

To calculate the Economic Internal Rate of Return (EIRR), both the economic value of exported electricity agreed upon between Ethiopia and Djibouti (0.06 US$/kWh) and between Ethiopia and Kenya (0.07 US$/kWh) have been considered. In the former case the EIRR results to be 7.6 %, whereas in the latter case it rises to 10 %.

Financial Analysis

The scope of the financial analysis includes the development phase and the commercial operation phase, to assess the conditions under which the geothermal resource is commercially viable, hypothesizing that the Ethiopian Electric Energy Agency (EEP) is directly in charge of project development and assuming the previous exploration activities as financial sunk costs.

Two scenarios have been analyzed: (1) Base Scenario: EEPCo Developer with repayment of wells drilling costs at EEPCo tariff and GoE loan conditions; (2) Sensitivity Scenario: EEPCo Developer without repayment of wells drilling costs.

A series of assumptions have been made, including the possibility of obtaining a loan (in local currency) from the GoE at 6 % interest rate and the application of a tariff for local market of 0.030 US$/kWh and for export market of 0.068 US$/kWh.

In Table 2 shows the main results of the financial analysis, in term of Levelized Cost Of Energy (LCOE).

Scenario	LCOE
Base Scenario - EEPCo Developer with repayment of wells drilling costs at EEP tariff and GoE loan conditions	0.054 US$/kWh
Sensitivity Scenario - EEP Developer without repayment of wells drilling costs at EEP tariff and GoE loan conditions	0.046 US$/kWh

Table 2 - Results of the Financial Analysis

The result shows that the development of the project by EEP is compatible with a sound business practice.

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FIGURES

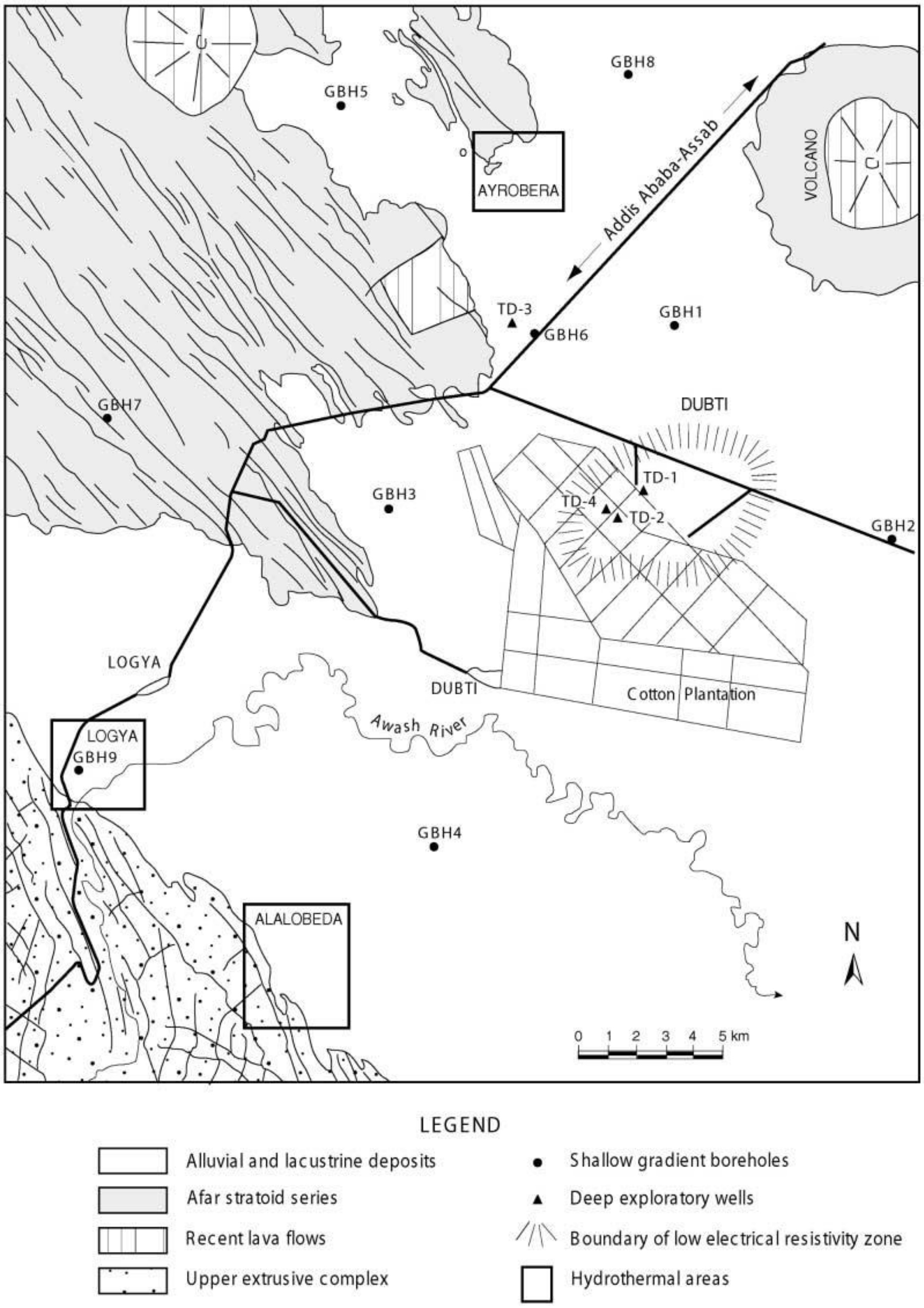


Figure 1 - Map of the Area of Geothermal Interest (from Battistelli et al., 2002)

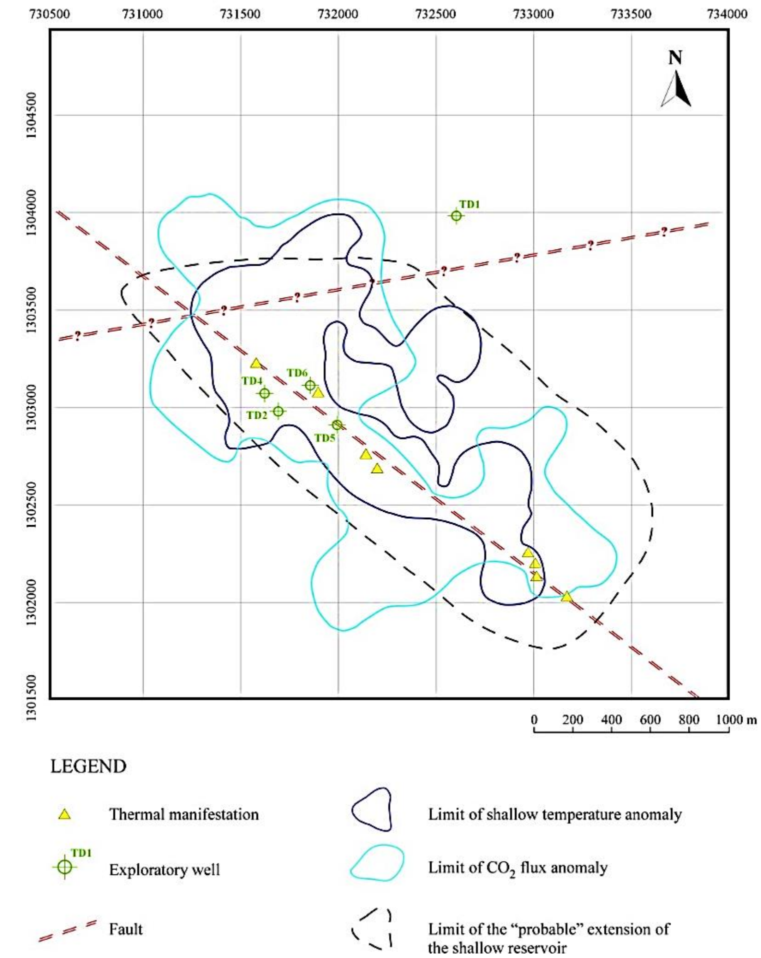


Figure 2 - Probable Extent of the Shallow Reservoir

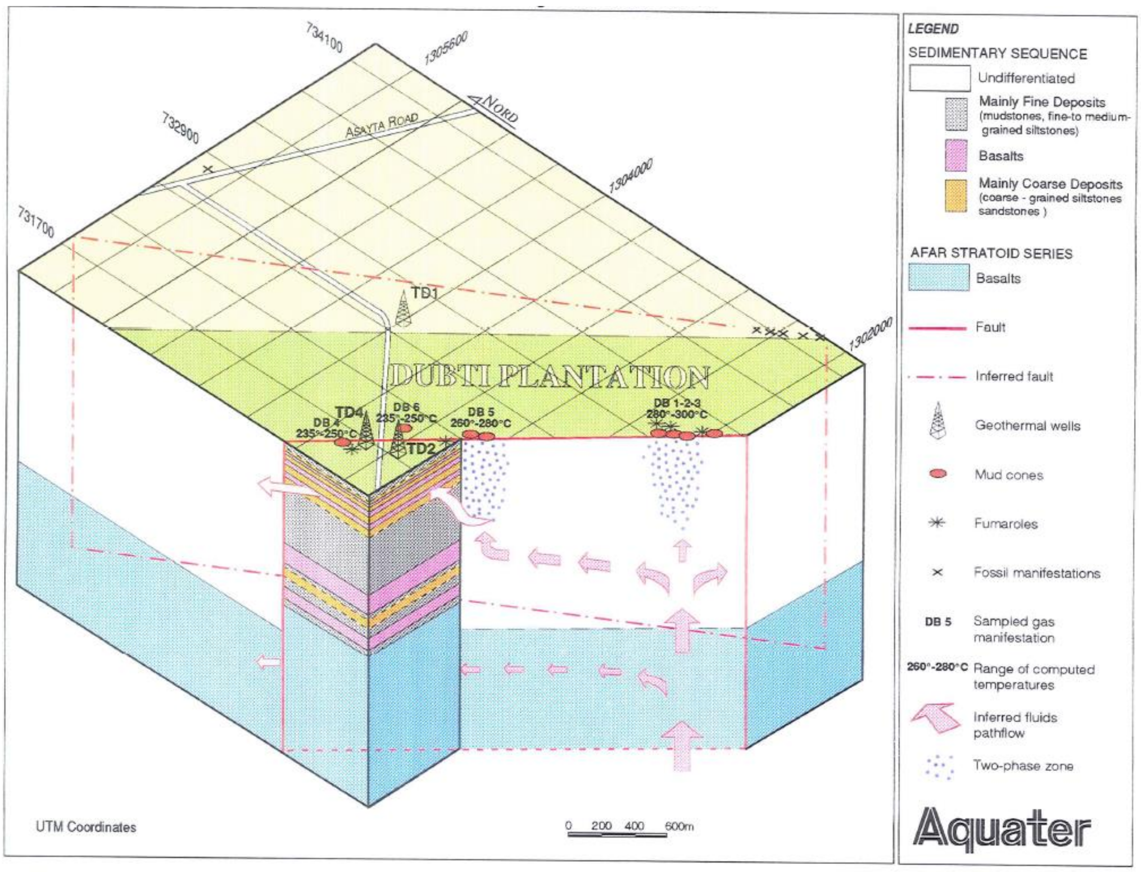
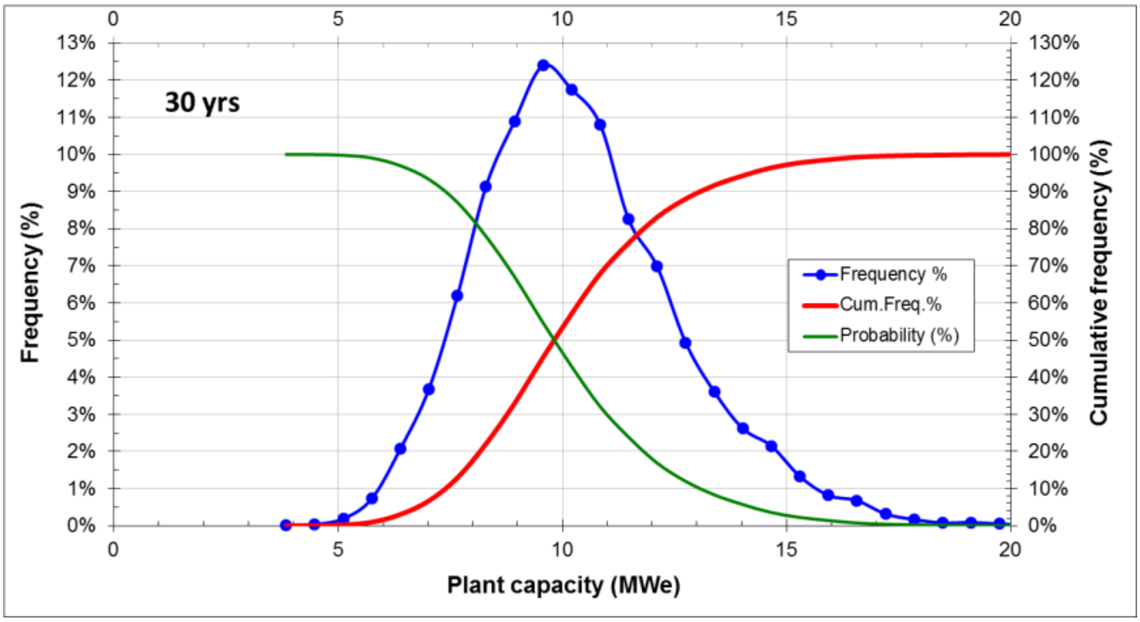
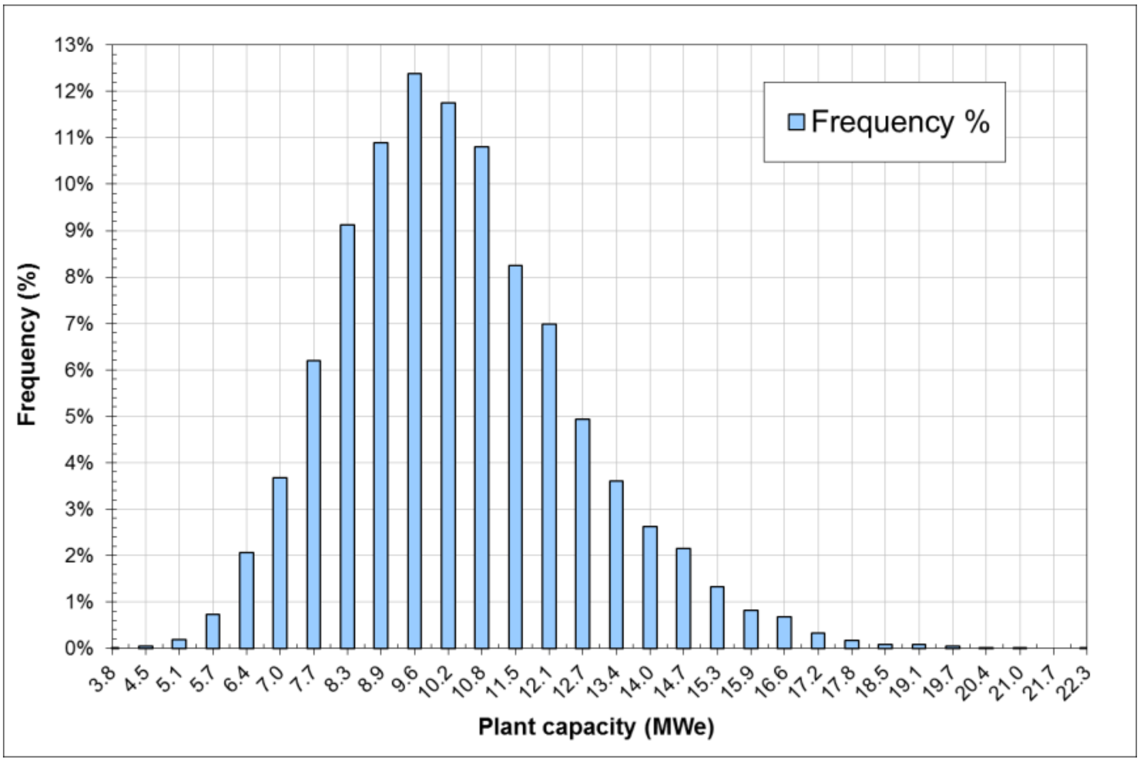


Figure 3 - Conceptual Model of Shallow Reservoir in Dubti (Aquater, 1996)



(a)



(b)

Figures 4a, b - Results of Monte Carlo Analysis for the Power Capacity of the Shallow Reservoir.

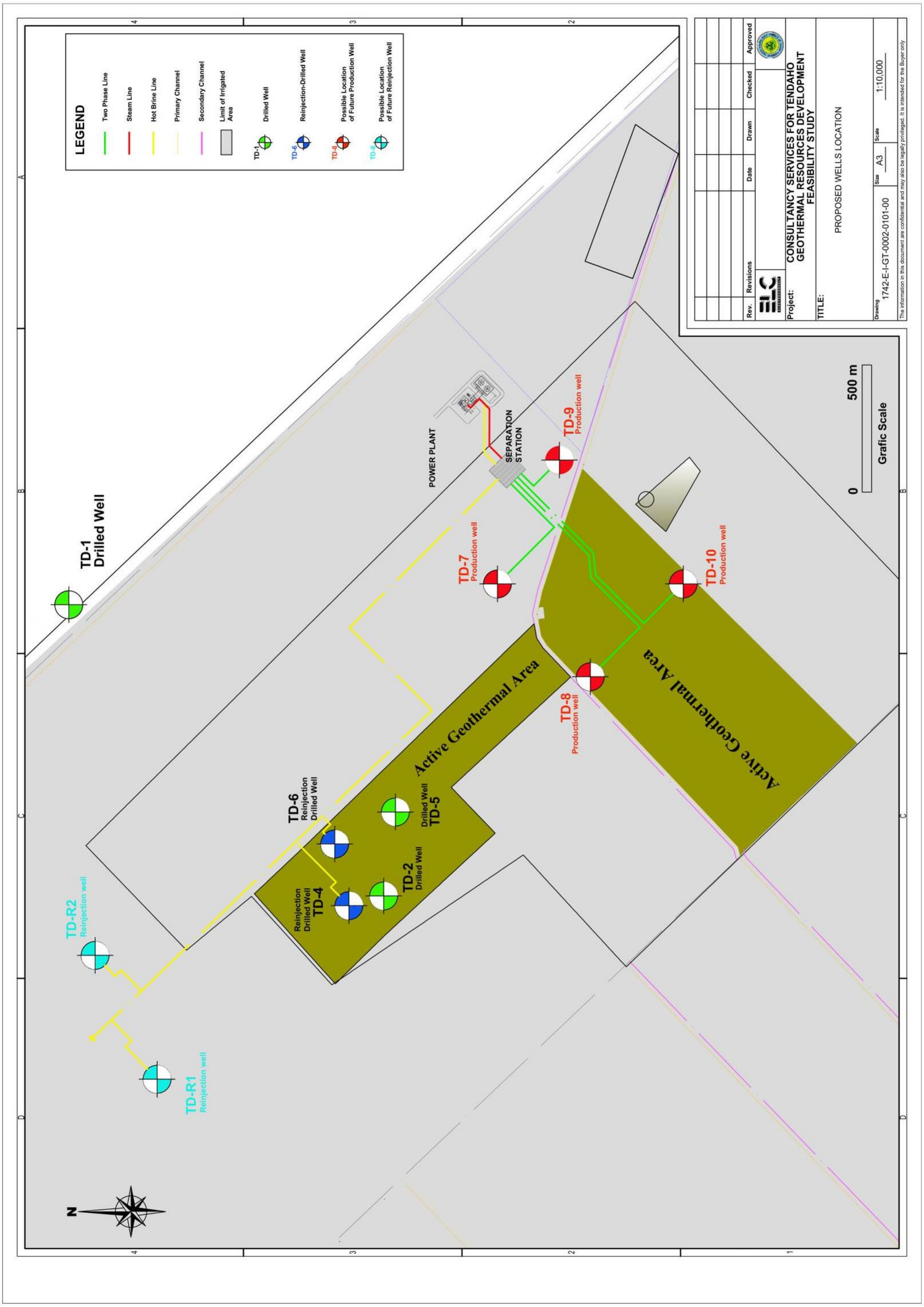


Figure 5 - Proposed Wells Location

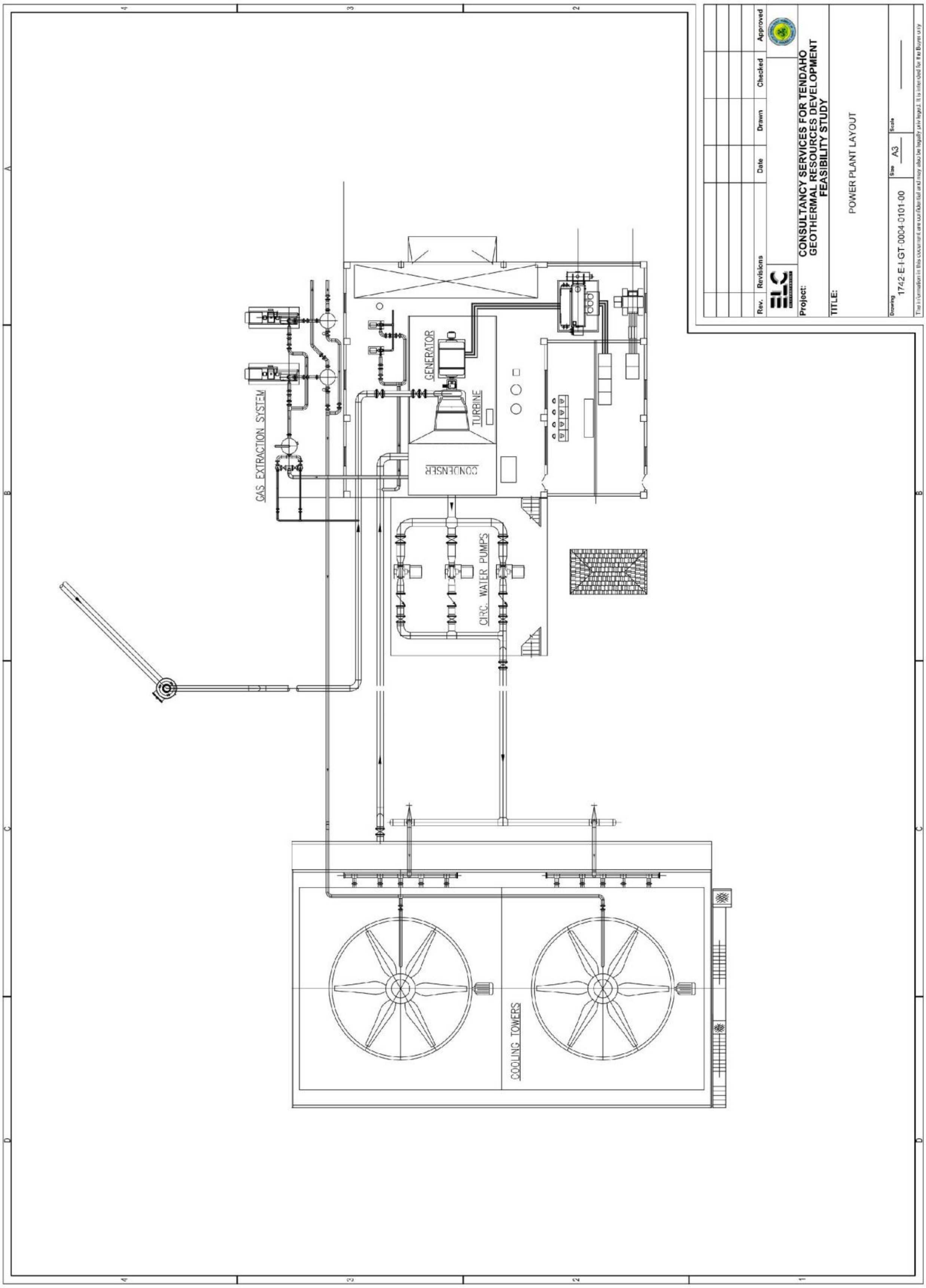


Figure 6 - Power Plant Layout