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GEOTHERMAL EXPLORATION AND DEVELOPMENT IN ETHIOPIA

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ABSTRACT

The limited resources; the continuing rise in the price of fuel; and the environmental impact awareness brings renewable energy resources from a minor curiosity to a respectable level. Although Ethiopia is endowed with substantial renewable energy resources (hydropower, geothermal, solar and possibly wind energy resources), the bulk majority of the people as yet have no access to electricity and over 90% of the energy consumption is based on biomass – which forces the felling of trees for firewood, accelerating impacts such as deforestation, soil erosion and the loss of wildlife. Therefore, improving the modern energy supply especially from renewable energy is synonymous with the fight against poverty and global warming. Other than hydro and geothermal, other renewables have not yet been studied in a manner that can secure a good and reasonable return. Hydropower is strongly affected whenever there is a drought and until recently, virtually the entire energy budget was allocated to conventional large-scale investments, which resulted in the smaller-scale renewables being largely left out. Indeed, currently it is argued that a shift from large-scale to small-scale power generation initiatives will decrease the level of investment and increase the impact on population. Similarly, not much has been done in improving energy efficiency as well. The current rate of increasing energy demand outpaces the rate of increases in supply in Ethiopia. This shortfall clearly is a “wake up call” for implementing the energy mix system. For instance, Ethiopia has possibly the greatest share of this huge and valuable energy resource associated with the Great East African Rift System. Therefore, it can be developed aggressively for the benefit of the country and to reduce exposure to high oil import costs (nearly ten million USD spent in three months just to back up the hydropower moderately during shortage periods of this year). Moreover, the rationale behind promoting renewables and energy efficiency in Ethiopia includes enhanced energy security; availability of plentiful and cost-competitive renewables, especially hydro and geothermal; ability to provide cost-competitive energy services to remote rural settlements; and significant job and enterprise creation potential. Therefore, the need to diversify power sources through the utilization of indigenous energy resources that would be economically competitive, reliable and are environmental friendly is becoming increasingly recognized. Inevitably, Ethiopia seems to be moving to a phase of action that ensures the development of geothermal resources in the country whereby the resource development will be facilitated by implementing an aggressive and sustainable development scheme that involves Public-Private Partnership (PPP) and Independent Power Producers (IPP) as well.

FIGURE 1: Physiographic map of Ethiopia

1. COUNTRY PHYSIOGRAPHY AND ENERGY BACKGROUND

1.1 Physiography

Ethiopia is located in the Horn of Africa between 3.5° and 14°N and 33° and 48°E (Figure 1). It is dissected by the Great East African Rift System from northeast to southwest that has a thin crust allowing a regional high heat flow. The Rift has created a conducive environment for the existence of geothermal that Ethiopia is sharing significantly along with some of the East African countries (Eritrea, Djibouti, Kenya, Uganda and Tanzania). The Rift in Ethiopia covers an area of about 150,000 km^2 that is close to 12% of the total land area. Ethiopia, is not only known for its high plateau that rises up to 4600 m but also for the most depressed lowlands, Danakil Depression (120 m b.s.l.), in Africa. The average annual rainfall in the highlands is 1,200 mm in the northern half of the country and 1,800 mm in the southwest. The lowlands annually receive below 600 mm of rainfall. About 70-80% of the rain falls during mid-June to mid-September, during the Meher cropping season. The small rains of the Belg cropping season fall during March to April. In the more populated highlands, the maximum monthly average temperature ranges between 23 and 27°C and the minimum between 10 and 13°C. In the lowlands, these temperatures range much higher.

1.2 Energy background

Energy plays a critical role in improving social services such as water supply, health services, education opportunities and telecommunications services that are useful to create favourable living conditions in the 21st century. Availability of a sustainable and competitive energy supply would build confidence among investors, encouraging them to invest further and ultimately creating a secondary benefit of better job opportunities.

Energy consumption in Ethiopia is made up of less than 1% electricity, about 5.4% hydrocarbon fuels and the rest, traditional biomass fuels (EEPCO Data File). Most petroleum products are consumed in the transport sector, whereas household energy comprises primarily of biomass fuels. It is estimated that annually about 40 million tons of wood fuel, and 8 million tons of agri-residue is consumed. Wood fuel use has contributed to environmental degradation through the loss of large areas of forest cover. The use of crop residues and animal waste for fuel contributes to decreasing farm yields due to the decline of agricultural soil fertility.

At present the total generation capacity is 783 MW, with hydro-generation accounting for 90%. Out of which, 669.9 MW are from 8 hydropower stations; 113.1 MW from widely distributed diesel capacity and 7.3 from the Aluto-Langano geothermal pilot power plant that feeds the interconnected system (ICS) (Table 1). In Fiscal year 2007, the recorded energy generation has reached 3,339 GWh. Records of the recent history of electric demand in the Ethiopian Interconnected System (ICS) show a dramatic rise because of the rapid new investment growth in all spheres of the economy, industrial, commercial, agricultural, domestic and rural besides the internal growth within these spheres. On the other hand, the government is committed to increased access to electricity and expanded rural electrification in all regions of the country, through its Universal Electricity Access Program (UEAP). Taking into consideration such an increase in demand, coupled with poor rainfall, the prevailing load shedding is a natural outcome of routine operation until sufficient rainfall is available and the new power plants under construction are operational. In a hydro-dominated system like ours, the reliability of supply depends much on the availability of firm hydro energy. In order to have a firm hydro energy, a new generation plant is required to be commissioned before the demand approaches the firm energy generation capacity. An alternative strategy to this is obviously promoting energy generation mix that involves other renewable energy resources other than hydro. The 2006 updated Ethiopian Power System Expansion Master Plan (EPSEMP) envisaged the rehabilitation and expansion of the Aluto-Langano geothermal pilot power plant to a full operational condition of > 30MWe at the earliest date possible; and the development of the Tendaho geothermal field during the year 2013 following the Aluto-Langano expansion.

TABLE 1: Existing power plants (interconnected system) and their generation capacity (EEPCo Data File)

Existing power plants (Interconnected system)			
	Power plants	**Installed capacity (MWe)**	**Energy (MWh)**
1	Koka	43.20	116,306.00
2	Awash II	32.00	146,398.00
3	Awash III	32.00	170,934.00
4	Finchaa	134.00	824,845.00
5	Melka Wakena	153.00	480,461.00
6	Tis Abay I	11.40	44,461.00
7	Tis Abay II	73.00	528,994.00
8	Gigel Giebie I	184.00	947,389.00
9	Aluto-Langano geoth. pilot plant	7.30	
Sub total		**669.90**	
Diesel power plants			
1	Alemaya	2.30	
2	Dire Dawa	4.50	
3	Adigrat	2.50	
4	Axum	3.20	
5	Adwa	3.00	
6	Mekele	5.70	
7	Shire	0.80	
8	Nekempt	1.10	
9	Awash 7 kilo	35.00	
10	Kaliti	14.00	
11	Dire Dawa	40.00	
12	Jima	1.00	
Sub total		**113.10**	
Grand total		**783.00**	

2. ENERGY POLICY AND RELATED LEGISLATIONS

The National Energy Policy of 1994 has the objective of facilitating the development of energy resources in appropriate forms and in the required quantity and quality. The strategies consist of the accelerated development of indigenous energy resources and the promotion of private investment in the production and supply of energy. Due to the underdeveloped state of electricity supply in Ethiopia, the major objective has become the achievement of a high level of penetration by the transmission and distribution system into all parts of the country in the shortest time possible by involving all stakeholders and investors. The Electricity Proclamation No. 86/1997 governs investment in electric power and seeks to promote both domestic and foreign private investment in power generation from all sources. Independent power producers (IPPs) may generate electric power for sale to the Ethiopian Electric and Power Corporation (EEPCo) grid under the single buyer model where the grid exists, or to operate independent supply systems in areas not served by the grid. Licenses may be acquired with a validity of a maximum of 40 years for power generation plants, a maximum of 50 years for transmission, distribution sales licenses and a maximum of 10 years for power export or import licenses. Licenses are subject to renewal based on the provisions of the electricity operation regulation. The incentives provided in the investment proclamation (including facilitated access to natural resources and land, the duty free importation of capital goods and beginning stock of spare parts, maintenance of foreign currency accounts in local banks, free remittances outside the country of all proceeds from investments, carry forward of losses, tax holidays on targeted investments from start-up or from capacity expansion, etc.) are also applicable to those investments in the electricity sector.

Investment in geothermal resource development is subject to the Mining Proclamation No. 52/1993, as amended, which provides licensing for the duration of the "resource life". As per the choice of the prospective licensee, separate licenses can be acquired for prospecting (1 year), exploration (3-5 years), development (duration as per feasibility study) and production (25 years and renewable). Alternatively a "cradle to grave" license encompassing all these may be acquired. The Environmental Impact Assessment Proclamation No. 299/2002 seeks to “harmonize and integrate environmental, economic, cultural and social considerations into a decision making process in a manner that promotes sustainable development”. Development activities to be designated by directive (geothermal resource development is so designated) require, before implementation, the authorization of the Federal Environmental Protection Authority (EPA) or regional environmental agencies as necessary.

2.1 Institutional mandates

The Geological Survey of Ethiopia (GSE) is the sole Federal institution responsible for the exploration of the underground energy resources of the country out of which geothermal is one. The Ethiopian Electricity Agency (EEA) is the government authority which is responsible for the licensing and regulation of electric supply systems. The state owned power company, the Ethiopian Electric Power Corporation (EEPCo), is responsible for the generation, transmission, distribution and sale of electric power. It may purchase bulk power from an IPP or surplus producer for distribution through the grid. Other organizations have small diesel generating facilities installed for their own use. The Ethiopian Rural Electrification Board (EREB), established on 6 February 2003 by Proclamation No. 317/2003, is responsible for the promotion and support of private sector power supply in rural areas that are not served by the EEPCo grid. The Ethiopian Investment Authority (EIA) has the responsibility for the licensing of investments, other than in electricity and mining. The administration of the mining proclamation that governs geothermal resource development is the responsibility of the Mining Operations Department of the Ministry of Mines and Energy (MoME). The Ethiopian Environment Protection Authority (EPA) has the responsibility for the authorization of projects licensed under federal authority and to monitor implementation and operations. Regional environmental protection agencies have similar authority over projects that are licensed (projects that do not have inter-regional impacts) by the regions. Other than EPA and EIA, all other mentioned institutions are under the umbrella of the MoME.

2.2 Involvement of independent power producers

Although there have to date been memoranda of understanding with foreign investors for the installation of three hydro and one coal burning power plants, there is as yet no operating IPP. A prospective MoU is signed between EEPCo and the Reykjavik Energy Invest (REI) Company, Iceland that holds exploration and development license for the Tendaho geothermal resource area for the eventual power development of 100 MWe.

3. STATUS OF GEOTHERMAL EXPLORATION AND DEVELOPMENT IN ETHIOPIA

Based on available scientific information and experiences on the rift geothermal systems both in Kenya and Ethiopia, a single field could support over 100 MW. Taking this; the power density for most geothermal fields worldwide, i.e. 8 MW/km^2 at 230°C and up to 30 MW/km^2 at 300°C (Grant, 2000); and the size, frequency and extent of volcanic and hydrothermal activities all along the 1,500 km length of the Ethiopian Rift, it is plausible to assume the presence of a huge geothermal energy base in Ethiopia. If developed, geothermal energy has the benefit of providing energy diversity in Ethiopia, thereby decreasing the risks of supply breakdowns / outage experienced whenever there is drought and cost fluctuations due to oil price rises. In a cascade system it can be used for electricity power generation (T >150°C) and direct uses (T< 150°C) that include amongst others industrial applications, aquaculture, horticulture, and balneology. International forecasts expect the share of renewable energy sources in the world energy mix to increase significantly. The total share of geothermal in electricity production from renewables follows hydropower and biomass. Currently, it is cost competitive with that of hydropower and is cheaper than biomass, wind or solar.

Over the years, an inventory of the possible resource areas within the Ethiopian sector of the East African Rift system, as reflected in surface hydrothermal manifestations has been built up (Figure 2). The inventory work in the highland regions of the country is not complete but the rift system has been well covered. Of about 120 localities within the rift system that are believed to have independent heating and circulation systems, about eighteen are judged to have potential for high-enthalpy resource development, including electricity generation (Cherinet and Gebreegziabhier, 1983; Kebede, 1986; EIGS and ELC; 1986; Gizaw, 1993, 2002; Darling, et al., 1996; EIGS and Aquater, 1996; D'Amore et al., 1997; Ayele, et al., 2002; Teclu, 2003; Demlie et al. 2006).

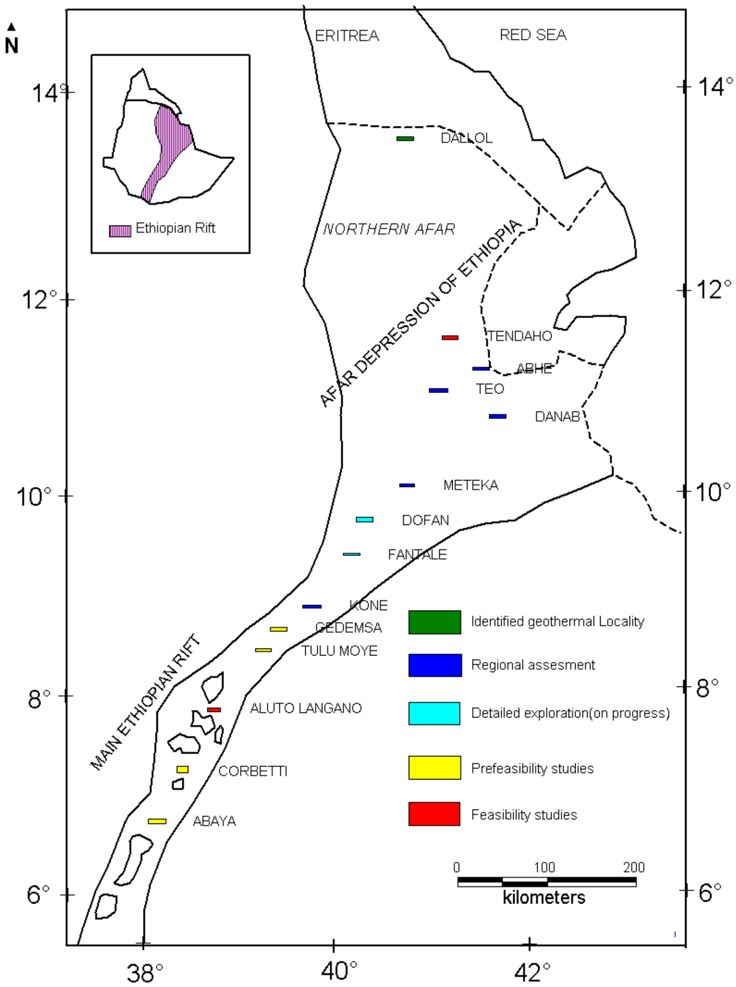

FIGURE 2: Location map of the Ethiopian Rift and geothermal prospect areas

This includes Abaya, Corbetti, Aluto-Langano, Tulu Moye, Gedemsa, Boseti Guda, Boseti Bericha, Kone, Fentale and Dofan in the MER; Meteka, Amoisa, Ayelu, Teo and Danab, Tendaho, Lake Abhe and Dallol areas Afar. Based on their anticipated potential; and, their strategic location with respect to proximity to the existing national grid and demand (population density), Aluto-Langano, Tendaho, Corbetti, Abaya, Tulumoye-Gedemsa, Dofan and Fantale have been subjected for better exploration schemes.

A much larger number are capable of being developed for non-electricity generation applications such as in horticulture, animal breeding, aquaculture, agro-industry, health and recreation, mineral extraction, space cooling and heating, etc.

Geothermal exploration at a level of deep drilling that started in Ethiopia at the Aluto-Langano field in the early 1980's and then at the Dubti geothermal field of the Tendaho graben helped the discovery of the resource in the respective fields. During the three decades that geothermal resources exploration work was carried out in Ethiopia, a good information base and a good degree of exploration capacity, in human, institutional and infrastructure terms, has accumulated, ensuring that selected prospects can be advanced to the resource development phase rapidly (EIGS and UNDP, 1973; Endeshaw, 1988; Endeshaw, and Belaineh, 1990; Gizaw, 2004, 2005; Teklemariam et al., 2000; Teklemariam and Beyene, 2005). Based on geological and geochemical information, the Ethiopian Rift may conveniently be divided into the Main Ethiopian Rift and the Afar Depression. Geothermal prospect are, therefore, described below under these categories.

3.1 Geothermal prospects in the Man Ethiopian Rift

The priority areas for geothermal electric power development in the MER are from south to north Abaya, Corbetti, Aluto-Lanagnao, Tulu Moye, Gedemsa, Boseti Guda, Boseti Bericha, Kone, Fentale and Dofan. The first experience Ethiopia had in deep exploration drilling was carried out in the Alutu-Langano geothermal field in the early to mid-1980s. As this is the relatively better explored field, results obtained so far are described below in detail. The exploration status and obtained results of other geothermal systems are also briefly summarised.

3.1.1 The Aluto-Langano geothermal field

Detailed geological, geochemical and geophysical surveys were carried out in the Aluto volcanic centre that covers an area of about 100 km^2 and in its close vicinity during the late 1970's and early 1980's, which was followed by drilling eight exploratory wells. Results revealed the existence of a commercially viable water dominated underground fluid at economically viable depths (Table 2).

Eight deep exploration wells have been drilled at the Aluto-Langano geothermal field. Out of the eight deep wells 5 are producers (Table 2). Subsurface temperatures as high as 335ºC have been measured in one of the deep wells, that produces 36 T/h and lies in the upflow zone. Two of the wells (LA-3 and LA-6) drilled on the Aluto volcanic complex produced 36 and 45 T/h geothermal fluid at a measured maximum temperature of 335°C, but estimated to be close to 360°C, along a fault zone oriented in the NNE-SSW direction. Two wells drilled as offsets to the west (LA-4) and east (LA-8) of this zone produced 100 and 50 T/h fluid with lower temperature, respectively. LA-5, drilled in the far southeast of the earlier two wells was abandoned at 1,867m depth due to a fishing problem but later showed a rise in temperature over an extended period of time. LA-7 was drilled in the SW but could discharge only under stimulation, being subject to cold-water inflow at a shallow depth. The earliest wells drilled in the prospect were drilled to the south (LA-1) and west (LA-2) of the present limits of the fault controlling the upflow.

A 7.3 MW pilot geothermal plant was installed in 1999 utilizing the production from the above exploration wells (LA-3, LA-4, LA-6, and LA-8). The plant has not been fully operational due to reasons that have to do with the lack of operational experience, but is now partially rehabilitated and put back into operation of about 3 MWe.

TABLE 2: An overview of the Aluto-Langano geothermal wells

	LA1	**LA2**	**LA3**	**LA4**	**LA5**	**LA6**	**LA7**	**LA8**
Drilling date:								
From	07.11.81	06.07.82	21.01.83	06.07.83	15.11.83	24.03.84	11.07.84	28.10.84
To	11.06.82	07.1182	14.06.83	12.10.83	11.03.84	02.07.84	17.10.84	09.03.85
Location:								
East (m)	474047	469849	477401	478300	478742	477649	476296	476946
North (m)	853808	861501	860723	860800	859427	861278	860832	862374
Elevation (m a.s.l.)	1601	1724	1921	1956	2038	1962	1891	1896
Total depth (m)	1317	1602	2144	2062	1867	2202.8	2448.5	2500
Well design casing depth (m)								
20"	57	45	41	40	29	41	39.3	40.
13 3/8 "	203	299	233	226	274	233	263	294
9 5/8 "	702	892	748	774	752.	754	956	721.
7 " liner top	690	887	723	726	---	728	941	666
7 " liner top Of slots	800	901	1035	746	__	1499	1788	1867
7 " liner bottom	1317	1602	2140	2035	__	2201.	2449	2464
Status of well	Non-prod.	Non-prod.	Prod.	Prod.	Non-Prod.	Prod.	Prod.	Prod.
Permeable zone (m)	__	__	2000- 2122	1445-1800	__	2000-2200	2100-2300	2300-2500
Maximum down hole temp. (°C)	__	__	315	230	__	>320	228	268

The volcanic activity at the Aluto volcanic complex was entirely contained in the Quaternary and this recent activity as demonstrated by its hydrothermal mineral assemblages and close to boiling extensive hydrothermal manifestations is indicative of the existence of a still hot plume that could serve as a heat source for the geothermal system sustainably. The residual gravity fields obtained using high pass and band pass filters that show the occurrence of high anomalies in the Aluto volcanic complex, indicating the existence of relatively denser mass (possible heat source) at a shallower depth than the surrounding rock masses is in line with this.

Tertiary ignimbrite, which is found below 1,400 m is the main aquifer, while the basalt overlain this is sealed with alteration minerals and is assumed to serve as a cap rock. The waters in the system are that of near neutral pH having total dissolved solids (TDS) below 5 g/L (Gizaw, 1993). The general lack of O isotope shifting in rift hydrothermal systems suggests a high water-rock ratio, with the implication that these systems are mature. Similarly, the studies on carbon isotopes on the predominantly bicarbonate waters of the rift in general and in the Aluto-Langano geothermal system in particular show (Darling et al., 1996) the evolution from dilute meteoric recharge (essentially from the eastern escarpment) to highly alkaline waters, via the widespread silicate hydrolysis promoted by the flux of mantle carbon dioxide which occurs in most parts of the rift. There is both boiling (at greater depths) and mixing in the system at shallower depths, but that part is "solid cased" in deep and hence it could be assumed that the wells locating in the upflow zone (along LA-3 and LA-6) have similar chemistries with that of the reservoir. The deep water flows mainly towards the south, southwest and southeast, but also towards the east, supplying the springs and shallow temperature gradient wells and fumaroles at lower and higher elevations, respectively.

The lateral and vertical extent of the upflow zone is not yet exactly delineated, however, based on the available information, ELC (1986), estimated the probable potential up to 60 MW. Based on the thermal energy of saturated water and rock (Banwell, 1963), Gizaw (1993) with a conservative temperature range of the system temperature (220-230^{o}C) and a porosity of the system, assessed an electric generating potential of 10-20 MWe / km^3 for over 30 years.

3.1.2 Other prospect areas in the main Ethiopian Rift

Other prospects where surface investigations were carried out in the MER include, from south to north, Corbeti, Abaya, Tulu Moye, Gedemsa, Boseti Guda, Boseti Bericha, Fentale and Dofan.

Although noted testing by deep drilling, a relatively detailed surface exploration backed by shallow temperature gradient (TG) wells has been done in the Corbetti, Tulu Moye and Gedemsa prospect areas. Although TG wells were not drilled, a relatively detailed surface exploration was also done at the Abaya, Dofan and Fentale prospects. A regional assessment of the fields in the MER also includes the Kone, Boseti Guda and Boseti Bericha geothermal prospect areas. The results have been encouraging from the point of view of the heat source, temperature, recharge and fluid availability. The common features in these prospect areas is that the systems are largely acid-volcanics dominated having a sodium bicarbonate primary fluid. Geothermometry results in all these prospects suggest the presence of a high temperature underground, > 250^{o}C. The primary permeability seems less important than the secondary one, that is, the upflow zones are more likely fault controlled. The limiting factors amongst others seem to be permeability. Consequently, the current focus on surface exploration is on employing the state-of-the art geoscientific techniques so as to have a clearer understanding of the structural fabrics, and recharge mechanisms.

3.2 Geothermal prospects in the Afar Depression

The priority areas for geothermal electric power development in the Afar Depression are the Meteka, Amoisa, Ayelu, Teo Danab, Tendaho, Lake Abhe and Dallol areas. The first field explored in the Afar Region at an exploration drilling level is that of Dubti in the Tendaho Graben. Details of the relatively better explored field, Dubti and a brief summery of the results obtained in the rest are described below.

3.2.1 The Dubti geothermal field, Tendaho graben

Tendaho graben is a 50 km wide and a 400 km^2 structure of Plio-Pleistocene age, which is believed to have two or possibly three potential areas for development: Dubti, Ayrobera and the area in the south-eastern part of the graben near Allalobad. Following its identification as a prime resource area on the basis of the 1969-72 inventory survey, Tendaho was subjected to detailed surface surveys till the early 1980's. That was followed by exploration drilling in the Dubti farm area during 1993-98. Well testing and reservoir engineering studies as well as geochemical monitoring have been carried out since then.

The extensive fissural volcanism, in the Pliocene to early Pleistocene (<4 million years), is believed to have remnants of magma injected along crustal separation zones to serve as a heat source for the geothermal system. The deep and shallow exploratory wells drilled in Tendaho have proved the existence of a commercially attractive geothermal resource at shallower level (Table 3). Surface and sub-surface measurements conducted so far have determined that the shallow reservoir's temperature is 220-250°C. The permeability is relatively high (3-10 Dm). The relatively low content of total dissolved solids in the shallow resource (about 2 g/l) and the low gas content confirm the suitability of the fluids for commercial purposes. The anticipated upflow zone is yet to be discovered by deep drilling, however, it is estimated that about 3 MW of electric power can be generated from the existing shallow wells employing back pressure turbines (EIGS and Aquater, 1996).

The Tendaho geothermal field is water dominated and probably has one or more independent reservoirs with temperatures exceeding 230°C by the presence of a large thermal anomaly was indicated in the graben by the presence of high concentrations of leakage detectors such as NH_4, CO_2 and B (D'Amore et al., 1997). There are slight differences between the gas chemistries of the Dubti, Allalobad and Ayrobera locality manifestations. Nevertheless, isotopic evidence suggests an original magmatic source for the gases, including the main gas CO_2, from all three localities (D'Amore et al., 1997). The water discharged from the Dubti exploratory wells, the hot springs at Allalobad and Begalodoma Lake; and the waters from the temperature gradient wells (temperatures lower than 50°C) are all of the sodium chloride type. However, the remarkable presence of sulphate at Allalobad could be attributed to circulation in the sedimentary rocks. As a result, the waters at Allalobad are either in equilibrium or supersaturated with respect to anhydrite. The fluids from the exploration wells are in equilibrium with the host rock and hence no strong mixing occurs in the subsurface at Dubti, having a chloride concentration not exceeding 800 mg/l. The isotopic information highlights that the recharge of the geothermal reservoir(s) in Tendaho graben originate(s) in the western escarpment and plateau at elevations above 2,000 m and excludes local recharge. The residence time of the water from the recharge area for instance to the Dubti reservoir does not exceed 7,000 years (from C^{14} dating). This and the absence of tritium and the presence of significant ^{18}O isotopic shift in the waters indicated very long circulation times and a high level of water-rock interaction.

For the Dubti geothermal field alone: on the basis of the available geoscientific information, it is inferred that a single liquid phase with an initial temperature of ~ 300°C in the reservoir is believed to ascend vertically along the NW-SE structural fault planes located to the southeast of the already drilled wells. Once the fluid reaches shallow horizontal permeable zones, it can expand and the out-flow supplying the manifestations and the shallow wells to the northwest (TD2, TD4, TD5, and TD6).

TABLE 4: Salient data on the exploratory wells drilled at Tendaho

Well No.	TD1	TD2	TD3	TD4	TD5	TD6
Drilling period	20/10/93 - 27/02/94	13/03/94 - 10/05/94	07/09/94 - 19/10/94	27/04/95 - 09/05/95	20/12/97 - 14/12/98	01/02/98 - 20/02/98
Drilled depth (m)	2196 (1550*)	1811	1989	466	516	505
Elevation (m a.s.l.)	365.9	365.7	366.8	365.2	366.3	366
Permeable zones	400-600** 1200-1300	220-500** 1200-1300	50-200**	220-466	220-516	220-505
Maximum down-hole temp. (°C)	278	245	198	245	253	245
Status of the well	Non-product.	Productive	Non-produ.	Productive	Productive	Productive

Note: * Re-drilled - current depth ** Cased

3.2.2 Other explored prospects in the Afar Depression

Other high temperature geothermal fields that warrant additional investigation for power development in the Afar Depression include: Meteka, Ayelu, Amoisa, Teo, Danab, Lake Abhe and Dallol.

Lake Abhe, Teo, Danab, Ayelu, Amoisa and Meteka have been assessed as potential prospect areas while the Dallol Depression is in a state of identification. Preliminary geoscientific investigations in these areas also warrant further detailed explorations. Likewise the MER prospect areas, the results have been encouraging from the point of view of the heat source, temperature, recharge and fluid availability point of views. Unlike the MER, however, the geology is basaltic dominated and with sodium chloride type waters. Geothermometry results in all these prospects suggest the presence of a high temperature underground, > 250°C. The primary permeability seems less important than the secondary one, that is, the upflow zones are more likely fault controlled. Like in the MER, the limiting factor for having a potential field in the Afar Depression is permeability as well. This makes the focus of geoscientific investigations amongst others in tracing fault zones (hidden or otherwise) that could sufficiently allow the ascent of fluid.

Detailed surface exploration to be followed by exploration drilling is envisaged to be conducted in the future.

4. CONCLUSIONS AND RECOMMENDATIONS

Ethiopia is endowed with a huge geothermal resource base. Geothermal exploration and development programmes in Ethiopia have been conducted for the last four decades in the Ethiopian part of the Great East African Rift System that covers an area of 150,000 km^2 and have discovered over 18 prospective areas. Despite this, the country has not yet benefited from this indigenous and environmentally friendly resource in a meaningful manner. This is fundamentally due to the lack of a sufficient budget to explore and develop in an aggressively and sustainable manner; the dependency syndrome developed over the years on hydro alone, a unilateral energy base that is drought prone; the fact that the exploration and the development phases were handled by two different public organizations which have differing mandates. As geothermal experience in the geographically and geologically close neighbouring country, Kenya, showed, this valuable energy resource can be developed in a short time provided that a full fledged, effective and efficient public enterprise is set up to handle both the exploration and development phases in the country. In summary, opportunities of increasing geothermal development and utilisation in Ethiopia are inspired by:

- The energy shortage we have and envisaged from the ever increasing energy demand;
- The critical role of modern energy supply in our development endeavour's;
- Vulnerability to drought of our current main energy supply, hydropower;
- The ever increasing world oil price;
- The availability of rural electrification focused policy that requires flexible energy supply schemes;
- The presence of a huge geothermal resource base that is renewable, and cost-competitive;
- The fact that geothermal is not instantly and significantly affected by sporadic drought, which means that the geothermal power would serve as a base load and main backup of hydropower;
- Clean Development Mechanism (CDM) availability for the resource;
- The ever growing worldwide scientific and engineering experience and its utilisation that helps to make the resource much more feasible;
- Job creation opportunities;
- The presence of geoscientific, drilling and reservoir engineering experiences; and
- The availability of two deep drilling rigs (MASSARANTI 7000 TR and KREMCO-600 TRAIL), which are both stored in a working conditions; and other facilities.

The constraints for the development of geothermal resources in Ethiopia are largely related to prioritization, funding and institutional set up. A national energy mix is the solution to the drought prone region of ours. Apart from hydro, geothermal is found to be the most economically feasible renewable resource in Ethiopia. As an indigenous resource, it helps not only to supplement the energy supply but also reduce foreign currency spending on fossil fuels. Like other similar energy resources, it requires a high initial investment cost. However, due to it's more than 90% availability/load factor, the return is fast, < 5 years. The high load factor of geothermal means, its energy supply is double to that of hydropower of similar installed capacity in the Ethiopian situation. Considering its profound benefits, it is worthwhile to give sufficient attention to fulfil the suggested enablers.

Consequently, it is recommended to:

- Integrate geothermal in the National Energy Plans explicitly.
- Establish a process/system for uninterrupted geothermal exploration and development activities. A fast track approach that enables a power plant erection every 5-7 years could be instigated. Indeed, a parallel exploration scheme could also be employed by utilising the available drilling rigs.
- Establish a mechanism to provide a large enough budget. This may include: promotion PPP, IPP, etc.; encouraging the participation of financial institutions, bilateral donors and

development agencies; using the opportunity of risk mitigation funds (RMF) and transaction advice funds (TAF) and the likes; and revolving revenues after initial developments.
- As proved in the Aluto-Langano and Tendaho geothermal fields, the upflow in the Rift in general seems fault controlled. Moreover, any one of the systems might have more than controlling faults that could possibly have similar potential. Hence, trying to trace them using the state-of-the-art surface methodologies of structural geology, geochemistry and geophysics to minimize uncertainties is of paramount importance.
- Heat flow mapping of the geothermal prospect shall be carried out to help in better conceptual modelling of the geothermal field.
- Although scaling and corrosion do not seem to be significant problems in the Rift as proved by the wells drilled in the upflow zone, it is essential to closely anticipate and study the case so that possible remedies are implemented if necessary.
- The recharge mechanism in the Rift is grossly understood, however, a detailed and quantitative approach needs to be exercised for better anticipation of resource sustainability.
- Finally, regular geochemical, micro gravity, and reservoir engineering monitoring should be made in feasible geothermal fields that are fully or partially utilised in order to evaluate mass changes in the reservoir either due to exploitation and/or other reasons, like reinjection and recharge.

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REFERENCES

Ayele, A., Teklemariam, M., and Kebede, S., 2002: *Geothermal resources exploration in the Abaya and Tulu Moye - Gedemsa geothermal prospects, Main Ethiopian Rift.* Geological Survey of Ethiopia, compiled report.

Banwell, C.J., 1963: Thermal energy from the earth's crust. Introduction and part I. *NZ J. Geol. & Geophys., 6*, 52-69.

Cherinet, T., and Gebreegziabhier, Z., 1983: *Geothermal geology of the Dofan and Fantale area, Northern Ethiopian Rift.* EIGS, Geothermal Exploration Project

D'Amore, F., Giusti, D., and Gizaw, B., 1997: The geochemical assessment of Northern Tendaho Rift, Ethiopia. *Proceedings of the 22nd Stanford Geothermal Reservoir Engineering, Stanford, CA,* 435-445.

Darling, W.G., Gizaw, B., and Arusei, M.K., 1996: Lake-groundwater relationships and fluid-rock interaction in the East African Rift Valley: isotopic evidence. *J. African Earth Sciences, 22-4,* 423-431.

Demlie, M., Wohnlich, S., Gizaw, B., Stichler, W., 2006: Groundwater recharge in the Akaki Catchment, Central Ethiopia: Evidence from environmental isotopes ($\delta^{18}O$, $\delta^{2}H$ and ^{3}H) and chloride mass balance. *J. Hydrological Processes 21-6,* 807-818.

EIGS and Aquater, 1996: *Tendaho geothermal project, final report.* Ministry of Mines and Energy - Geological Survey of Ethiopia - Ministry of Italian Foreign Affairs, San Lorenzo in Campo.

EIGS and ELC, 1986: *Geothermal exploration project – Ethiopian Lakes District, exploitation of Aluto-Langano geothermal resources, feasibility report.* ELC, Milano, Italy, irregularly paged.

EIGS and UNDP, 1973: *Investigation of geothermal resources of Power development Geology, Geochemistry and Hydrology of hot springs of the east African Rift System within Ethiopia*. United Nations, New York, DP/SF/UN 116 - technical report, 275 pp.

Endeshaw, A. , 1988: Current status (1987) of geothermal exploration in Ethiopia. *Geothermics, 17-2/3,* 477-488.

Endeshaw, A., and Belaineh, M., 1990: Status of geothermal energy in Ethiopia. *Geothermal Resources Council, Transactions, 14- I,* 47-53.

Gizaw, B., 1993: Aluto-Langano geothermal field, Ethiopian Rift Valley: Physical characteristics and the effects of gas on well performance. *Geothermics, 22-2,* 101-116.

Gizaw, B., 2002: *Hydrochemical and environmental investigation of the Addis Ababa region, Ethiopia.* Maximillans University of Munich, PhD thesis.

Gizaw, B., 2004: The status of geothermal energy in Ethiopia. *Ministry of Mines Newsletter 3-2,* 17-23.

Gizaw, B., 2005: The status of geothermal energy in Ethiopia. *Ministry of Mines Newsletter, 4-1,* 12-16.

Grant, M.A., 2000: Geothermal resource proving criteria. *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan,* 2581-2584.

Kebede, S., 1986: *Results of temperature gradient survey and geophysical review of Corbetti geothermal prospect.* Geological Survey of Ethiopia, Addis Ababa, internal report.

Teclu, A., 2003: *Geochemical studies of the Dofan Fantale geothermal prospect areas.* Geological Survey of Ethiopia, Addis Ababa, internal report.

Teklemariam, M., Amdeberhan, Y., Beyene, K., and Gebreegziabheir, Z., 2000: Geothermal exploration and development in Ethiopia. *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan,* 475-480.

Teklemariam, M., and Beyene, K., 2005: Geothermal exploration and development in Ethiopia. *Proceedings of the World Geothermal Congress 2005, Antalya, Turkey*, CD, 9 pp.