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Addressing essential hydrogeological and environmental constraints for geothermal development in East Africa

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ABSTRACT

Geothermal energy is vastly under-utilized and represents an exciting means of addressing energy challenges, alleviating poverty, and promoting economic development in the nations of the East African Rift System (EARS). The countries that straddle the rift system are home to a combined population of more than 400 million, a significant proportion of whom do not have access to power or safe drinking water resources. These coexisting water and energy issues have traditionally been tackled as separate challenges. The Combined Power and Freshwater Generation (Combi-Gen) project aims to initiate a disruptive shift in the approach to the twin challenges of energy shortage and water-scarcity through development of a novel thermal chimney driven air-cooled condenser that will capture a substantial portion of the post-flash and reaction turbine geothermal vapour and convert it into potable water, without creating a parasitic power load. In order to enhance the design of such systems, a robust understanding of the geothermal resource and the wider hydrogeological systematics must be obtained. This is essential for assessment of fluid composition, analysis of scaling and corrosive species, flow rate and pressure control, and ultimately optimization of engineering performance. In addition, it is also imperative to gauge the wider hydrological connectivity of geothermal ground waters in order to establish potential impacts on the environment and existing essential water resources.

1. INTRODUCTION

The geothermal potential in the nations of the East African Rift System (EARS) has long been acknowledged thanks to reconnaissance surveys that were carried out as early as in the mid-1950s (Alexander and Ussher, 2011). The EARS is a classical continental rift system extending over 4,000 km from the Afar Triangle near the Red Sea in the north to Mozambique in the south (Figure 1). The rift divides into two branches skirting around Lake Victoria, with the eastern branch more active than the western, resulting in a greater geothermal potential in that branch (Darling, 1998; Omenda, 2009; Teklemariam, 2008). To date, eleven pilot power plants in five different geothermal fields have been commissioned with variable success. Two of them, one in the Democratic Republic of Congo (DRC) and the other in Zambia, were never operational or only working for a short period (Muanza, 2015; Musonda and Sikazwe, 2005). The Aluto-Langano pilot plant in Ethiopia, commissioned in 1998 and with a capacity of 7.2 MWe, is still running despite several periods of inactivity due to operational difficulties (Biru, 2016). The eight remaining power plants are located in Kenya: the first one was commissioned in the 1980s (Olkaria I); the others more recently, in the 2000s and 2010s. Seven of them are located in the Olkaria geothermal field whereas the remaining is in Eburru geothermal field (Omenda and Mangi, 2016). The installed capacity for geothermal energy in Kenya is currently 727 MW (Unit I of Olkaria V online on 27th July 2019; Richter, 2019) and 43% of its electricity was generated from this resource in 2016 (IEA, 2019). With an estimated geothermal potential of 20 GW (Teklemariam, 2018), geothermal energy is therefore vastly under-utilised in the EARS.

The EARS is home to more than 400 million people of which a large proportion (66% in 2017; World Bank 2019) does not have access to electric power. There are large disparities between the countries - less than 10% of the Burundi population has access to electricity, more than 60% in Kenya and Djibouti (2017 figures; World Bank, 2019) - and also between rural and urban areas with less than one third of the population having access in rural areas (Kenya the exception with 57% in 2017; World Bank 2019). In urban areas, at least half of the population has access (except in the DRC, 49%; World Bank, 2019). Access to basic drinking water services (safe water accessible with a 30-min round trip) is equally variable across the EARS countries, from 19% in Eritrea to 77% in Djibouti, generally between 40 and 60% (2015 figures; WHO, 2018), and between rural and urban areas. At least 70% of the urban populations (regardless of country) have access to basic drinking water whereas less than half of the rural populations have (one third of the EARS population; WHO, 2018). These figures drop dramatically when considering access to safe drinking water on personal premises.

These coexisting water and energy issues have traditionally been tackled as separate challenges. It is only recently that the use of geothermal energy for production of freshwater by desalinisation has been recognised as a sound choice (Bundschuh and Koinkis, 2012). However, geothermal energy is under-utilised in desalinisation applications and mostly at the conceptual, prototype or pilot stage (Ghaffour et al., 2015; Gude, 2016; Gude, 2018). To produce freshwater from brackish or sea water, the geothermal resources are directly used as a source of energy (desalination powered by heat) or to generate the electricity necessary to run the process depending on the desalinisation technology (Kalogirou, 2005). Produced freshwater can be used for irrigation e.g. seawater greenhouse technology (Paton and Davies, 1996; Mahmoudi et al., 2010) or for drinking water e.g. Milos Island in Greece (Karytsas et al., 2004) - although there is no evidence that the project was ever completed. There are a few examples where the geothermal fluid is directly used for drinking water following a simple treatment e.g. low-enthalpy fluids from Mszczonów in central Poland, or after desalinisation (Tomaszewska and Szczepański, 2014). Condensate from fumaroles in the Eburru geothermal plant, Kenya, is informally used at local scale for drinking water (Ndetei, 2016).

It is within this context that the Combined Power and Freshwater Generation (Combi-Gen) project was developed. Addressing environmental constraints is essential for a robust design of the system and ensuring its sustainability. In the following sections, we will describe the Combi-Gen technology, explain its role within the water-energy nexus, and highlight hydrochemistry as a tool to enhance the performance of the system and uncover the potential impacts on the existing water resources.

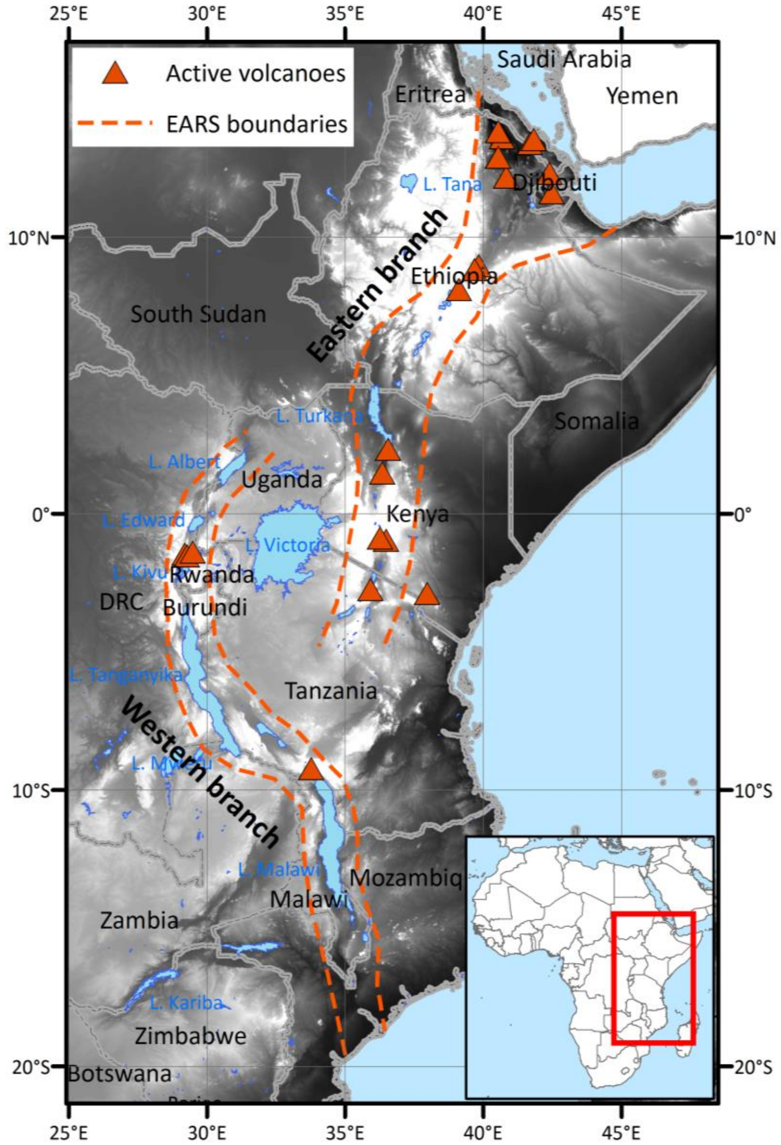

Figure 1: Extension of the East African Rift Systems showing the two branches. Active volcanoes identified by Wadge et al. (2016) are also shown on the map. The Digital Elevation Model (DEM) was published in 1996 by the U.S. Geological Survey's Centre for Earth Resources Observation and Science (EROS) and is available at https://databasin.org. The water bodies were published in 2015 by the Regional Centre for Mapping of Resources for Development (RCMRD) and are available at https://energydata.info/.

2. THE ENERGY-WATER NEXUS AND THE COMBI-GEN PROJECT

2.1 Energy-Water Nexus in East Africa

Most of the EARS countries rely on hydropower and/or fossil resources for electricity production but generally only one of the two (Figure 2), making them vulnerable to climatic conditions for hydropower or fluctuating oil and gas supply and prices. Whereas the use of hydropower is not unexpected in countries with important freshwater resources (e.g. the DRC, Zambia and Mozambique; World Bank, 2019), the reliance on hydropower in countries facing water scarcity (< 1,700 m^3 per capita and per year; Falkenmark, 1989) is more challenging. Indeed, the region experienced severe droughts in the last decades with the last one lasting at least two consecutive years (2016-2017) and affecting most of eastern Africa (UCL, 2018). Kenya is the only country which has a diversified energy mix (Figure 2), where 43% of its electricity is produced by harvesting of geothermal energy, and therefore is likely to be the most resilient to adverse conditions. Other renewable energy sources are mostly negligible in the other countries of the EARS (Figure 2).

In these fast-growing countries, energy needs are far from being met. This is why EARS nations have been looking into their geothermal sources as a source of electric power or, if not possible, for direct uses as heat. Kenya is the leader in the use of geothermal energy for electricity and recently doubled its production from 2,000 to 4,000 GWh (in 2014; Figure 3).

In response to the twin challenges of energy shortage and water scarcity and moving away from current practice that mostly focuses on power generation, the Combi-Gen project aims to develop a novel geothermally sourced combined power and freshwater generation technology that would deliver more benefits to the economic development of these countries.

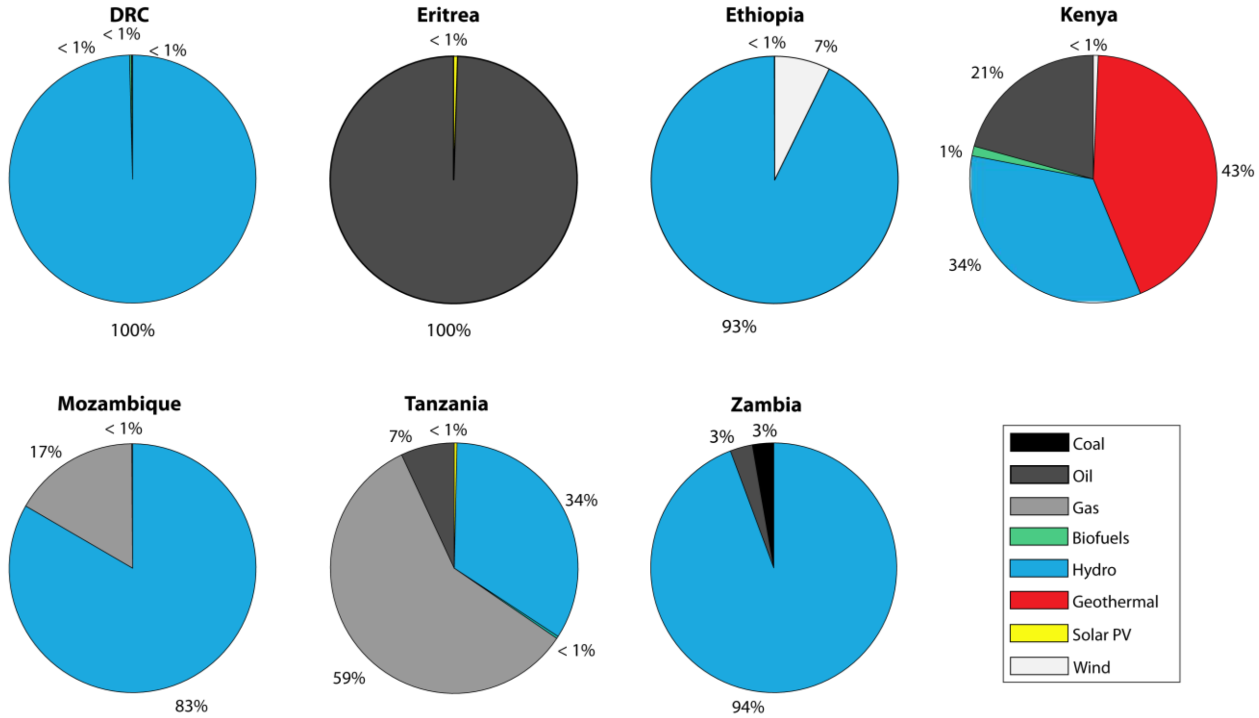

Figure 2: Energy mix for electricity production in 2016 for EARS countries with data available (data from IEA, 2019).

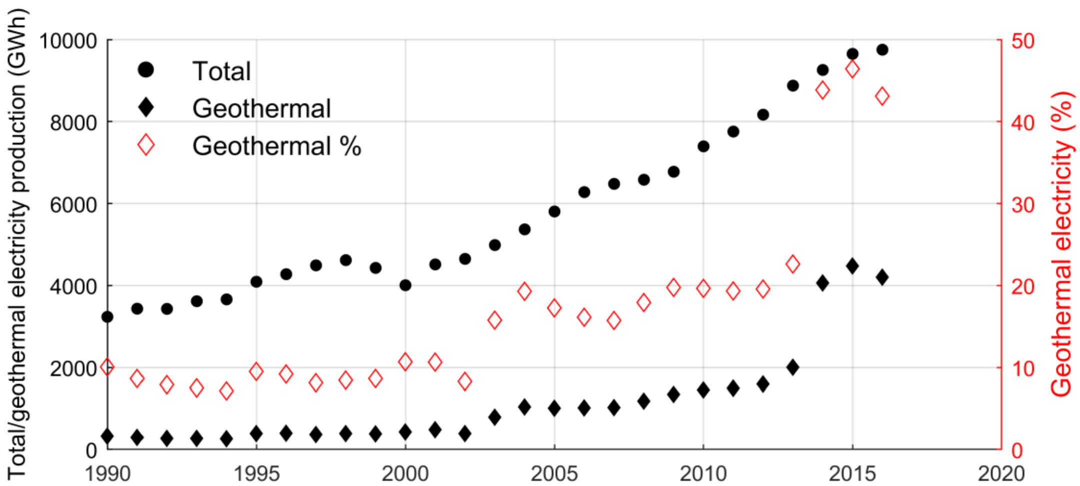

Figure 3: Evolution of electricity production and the geothermal share for the period 1990-2015 in Kenya (data from IEA, 2019).

2.2 The Combi-Gen Technology

The Combi-Gen technology is inspired by the use of a trilateral flash cycle (TFC) with a two-phase flow turbine to simultaneously produce electricity and freshwater using solar energy, demonstrated by Date et al. (2015). However, this concept has several major impractical issues for such geothermal applications: (1) It requires an oversized water-cooled condenser and therefore a large quantity of freshwater which is typically in short supply in the EARS; (2) An air-cooled condenser can be used instead but it requires electricity to power fans, reducing the net power generation; (3) The flash tank requires vacuum conditions that may be compromised by the presence of non-condensable gases in the geothermal fluid and (4) The two-phase turbine is still not yet fully understood and its efficiency is relatively low.

To address these challenges, the Combi-Gen technology includes a novel thermal chimney driven air-cooled condenser. Hot geothermal water passes a two-phase reaction turbine, and partially flashes into vapour. It spins the turbine, and subsequently the generator, to produce power, and the vapour can then be condensed to produce freshwater. The non-flashed concentrated saline water in the flashing tank is still hot and then passes through the air heater, to heat air in the thermal chimney. The heated air rises due to the buoyancy, dragging cool air through the air-cooled condenser. After further rejecting heat via the air heater, the concentrated saline water is then pumped into the reinjection well to help maintain pressure in the geothermal reservoir. The Combi-Gen technology is illustrated by Figure 4.

The Combi-Gen technology addresses the impractical issues mentioned above: the thermal chimney replaces the electric fans, increasing the efficiency of power generation and the system operates at high temperatures, removing the need to ensure vacuum conditions and bypassing the potential issue with non-condensable gases.

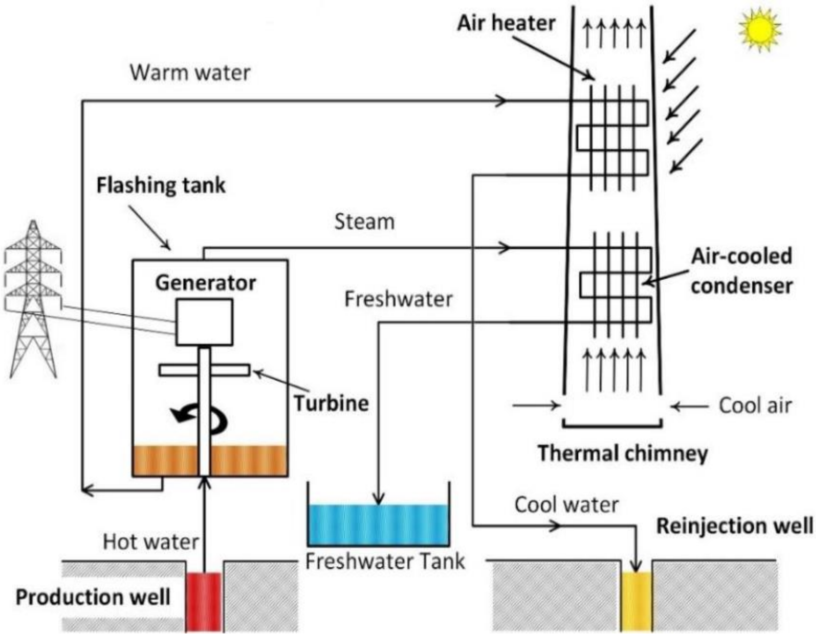

Figure 4: Schematic of the Combi-Gen concept.

3. ADDRESSING ESSENTIAL ENVIRONMENTAL CONTRAINTS

The Combi-Gen technology is developed within a responsible-innovation framework (Owen et al., 2012), to ensure the sustainability of the innovative technology and its societal acceptability. Here we focus only on the sustainability aspect.

3.1 Sustainability Appraisal

Key sustainability issues for the Combi-Gen technology essentially demand reconciliation of subsurface abstraction points with surface infrastructure for both energy and water provision. A review of geothermal use in the EARS was carried out to identify potential sites for the Combi-Gen technology. The review focused mostly on Kenya and Ethiopia which have active geothermal power generation and are also in the most advanced stages of exploration for a number of geothermal fields (Table 1). The remaining countries of the EARS are mostly at the exploration stage, with Djibouti (Assal-Fiale field) the most advanced (ongoing exploration drilling visible on Google Maps).

Table 1: Main geothermal fields of Kenya and Ethiopia, and their status. *Italics*: surface exploration/drilling supposedly ongoing (no recent updates in the media). The date indicates when the exploration drilling is planned to start.

Status	Kenya	Ethiopia
Reconnaissance study	Other sites	Dallol; Danakil depression; Alaita; Boina ; Dobi graben; Abhe; Teo; Danab; Meteka; Sodere
Detailed surface exploration	Baringo; Bogoria-Arus; *Magadi*; *Barrier; Namarunu; Emuruangogolak; Homa Hills*	Dofan; Abaya
Exploration drilling	Paka; *Silali (after Paka); Korosi (after Paka)*; Akiira; *Longonot*; *Suswa*	Tendaho; Tulu Moye (Sept. 2019); Corbetti (Sept. 2019); *Fantale*
Production drilling	Menengai	
Operation	Olkaria; Eburru	Aluto-Langano

One of the constraints for the proper functioning of the Combi-Gen technology is the fluid temperature and its content in NCGs. This information is available for the reservoirs located in the geothermal fields at an advanced stage. Olkaria and Tendaho were identified as the sites with the lowest NCG content (1% or less). Measured downhole temperatures are above 300°C in Olkaria (Ouma, 2013) and 220°C in Tendaho (Battistelli et al., 2002). In that respect, these two sites appear to be the most appropriate for the Combi-Gen technology. Menengai is also of interest due to its highest temperatures in the centre of the caldera (up to 400°C; Omenda and Simiyu, 2015) which are associated with a low NCG content (Montegrossi et al., 2015). The four soon-to-be power plants i.e. Menengai, Corbetti, Tulu-Moye and Assal-Fiale are located in prospects with high-temperature reservoirs (200°C or more). The other sites to be developed at medium-term scale are mostly high-enthalpy geothermal areas for electricity generation. Besides Menengai already mentioned, they could be potential sites for the Combi-Gen technology if they hold low NCG contents.

With regard to the water demand, the currently under-development geothermal fields are located in areas where the water demand is high. Olkaria is located on the southern shore of Lake Naivasha, a freshwater lake that supports a growing flower industry accompanied by a rapidly increasing population. Lake Naivasha, rivers and groundwater are used for irrigation and drinking water. Lake Naivasha and its feeding rivers are affected by droughts. The declining water quality of all resources is also a concern (van Oel et al., 2013). The Combi-Gen technology (should other power plants be built at Olkaria in the future) could ease up the pressure on the lake, a declared Ramsar site (Everard and Harper 2002). Tendaho is located in the Afar depression (northern Ethiopia), a water-scarce region which relied mainly on groundwater characterised by high concentrations in sodium, chloride and/or fluoride (above drinking water limits; Ayenew et al., 2008). The Tendaho reservoir now supplies freshwater mainly for irrigation of sugar plantation but also for drinking water (in addition to hydropower). Despite the Tendaho Reservoir, farmers, especially pastoralists, are still struggling during severe drought, as reported by Planel and Labzaé (2016). Therefore, the demand for freshwater is still high in the region. Menengai is located just north of Nakuru, one of the biggest cities of Kenya. The nearby Lake Nakuru, within the national park of the same name, is a hotspot of biodiversity and is under lots of pressure. Nakuru suffers from chronic water shortages and conflicts over water access are common (Raini et al., 2009). There are also plans to develop an industrial complex within the caldera, which will require freshwater (at least for drinking purposes). Those are some examples to illustrate the high demand for freshwater in the immediate areas of the geothermal sites where the Combi-Gen technology could be implemented.

3.2 Composition of produced water

Critical design constraints include the thermal resource magnitudes, anticipated production well flow rates, water and gas compositions. From this perspective, an exhaustive literature review was carried out and a database was built based on the publicly available information for existing geothermal sites in East Africa (Kenya and Ethiopia), representing a spectrum of temperature and pressure conditions that are used for the design of the Combi-Gen prototype. Combined with the quality of the fluids, it also provides vital information about the risk of silica (or other product) scale accumulation and/or corrosion in the engineered infrastructure. Geochemical modelling will be used to assess any risk of scaling/corrosion and the efficiency of geothermal fluid pre-treatments if required. Corrosion may be expected in the Afar Depression where the geothermal fluids are more saline. This is the case in the Assal-Fiale geothermal field (Djibouti) where further studies have been halted until recently (Jalludin, 2013).

3.3 Hydrochemistry as indicator of environmental sensitivity of geothermal resource development

The information collected was not limited to data from the geothermal fields themselves. The database also includes information (mainly chemical quality) on water resources around geothermal areas. This information helps to build a greater understanding of the wider hydro(geo)logical systems in order to ensure a sustainable development of the geothermal resources. Our main focus is on low-cost and efficient characterisation of hydrological parameters of surface and ground waters in areas of particular interest to Combi-Gen technology application. Key indicators include (a) *in situ* physico-chemical parameters (T, Eh, pH); (b) major and trace solutes indicative of geothermal dynamics; and (c) stable isotopes of O, H, C and S (Haizlip, 2016). To complement the literature review, fieldwork has been carried out in the Kenyan Rift Valley and in the area around Fantale, Ethiopia. Data interpretation is still ongoing and some preliminary results have been published (Burnside et al., 2019).

4. CONCLUSIONS

There is significant geothermal potential in the East African Rift, but to date this resource has been vastly underutilised. The countries present in this area have rapidly expanding populations, and a duel lack of access to power and safe water. The Combi-Gen project aims to tackle the twin challenge of water and energy access by developing disruptive technology that will exploit geothermal fluids for power production whilst simultaneously providing potable water. The technology includes a novel thermal chimney driven air-cooled condenser that does not require any parasitic power load. In order to enhance system design and optimise performance, a robust understanding of geothermal resources and their wider hydrogeological systematics must be obtained in order to assess fluid composition, scaling and corrosive species, flow rate, and pressure control. Efforts to collate and assess hydrogeological data for surface and ground waters, through extensive literature review and field work efforts in Kenya and Ethiopia have allowed for a development of a robust database which will be used to assess ideal locations for implementation of the Combi-Gen technology. The database also enables assessment of sustainable geothermal development in relation to other essential water uses in already water-stressed environments. This work in ongoing, but when completed will provide a powerful baseline for assessment of geothermal resources in East Africa.

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