RSER Review article

Status of geothermal industry in East Africa: A review of Eastern Branch countries

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ABSTRACT

The role and potential of geothermal energy in countries along the East African Rift System (EARS), geographically extending from Eastern to Southern Africa, is reviewed. The general objective of the review is the state-of-the-art on the geothermal resource development in selected East African Countries crossed by the Eastern branch of the EARS: Eritrea, Djibouti, Ethiopia, Kenya and Tanzania.
The focus is on geothermal activities aimed at generating electric power by using either flashing or Organic Rankine Cycle plants with geothermal fluids extracted from medium to high temperature hydrothermal systems. The business models implemented are discussed, in relation with the peculiar features of the geothermal energy which is characterized by important initial investments and limited operating and maintenance expenditures, as most of the renewable energy sources, but having peculiar remarkable mining risks mainly related to the exploration drilling phase. Constraints delaying a more widespread use of geothermal energy for electric power generation in East Africa are addressed. A review of the present status of geothermal development initiatives underway in each of the 5 countries is presented, distinguishing between the different phases of resource development.

HIGHLIGHTS

- Geothermal energy may contribute to the energy mix of East African countries
- Most of EARS geothermal resources are concentrated on the Eastern Branch
- Djibouti is accelerating the efforts for the development of its first geothermal field
- The large resources of Ethiopia are starting to be developed
- Kenya is proceeding on its successful path for a sound and accelerated development

KEYWORDS

Geothermal energy, Geothermal potential, East Africa, East Africa Rift System

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LIST OF ABBREVIATIONS

AFESD	Arab Fund for Economic and Social Development
AGCE	Africa Geothermal Center of Excellence
AGID	Africa Geothermal Inventory Database
ARGeo	African Rift Geothermal (Facility)
CERD	Djibouti Center for Studies and Research
CFE	Comisión Federal de Electricidad
EAGER	East Africa Geothermal Energy Facility
EARS	East African Rift System
EDC	Energy Development Corporation
EEA	Ethiopian Energy Authority
EEP	Ethiopian Electric Power

EGS	Enhanced Geothermal Systems
EPC	Engineering Procurement & Construction
ESIA	Environmental and Social Impact Assessment
ESMAP	Energy Sector Management Assistance Program
FCRS	Fluid Collection and Reinjection System
GDC	Geothermal Development Company (of Kenya)
GDP	Gross Domestic Product
GEP	Geothermal Exploration Project
GHG	GreenHouse Gas
GRMF	Geothermal Risk Mitigation Facility (for Eastern Africa)
GSE	Geological Survey of Ethiopia & Geological Survey of Eritrea
GSDP	Geothermal Sector Development Project
GTP	Geothermal Training Program
IA	Implementation Agreement
ICE	Instituto Costarricense de Electricidad
IEA	International Energy Authority
IFC	International Finance Corporation
IGA	International Geothermal Association
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency
ISOR	Iceland GeoSurvey
JICA	Japan International Cooperation Agency
JRC	Joint Research Centre
JV	Joint Venture
KenGen	Kenya Electricity Generating Company
KETRACO	Kenya Electricity Transmission Company
KFAED	Kuwait Fund for Arab Economic Development
LCOE	Levelised Cost of Electricity
NCG	Non-Condensable Gas
NDF	Nordic Development Fund
ODDEG	Office Djiboutien de Developpement de l'Energie Geothermique (Djibouti Office for Geothermal Energy Development)
O&G	Oil and Gas
O&M	Operation and Maintenance
ORC	Organic Rankine Cycle
PGE	Pertamina Geothermal Energy
PLN	Perusahaan Listrik Negara (Indonesian State Electricity Company)
PPA	Power Purchase Agreement Public Private Partnerships
PPP	Public-Private-Partnerships
PV	PhotoVoltaic
R&D	Research & Development
RG	Reykjavik Geothermal
TFC	Total Final Consumption
TGDC	Tanzania Geothermal Development Company
TPES	Total Primary Energy Supply
UN	United Nations
UNDP	United Nations Development Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNU	United Nations University
WB	World Bank
WEFE	Water-Energy-Food-Ecosystem
WGC	World Geothermal Congress
WWW	World Wide Web

1 Introduction

I suggest that you write/insert some additional paragraphs that explain why geothermal, in terms of challenges, then explain why this paper/what is it contributing to the existing body of published literature at the start of the introduction. This needs some references…are there geothermal targets etc in EU elsewhere?

The paper presents a review of the status of geothermal industry in 5 countries crossed by the Eastern Branch of the East African Rift System (EARS). The activity has been performed as part of the WEFE nexus analysis implemented over selected river basins in sub-Saharan Africa, and particularly the Blue Nile and the lake Victoria in Eastern Africa, in the framework of the project "The African Networks of Centres of Excellence on Water Sciences PHASE II (ACE WATER 2)". Funded by DG-DEVCO and implemented by JRC in partnership with UNESCO, the project aims at fostering sustainable capacity development at scientific, technical and institutional level in the water sector.

In the above framework and in the light of the debate on energy production, hydropower and renewable energy, the role and potential of geothermal energy in 11 countries crossed by the Eastern and Western Branches of EARS have been reviewed based on published papers and documents, newsletters and on institutional web sites of geothermal operators and international stakeholders. The focus was on medium and high temperature geothermal resources suitable to be used for electric power generation. The present review is focused on 5 countries crossed by the Eastern Branch, namely Eritrea, Djibouti, Ethiopia, Kenya and Tanzania, where some 95% of the total inferred EARS geothermal potential is located.

An overview of main characteristics of geothermal energy is reported, followed by the discussion about the steps customary followed for the development of a geothermal prospect from early surface exploration to the operation of the power plant. Then the main characteristics of geothermal resources of the EARS are reminded followed by the review of geothermal development models applied so far in East Africa. A synthetic overview of the recognized obstacles to the development of geothermal resources in East Africa is also presented. Finally, the present status of geothermal industry in each of the 5 selected countries is given, trying to compare the actual results achieved so far to planned goals and expectations.

2 ????

2.1 Geothermal Energy: A Low Environmental Impact Renewable Energy

Geothermal resources, consisting in the heat contained in the Earth crust, are presently exploited for both electric power generation and for direct uses. Apart for the utilization of low temperature resources (<100°C) only made for direct uses, the generation of electric energy is made from medium (between 100°C and 200°C) and high (>200°) temperature geothermal systems. Geothermal systems which can be at present economically and technically exploited at depth generally not exceeding 4,000 m, are found in peculiar geologic and geodynamic environments which are strictly linked to plate tectonic features enhancing locally the heat transmission from the mantle towards the Earth crust. Figure 1 (IRENA, 2014) shows as most of geothermal plays are located in volcanic areas corresponding to mid-oceanic ridges, subduction zones, strike-slip zones, and intracontinental rifts.

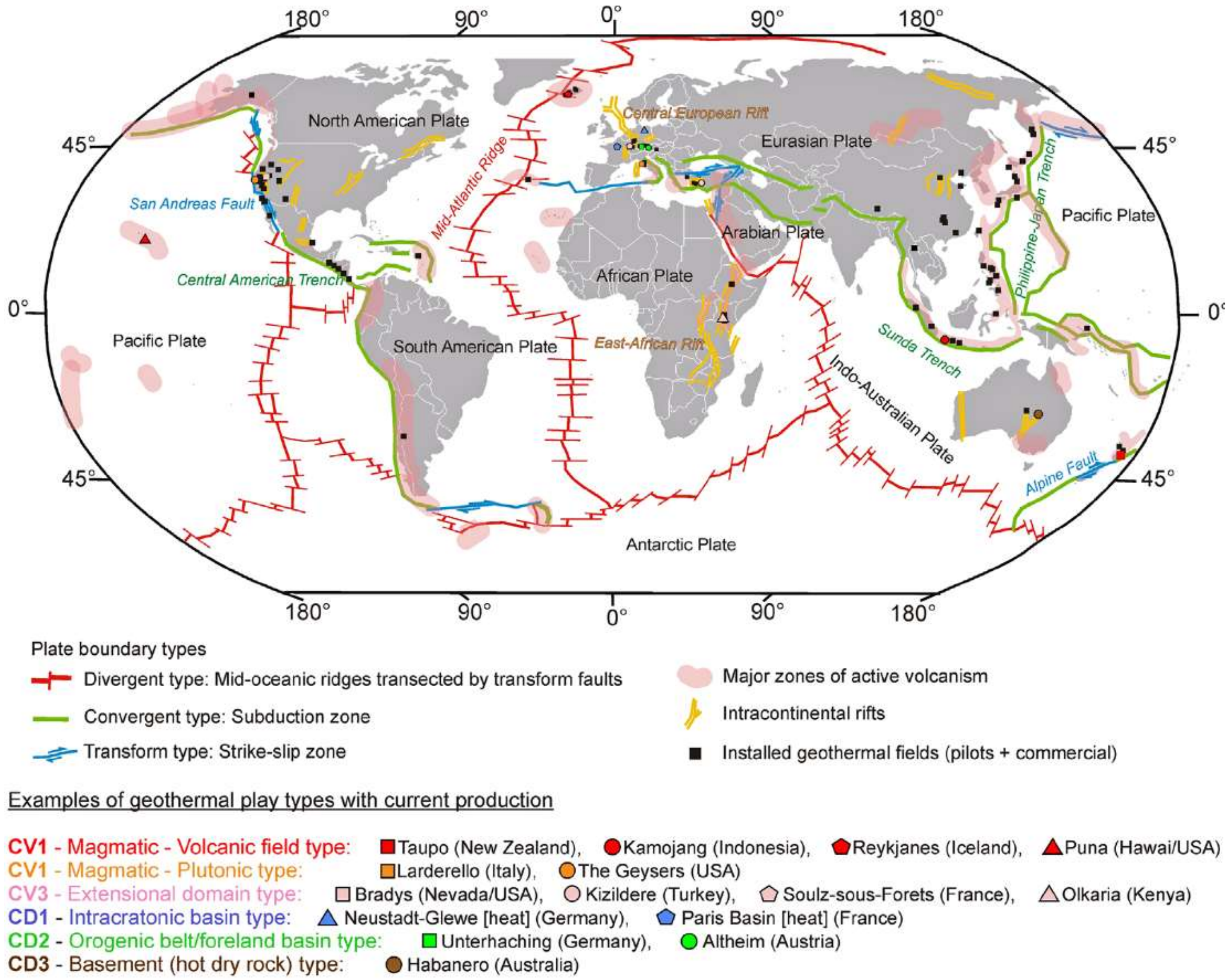


Figure 1. Plate tectonics and location of exploited (pilot + commercial) geothermal fields (IRENA, 2014).

All the high temperature geothermal systems commercially exploited today are hydrothermal systems from which heat is extracted by means of wells producing fluids contained in a permeable reservoir. According to thermodynamic conditions, the reservoir can be either vapour- or liquid-dominated depending on the fluid phase controlling the reservoir pressure distribution.

Vapor-dominated reservoirs produce dry steam, either saturated or superheated, which is piped to a condensing power plant. On the other hand, liquid-dominated high temperature reservoirs produce a two-phase mixture of brine and steam; after separation, the latter is piped to a single-flash condensing power plant. An alternative to a single-flash is a double-flash plant where the separated brine undergoes a second flash at a lower pressure to feed a low-pressure stage of the turbine. Liquid dominated medium temperature reservoirs may produce liquid brine at wellhead, in particular when production is assisted with downhole pumps. The brine is piped to an Organic Rankine Cycle plant (ORC), also known as binary cycle plants as the heat carried by the brine is transferred to an organic fluid whose vapor feeds the turbine. A possible alternative to the basic ORC plant fed by liquid brine is that of an ORC plant fed by wells discharging a two-phase mixture of steam and brine. This happens often when the reservoir has a high content of NCG, like in all the Turkish fields located in the Menderes Graben, which promote gas lift and boiling within the producing wells. In this case separators at well pads are used and steam and brine are piped separately to the power plant, where two different heat exchangers are used for the steam and brine streams. Schemes for the different power plants are discussed in detail, among the others, by DiPippo (2012) and Moon and Zarrouk (2012). Spent fluids, either separated brine, recovered condensed steam or cooled fluids at the exit of heat exchangers of ORC plants, are piped to reinjection wells to avoid the environmental impact linked to the discharge of fluids on surface streams, to recharge the exploited reservoir, and to reduce the risks of reservoir compaction and ground subsidence.

Geothermal power plants are typically used to supply the base load as field exploitation is performed following the natural well production decline with minimal well regulation. Only in particular cases, like plants feeding an isolated closed electric network on an island or in developed electric markets like in the USA, geothermal power plants are operated at variable load. Thus, geothermal energy supplies almost constant power with a load factor often in the order of 90% and more, independent on weather conditions and seasons. The main advantages and downsides or challenges associated with geothermal power generation are summarized in Table 1 as "pros" and "cons" (ESMAP, 2012). Among the major challenges of geothermal energy there are the high costs for field development and power plant EPC and the need to invest considerable funds before having the confirmation on the existence and characteristics of the geothermal resource (exploratory risks). As an example, the cost breakdown for two 110 MW plants in Indonesia is shown in Figure 2. Total drilling costs for exploration and field development amount to 24%, thanks to a relative competitive drilling market in Indonesia. Power plant and Fluid Collection and Reinjection System (FCRS, for steam field development) amount to 56%. The cost for infrastructures (access roads, well pads, base camps, water supply, etc.) amount to 7%.

In addition to specific field conditions, the final costs depend also on the power plant capacity and type. Figure 3 shows the estimated power plant cost per unit kWh installed for different power plant technologies (IRENA, 2017). Generally, ORC plants characterized by smaller capacity have a higher installation cost than flash plants, due to the scale economy which can be obtained with larger plants, but also to their lower conversion efficiency because of the exploitation of reservoirs with lower temperatures. On the other hand, ORC plants allow nowadays to generate electricity from liquid dominated reservoirs with temperature as low as 120°C, which is impossible with conventional flash plants (DiPippo, 2012).

Table 1. The Pros and Cons of Geothermal Power (ESMAP, 2012).

ADVANTAGE	DOWNSIDE / CHALLENGE
Globally inexhaustive (renewable)	Resource depletion can happen at individual reservoir level
Low/negligible emission of CO_2 and local air pollutant	Hydrogen sulfide (H_2S) and CO_2 content is high in some reservoirs
Low requirement for land	Land or right-of-way issues may arise for pipelines, access roads and transmission lines
No exposure to fuel price volatility or need to import fuel	Geothermal heat is non-tradable and it is location constrained
Stable base-load energy (no intermittency)	Limited ability of geothermal plants to follow load/respond demand
Relative low cost per kWh	High resource risk, high investment cost and long project development cycle
Proven / mature technology	Geothermal fields require sophisticated monitoring and maintenance
Scalable to utility size without taking up much land / space	Extensive drillings are required for a large geothermal plant

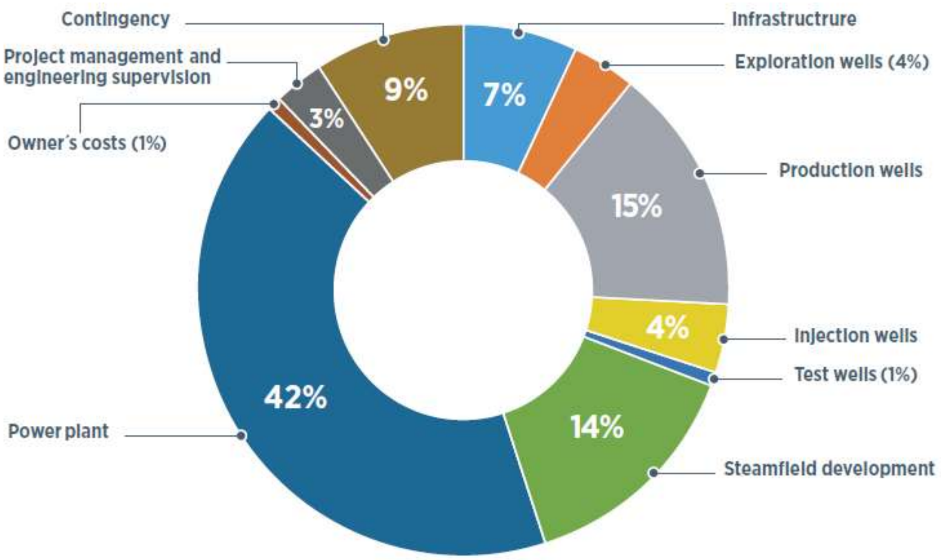


Figure 2. Total installed Cost Breakdown for two proposed 110 MW geothermal plants in Indonesia (IRENA, 2014).

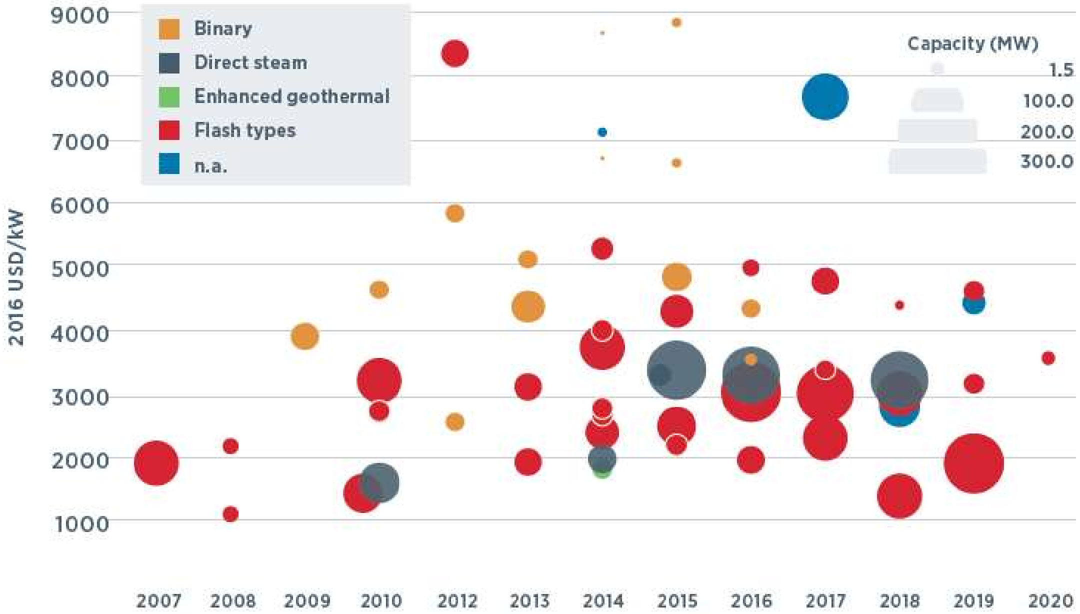


Figure 3. Geothermal power plant cost per unit kWh installed for different power plant technologies for the 2007-2020 period (IRENA, 2017).

The possible environmental impact of geothermal energy utilization (GEOLEC, 2013) slightly changes with respect to the type of geothermal facility, i.e. condensing turbine plants, ORC plant and Enhanced Geothermal Systems (EGS), the latter being outside of the scope of the present review. The environmental impact of geothermal facilities may be divided into the following main categories (GEOLEC, 2013):

- Surface disturbances, such as those caused during drilling, FCRS and plant construction, possibly affecting flora, fauna, surface water with access roads, pipe and power lines, plant and associated land use.

- Physical effects, like those of geothermal fluid withdrawal on natural manifestations, land subsidence, induced seismicity, visual effects.
- Noise, due to equipment use during well drilling and testing, well work-over, plant construction and operation.
- Thermal pollution, such as due to hot water and steam release at surface.
- Chemical pollution, like due to disposal of liquid and solid waste, gaseous emission to the atmosphere, natural radioactivity, etc.

All the above impacts need to be properly evaluated by conducting Environmental and Social Impact Assessments (ESIAs), and subsequently monitored and mitigated with appropriate measures during all the phases of field exploration, development and utilisation. Special attention shall be devoted to the emissions into the atmosphere of geothermal plants. This issue has two different aspects:

- The emissions of harmful NCG, such as H_2S and Radon, and of contaminants (Hg). This is one of the main concerns for the public acceptance of geothermal plants by local population in industrial countries.
- The level of GHG emissions of geothermal energy compared to other sources, which is becoming an issue to obtain funds from international financial institutions looking at the impact of funded projects on global warming.

Technologies for the abatement of H_2S and Hg from gaseous emissions in condensing power plants do already exist such as those applied by ENEL GreenPower in Italy. Similar installations could be in principle deployed in most of condensing power plants. About GHG emissions, the NCGs extracted from the condensers are at present discharged to the atmosphere. Figure 4 (IPCC, 2011) shows that, with respect to other renewables, lifecycle emissions from geothermal plants are higher than those of Hydropower and Ocean energy only, and lower than both Photovoltaic and Concentrating solar. Despite the above encouraging figures, in the last years the reduction of geothermal GHG emissions became more and more important and it is now the subject of several R&D projects. Technologies under consideration mainly include: i) the capture of NCGs (more than 90% usually represented by CO_2) and their injection back into the reservoir or connected aquifers; ii) the co-injection of NCG with either separated brine and/or recovered condensed steam. Even if the public acceptance of geothermal energy in East Africa still does not present particular issues, it is likely that funding institutions in a near future will require that new power plants will have GHG emissions below some predefined threshold.

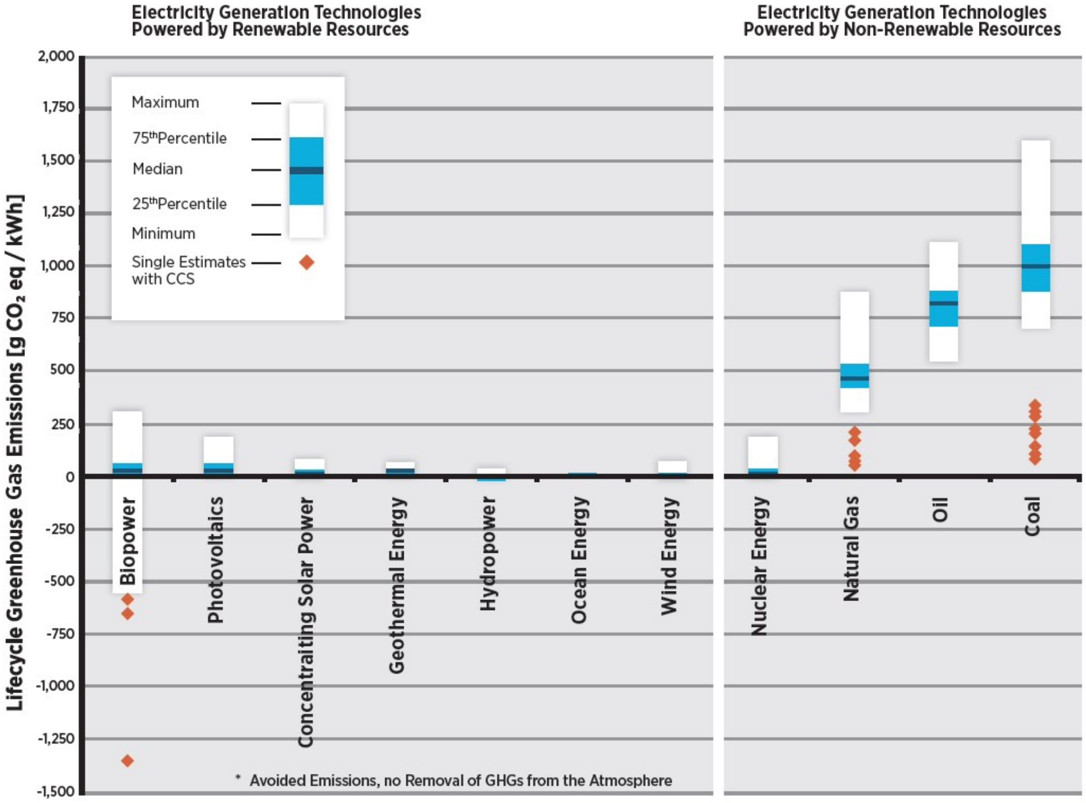


Figure 4. Lifecycle average greenhouse gas emissions for different electricity generation technologies expressed in terms of gCO_{2eq}/kWh (IPCC, 2011).

In addition to environmental impacts, also social impacts need to be addresses. International guidelines such as the IFC (2012) Environmental and Social Performance Standards (PS1-PS8) are applied also to the planning and performance of geothermal projects.

2.2 Phases of geothermal resources development

Even after decades of geothermal industry activities, different countries and agencies employ different methodologies and approaches for the development of a geothermal resource. The IGA (2014) guide for geothermal exploration divides the process of developing a geothermal resource into eight key milestones, in line with the ESMAP Geothermal Handbook (Gehringer and Loksha, 2012), as follows:

1. Preliminary survey
2. Exploration
3. Test drilling
4. Project review and planning
5. Field development
6. Power plant construction
7. Commissioning
8. Operation

According to the schedule in Figure 5 (Gehringer and Loksha, 2012), it may take approximately 7 years (generally between 5 and 10) to develop a typical full-size geothermal project with a 50 MW turbine as the first field development step. Required time may vary depending on the relevant country's geological conditions, information available about the resource, institutional and regulatory framework, access to suitable financing, and other factors. Due to this long development cycle, geothermal power is not a quick fix for any country's power supply problems, but rather should be part of a long-term electricity generation strategy.

After each milestone the developer, either a private company or a country's institution, must decide whether to continue developing the project or not. The first three milestones take the developer from early reconnaissance steps to field exploration and to test drillings. This first part of the project development either confirms the existence of a geothermal reservoir suitable for power generation or not: it represents the riskiest part of project development. Figure 6 shows the project cost and the risk profile of a typical geothermal project for a 50 MW power plant, as function of the 8 milestones listed above (Gehringer and Loksha, 2012). A strong reduction of the risk is obtained only after the positive results of the Test drilling, that is the confirmation of the existence of the geothermal reservoir by drilling and testing of exploration wells.

If the result of Test drilling is positive and the geothermal potential confirmed, milestone 4 is initiated with the actual planning and design of the power project, including the feasibility study, engineering of components, and financial closure. Milestones 5 to 7 comprise the development of the project itself, consisting of the drilling of geothermal production wells, construction of pipelines, construction of the power plant, and connection of the power plant to the grid. Completion of each milestone represents an increment in the developer's understanding of the geothermal system, a decrease in the overall uncertainty of the project's financial viability, a project decision point, and (usually) a requirement for significant financial investment. Consultants and developers may divide the process into a different number of phases (e.g., 4 phases: surface studies, exploration drilling, development drilling and construction of FCRS and power plant; or 5 (Omenda, 2018a): resource exploration, resource assessment, field development, power plant development, operation), but the underlying activities and philosophy are essentially the same.

While the 8 milestones above are required to build and operate a geothermal power plant, usually they are not performed as a continuous flow of activities. More often phases such as reconnaissance, surface exploration, test drilling and field development are separated by time intervals of different length during which the operator (sometime operators) is taking the necessary decisions, is looking for financing, and is applying for necessary licenses and permits. Often the reconnaissance phase is performed at a country or regional level on behalf of a state institution. Promising areas are then selected for the performance of detailed surface exploration activities either by a state institution, or directly by a public or private geothermal operator. The performance of surface exploration studies is usually subject to the award of an exploration license, a process which might take time in particular if licenses are awarded by the government on a competitive basis as happens in the most advanced geothermal markets.

The positive results of a surface exploration study allow to draw the prefeasibility study which delineates the prospect area to be investigated with deep exploration wells, locates the exploration wells, defines their basic design and the needs for infrastructures, and evaluates the overall costs of the exploration drilling phase. As the next step is characterized by an important investment, which may be in the order of 20-40 M USD for the drilling of 2-4 wells, and by a high mining risk, securing the necessary financing is usually challenging and might require considerable time.

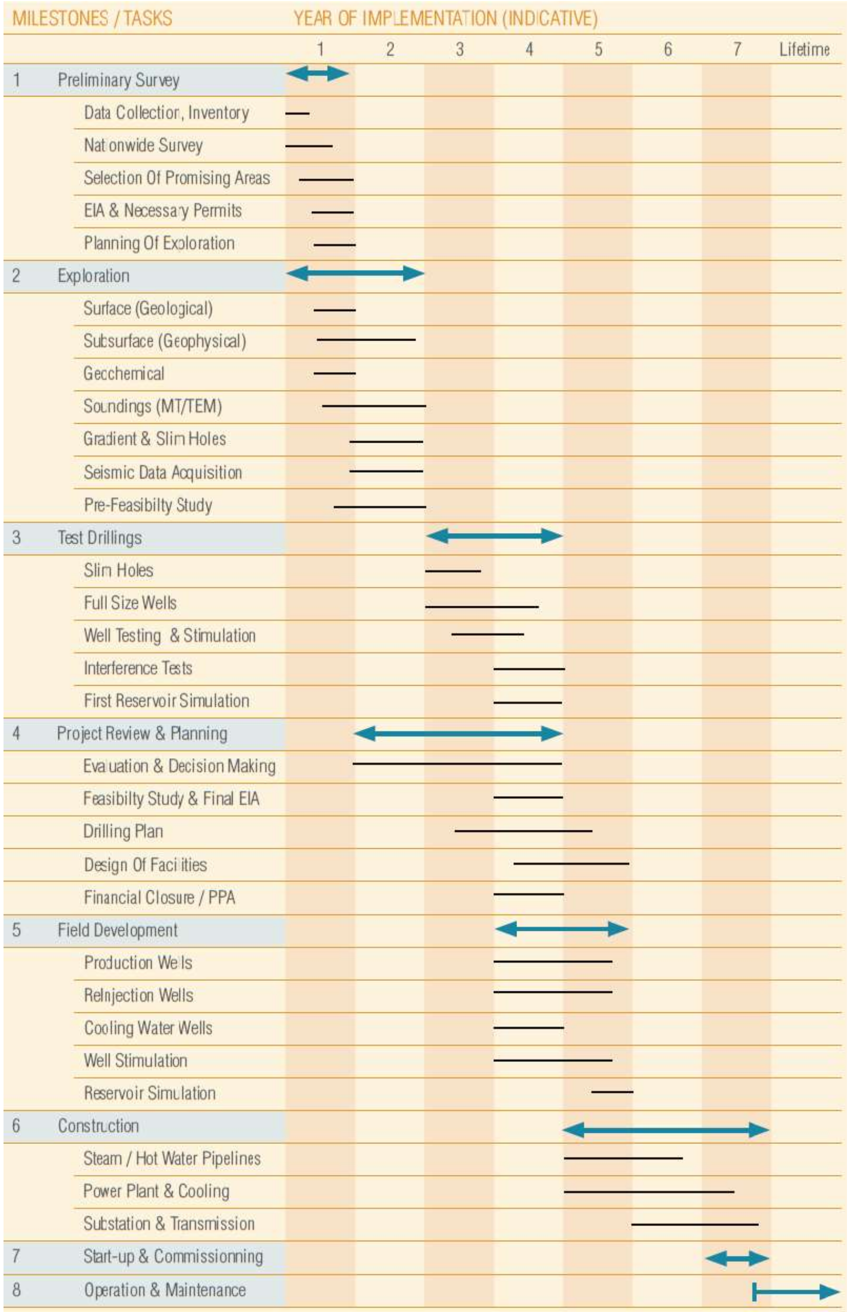


Figure 5. Geothermal Project Development for a Unit of Approximately 50 MW (Gehringer and Loksha, 2012).

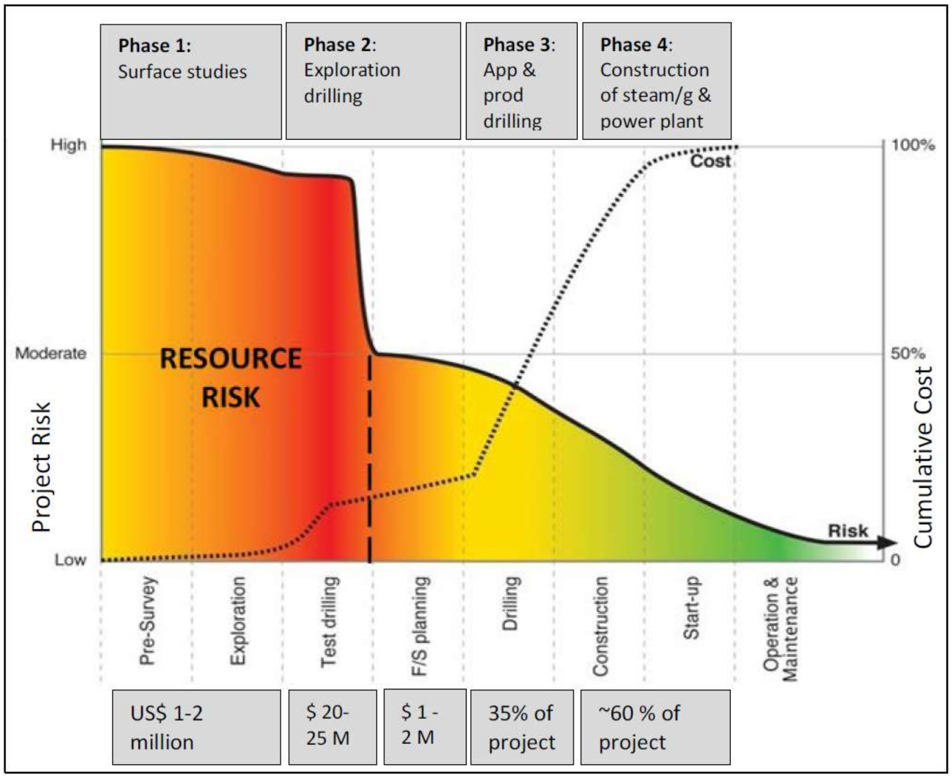


Figure 6. Project Cost and Risk Profile at Various Stages of Development (Gehringer and Loksha, 2012).

Usually within the same project the drilling and testing of exploratory wells is followed by the evaluation of resource potential and by the execution of a feasibility study related to the field development and the installation of a power plant. The study is used to find the necessary funds for the subsequent phases of field development (drilling of production and reinjection wells necessary at plant start-up), and of FCRS and power plant detailed engineering, procurement and construction (EPC). The development phase might require the switch from the exploration license to a field development and use license, as is for instance foreseen in Ethiopia.

Often the construction phase starts once the field development has been almost completed, a choice which allows the construction to occur when all the required wells have been drilled and tested. This reduces the risks related to an early design performed when only a fraction of necessary wells has been drilled and tested, but on the other hand requires a longer time as the two phases are performed in series. It is common that experienced geothermal operators perform the field development drilling and the EPC for the FCRS and the power plant almost in parallel. An approach often followed, when funds are provided by an international funding institution such as JICA or World Bank, includes the subsequent steps:

- Start of field development by drilling and testing the planned production and reinjection wells;
- Update the previous resource assessment and feasibility study after the drilling and testing of a number of wells enough to cover all the prospect area; a flexible design of FCRS is performed to account for the uncertainties linked to the flow rate and discharge enthalpy of wells still to be drilled.
- Complete the field development drilling while performing the EPC based on the updated feasibility study.

This approach considerably reduces the overall time necessary for field development and power plant construction, and the risks connected to an early design of gathering system and power plant.

3 Geothermal Energy in East African Countries

An overview of the geothermal resources along the East Africa Rift Systems is given, and the phases of geothermal resources development discussed together with the main obstacles to the development of geothermal industry in East Africa.

3.1 Geothermal resources in the East African Rift System (EARS

The EARS shown in Figure 7 (Omenda, 2014; 2018b), is an intracontinental rift, consisting in the continental branch of the worldwide mid ocean rift system that corresponds to the third arm of the Afar- Red Sea – Gulf of Aden triple junction. The EARS splits into an Eastern and a Western branch at about 5°N. The Eastern Branch comprises the Afar depression at the North and the Ethiopian, Turkana and Kenya Rift Valleys to the South, till the North of Tanzania. The Western Branch starts in Uganda to the North, and comprises Albert, Kivu, Tanganyika, Rukwa and Malawi Rift Valleys. Its SW extension comprises Luangwa-Kariba-Okavango rifts in Zambia.

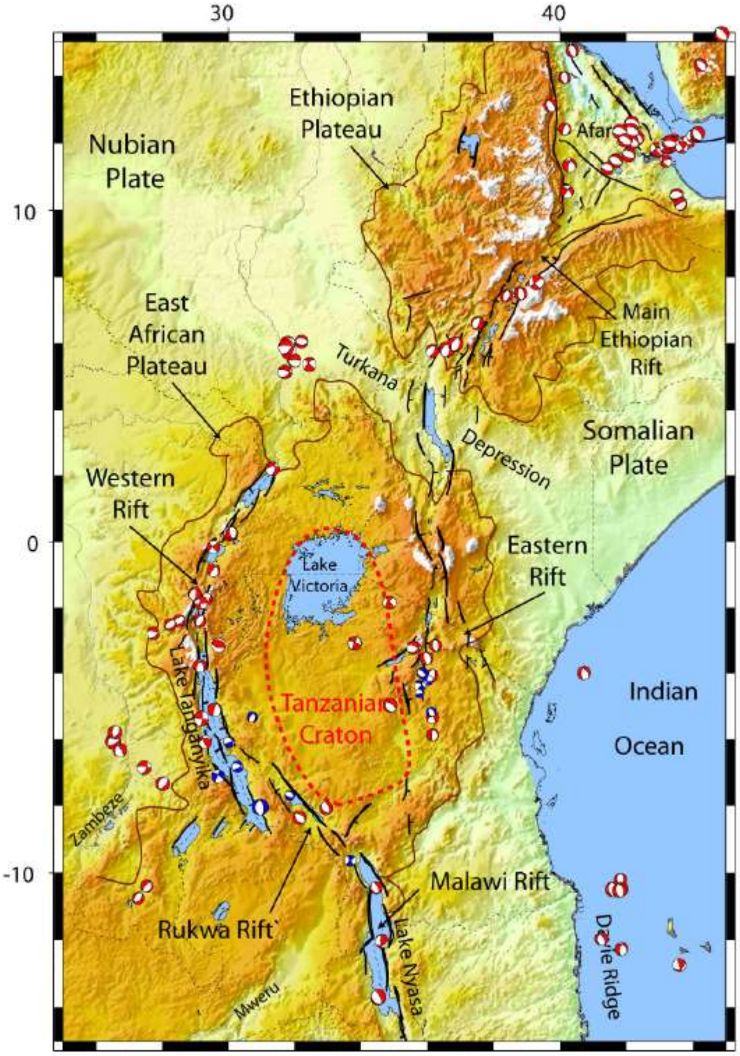


Figure 7. The East African Rift System (Omenda, 2018).

The Eastern Branch is characterized by a much widespread quaternary volcanic activity, with large calderas and volcanic centres along the rift axis, with the presence of shallow magma bodies. Geothermal prospects are mainly consisting in volcanic hosted high temperature geothermal systems. The Western Branch has limited volcanic centres, with the absence of shallow magmatic bodies and is characterized by geothermal prospects mainly associated to medium, rarely high, temperature fault controlled hydrothermal systems, similar to the large number of operating and drilled fields in the US Basin and Range region and in the Menderes Graben in Turkey (Alexander et al., 2016c). While the overall EARS geothermal potential has been estimated from 15,000 MW (Omenda, 2014) to over 20,000 MW (Omenda, 2018), the Eastern Branch is characterized by a much higher potential than the Western one, estimated in the order of 95% of the total one and being mainly concentrated in the Afar depression (Djibouti and Ethiopia) and the Ethiopian and Kenyan Rift valleys.

The above figures derive mostly from resource potential estimates based on the results of reconnaissance and surface exploration studies. Such estimates are customarily performed using variants of the heat stored method, also known as volumetric method, originally proposed by Muffler and Cataldi (1978) for the assessment of geothermal potential at regional scale. It is based on a static evaluation of heat in place, of its recoverable fraction and on the conversion of recoverable thermal energy into electric energy, neglecting all the hydrodynamic and thermodynamic processes that control the exploitation of a geothermal reservoir. The associated large margins of uncertainty, in particular with respect to the volume of the reservoir and to the recovery factor, are customarily handled using the Monte Carlo approach, as suggested by Sarmiento and Steingrimsson (2007; 2011). As the heat stored method historically proved to overestimate the actual resource potential (Grant, 2015), the above figures for the EARS geothermal potential should be considered as upper values and used with caution.

It is interesting to look at forecasted role of geothermal energy in the generation of electricity in sub-Saharan countries. Figure 8 shows the electricity supply by type, source and scenario in sub-Saharan Africa, excluding South Africa (IEA, 2019). The situation at 2018 is compared to two different IEA's scenarios (Stated Policies & Africa Case) at year 2040. The Stated Policies Scenario is based on current and announced policies, while the Africa Case is a new scenario built around Africa's own vision for its future. It incorporates the policies needed to develop the continent's energy sector in a way that allows economies to grow strongly, sustainably and inclusively.

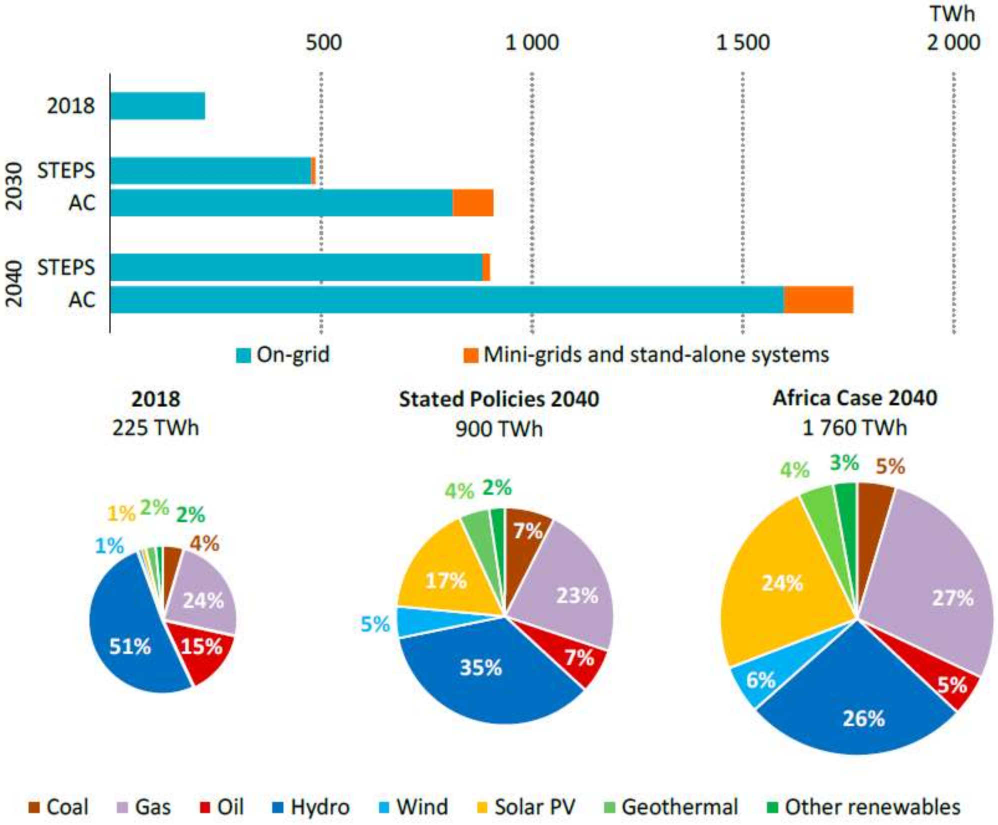


Figure 8. Electricity supply by type, source and scenario in sub-Saharan Africa (excluding South Africa), 2018 and 2040 (IEA, 2019).

In 2018 geothermal power accounted for 2% of electricity generation and is expected to represent in 2040 the 4% by both scenarios. Thus, geothermal is expected to double its contribution share in 2040, but still representing a small fraction of electricity generation, in particular if compared to the important increment of Solar PV which will compensate for the reduction of Hydro contribution. Both scenarios suggest that even if most of the investments on renewable energies will be likely drained by Solar PV, installed geothermal power shall anyway experience a large increment in order to meet its expected contribution.

3.2 Geothermal projects development in East Africa

Several business scheme for the development of geothermal resources have been implemented in countries with a well-developed geothermal industry. Related experiences represent useful examples for the development of geothermal resources in East Africa and are already successfully implemented in Kenya. The business schemes followed in East Africa are summarized by Omenda (2018a) as shown in Figure 9. The initial scheme followed was the full development of geothermal resource by a Public Entity, like the initial development of Olkaria field in Kenya by KenGen. This approach has been followed in the past in many countries either by electric power corporations or national oil companies such as ENEL in Italy, EDC in the Philippines, PGE and PLN in Indonesia, CFE in Mexico and ICE in Costa Rica.

The second business model foresees that a Public Entity performs the Resource exploration and assessment and the Field development phases, those characterized by the highest mining and financial risks, while the power plant development and operation is awarded to an Independent Power Producer (IPP). This model has been chosen by GDC for the Menengai field in Kenya, where the 105 MW field development was awarded on a competitive basis to 3 different IPPs. GDC performed the field development, constructed the steam gathering system and will manage the field exploitation by selling the steam to the IPPs. The IPP can be either a private company as well as a state-owned electricity utility.

The third model limits the intervention of the Public Entity to the Resource Exploration and Assessment phases, while the IPP develops and constructs the field and the power plant and subsequently is in charge of both the well field and the power plant operation. This approach is limited to few IPPs which are experienced geothermal operators acting internationally, such as Ormat, EDC, RG, Enel Greenpower. This approach has been followed by KenGen for Olkaria III 140 MW field expansion, with the staged field development and power plant construction awarded to Ormat through OrPower 4 Inc.

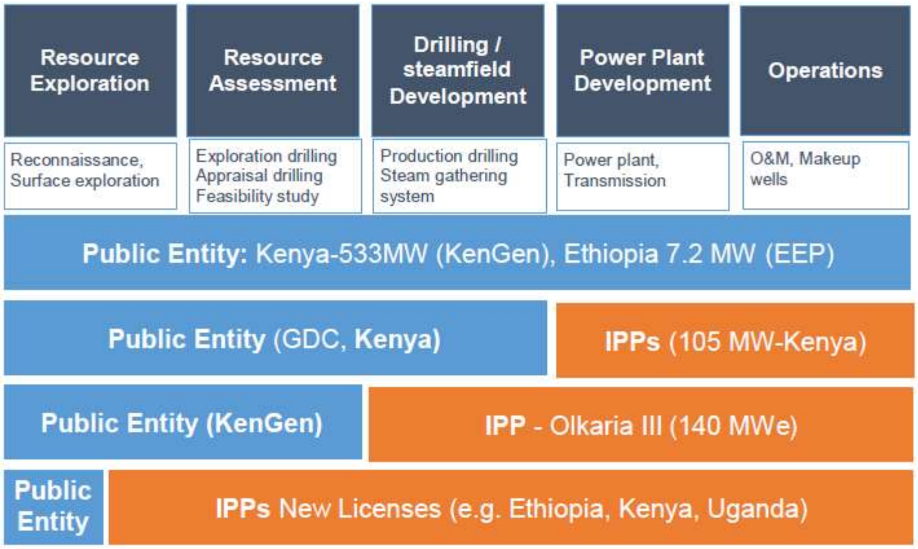


Figure 9. Geothermal projects development in East Africa (Omenda, 2018a).

The fourth model limits the Public Entity role to the Resource exploration phase with reconnaissance activities at regional scale and surface exploration of selected most promising prospects. Then all the subsequent activities are demanded to IPPs which in this case must be experienced geothermal operators, or JVs between operators, acting internationally.

Figure 9 suggests that geothermal development in Eastern Africa was driven mainly by the governments through state corporations, but the trend has since shifted to IPPs developing geothermal projects from very early stages. This trend follows what basically occurred in many countries all around the world, with an increasing shift from public to private operators. Generally, apart for highly developed open electric markets, a Public Entity is usually the final buyer of the generated electricity. This requires the signing of a Power Purchase Agreement (PPA) between the geothermal operator and the state-owned electricity utility. Opening to private skilled operators should of course allow to speed-up the development of geothermal resources, which is one of the stated targets of the East African governments.

3.3 Recognized obstacles to the development of geothermal resources utilization in East Africa

While the EARS geodynamic context creates high favourable conditions for the existence of exploitable geothermal resources, with a global potential estimated at 15,000 - 20,000 MW, at present only Kenya has developed its geothermal resources with an installed electric power of about 865 MW, against estimated resources from 7,000 MW up to 10,000 MW (Omenda, 2018b). Despite exploration drilling performed since the 80's in Djibouti and Ethiopia, no power generation is at present active in both countries.

While some reasons for the delay of geothermal resources development in East Africa are experienced almost everywhere (Gehringer and Loksha, 2012; ESMAP, 2016; JRC, 2019), other are more specific to East Africa:

- the lack of clear and coherent legislative frameworks regulating the activities of both public and private investors.
- the lack of local technical and managerial skills able to conveniently support the exploration and exploitation of geothermal resources.
- inadequate financing of the early stages of geothermal projects; commercial banks reluctance to participate in the exploration phase and the need for more risk reduction opportunities which facilitate the investment by both public and private operators.
- the remoteness of many East Africa geothermal areas from developed O&G regions where most of the drilling contractors and service providers are based, and then the absence of infrastructures and logistic facilities supporting the drilling activities characterising well developed O&G regions.
- competition from other energy sources, such as Hydro in Ethiopia and Solar PV in most of the countries, which creates a challenging environment for geothermal projects in the region.
- the issue of remunerative price for the generated electric power in still poor developed national electric markets.

In order to help East African countries to overcome the above issues, many international stakeholders are actively involved with different roles and at various stages of the geothermal resource development chain. Many of them are collaborating on common initiatives sharing funding contributions and management responsibility. Several stakeholders are actively collaborating with national governments to create the necessary legislative framework. They have facilitated the capacity building with the organization of dedicated courses and conferences and the creation of the Africa Geothermal Centre of Excellence (AGCE) in Kenya, taking advantage of the existing training facilities of GDC and KenGen. In addition, several international stakeholders are actively supporting all the phases of geothermal field development, from exploration to power plant EPC, with grants and soft loans and providing technical assistance and consultant support to national institutions and geothermal operators.

While the role of international institutions has been fundamental in supporting the geothermal exploration and development in East Africa in the last decades, sometime the support given was limited to a specific phase after which no further support was available, determining strong delays in the performance of subsequent phases. Often the same prospect has been explored and developed with funding coming in different times from different institutions, often with different consultants that had to review each time the data and results of previous activities.

This approach was not always effective, and produced changes in strategy, unnecessary reiteration of reviews and processing of data, and consequently delays in the development process and higher costs.

Geothermal development involves substantial initial capital requirements due to exploration drilling costs, for which it can be difficult to obtain bank loans. Since geothermal exploration is considered high risk, developers generally need to obtain some type of public financing. This risk is derived from the fact that capital is required before confirmation of resource presence or exploitability, and therefore before project profitability can be determined. Some of the Governments (Kenya, Tanzania, Djibouti) have decided to reduce this risk and the cost of capital for private developers by creating public companies in charge of initial exploration activities and in some case also to exploit geothermal resources and provide private IPPs (that install power plants and generate electricity) with the required steam. An important opportunity is represented by the Geothermal Risk Mitigation Facility for Eastern Africa (GRMF) which is providing grants covering a variable costs fraction for infrastructure construction, surface exploration surveys and exploration drilling, that is the exploration phase characterized by the higher mining risks. After 5 Application Rounds, grants have already been awarded to 30 projects located in Djibouti, Ethiopia, Kenya, Uganda, Tanzania and Comoros. The expression of interest for the 6th Application round started on May 6, 2020.

Finally, geothermal energy shall be as much as possible competitive with other energy sources, either other renewables or fossil fuels. Figure 10 (IRENA, 2017) shows the estimated levelized cost of electricity generation (LCOE) by geothermal plant technology for a 25-year economic life, O&M cost of 110 USD/(kW y), capacity factors based on project plans (or national averages if data were not available) and the capital costs outlined in Figure 3. Larger flash or direct steam plants allows to achieve lower LCOE than the smaller ORC plants, and most of the plants allow a LCOE lower than about 0.08 USD/kWh, which is competitive with electricity generated with fossil fuels.

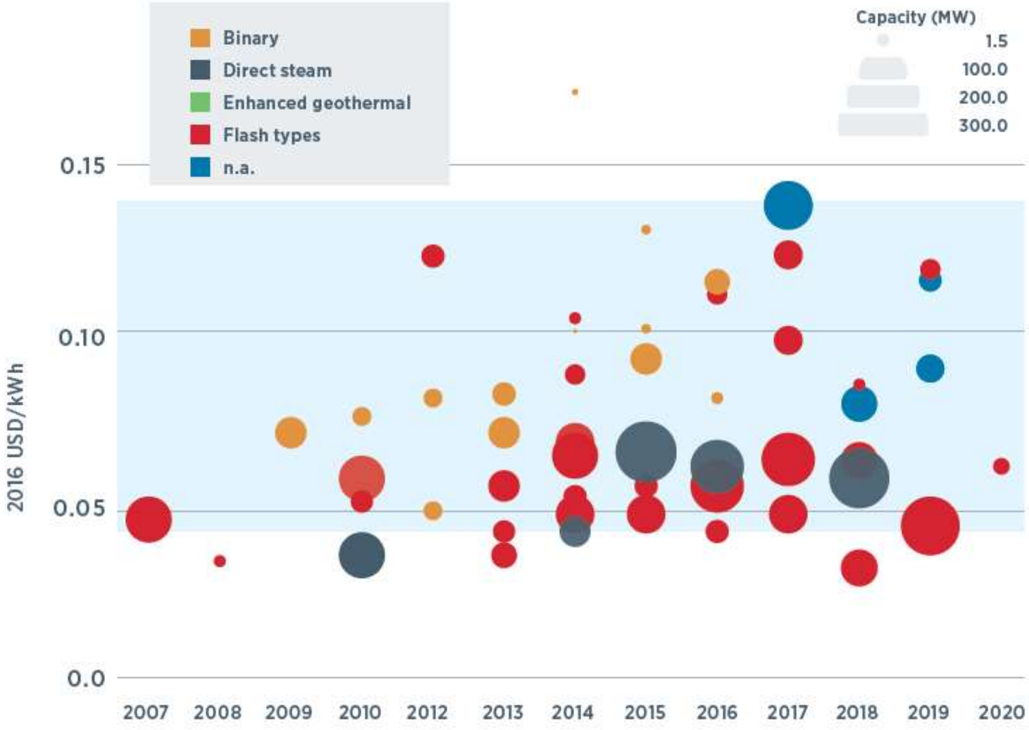


Figure 10. Estimated levelized cost of electricity generation (LCOE) by geothermal plant technology for a 25-year economic life. The blue band represents the range of costs for fossil fuel power generation. (IRENA, 2017).

An evaluation of global LCOE for renewable energies is that presented by IRENA (2019). Figure 11 shows the LCOE evolution for all the major renewables sources between 2010 and 2018. The average LCOE of Hydro is lower than that of geothermal energy, and this is a constraint for geothermal development in East Africa countries rich of Hydro resources, like for instance Ethiopia. Geothermal energy experienced an increment of LCOE between 2010 and 2018 at the global scale also due to the diffusion of ORC plants characterized by a higher LCOE. On the other hand, technological improvements on rapidly growing technologies such as Solar PV and Onshore Wind are the main reasons for the decline of their LCOE between 2010 and 2018. This might be a problem for geothermal energy development in East Africa as the solar resources in the region are substantial. Due to the expected raise of electric power requirements in the region, all the renewables will for sure give their contribution, but cheaper energy sources like Solar and Wind not affected by the mining risks of geothermal energy will likely be preferred by many international and national investors. Thus, the competitiveness of geothermal energy against Hydro, Solar PV and Onshore wind in East Africa countries shall be taken properly under consideration.

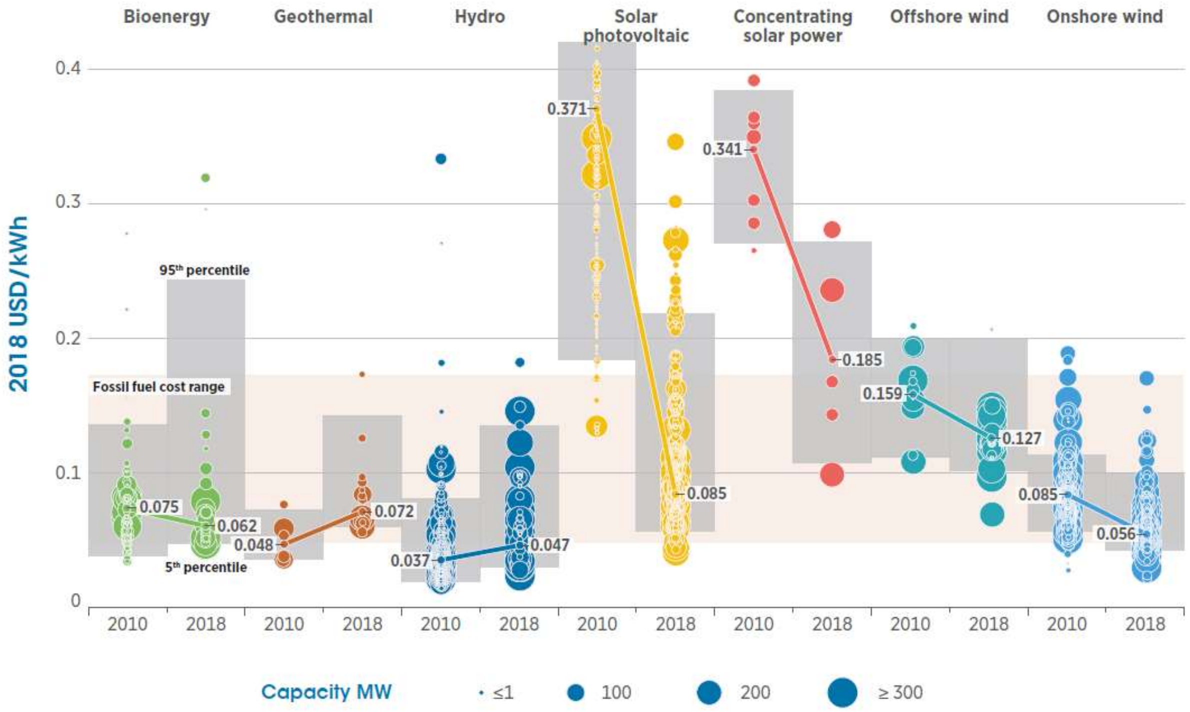


Figure 11. Global LCOE evolution of utility-scale renewable power generation technologies in the 2010–2018 period. Real weighted average cost of capital is 7.5% for OECD countries and China and 10% for the rest of the World. (IRENA, 2019).

4 COUNTRIES STATUS

The main goal of the present review is to frame the state-of-the-art on the geothermal resource development in East African Countries crossed by the Eastern Branch of the EARS, namely Eritrea, Djibouti, Ethiopia, Kenya, and Tanzania. The focus is on geothermal activities aimed at generating electric power by using either flashing or Organic Rankine Cycle (ORC) plants. Thus, direct uses of geothermal energy such spas, cooking, space heating and cooling, greenhouse heating, crop drying, aquaculture and heat for industrial processes are not addressed. While direct uses represent the natural utilization of low temperature resources, they can also successfully complement the exploitation of medium and high temperature resources for electric power generation to improve the resource recovery and the project rentability.

Before entering into the details of each country's status, a few general considerations on the evolution of the energy market in Africa since 1990 is deemed useful, as many trends are shared by East Africa countries. The data below are taken from IEA's Data and statistics web page (https://www.iea.org/data-and-statistics).

Figure 12 shows the evolution of Total Primary Energy Supply (TPES) by generation source for the whole Africa from 1990 to 2017. Thus, it also includes the contribution of North Africa countries, as well as big O&G producers, like Algeria, Libya, Egypt, Nigeria, and Angola. The figure shows that energy supply is dominated by Biofuels and waste, followed by fossil fuels like Oil, Coal, and Natural gas. Nuclear and Renewables still account for a marginal contribution. The enormous use of Biofuels is typical of many sub-Saharan countries in which a large fraction of the population still lives in the country side working on the agricultural sector. Only a limited fraction of them has access to electric energy. From about 2002 there was a change of the TPES steady increment, in particular for Oil, Natural gas and Biofuels. The huge increment of TPES over the period is well correlated with the population increment, as the TPES per capita changed from about 0.61 toe/capita in 1990 to 0.75 toe/capita in 2017. Figure 13 shows the Total Final Consumption (TFC) of energy by sector which is dominated by the Residential uses, which are mostly driven by cooking in the country side using Biofuels and by lightning and cooling in the urban areas.

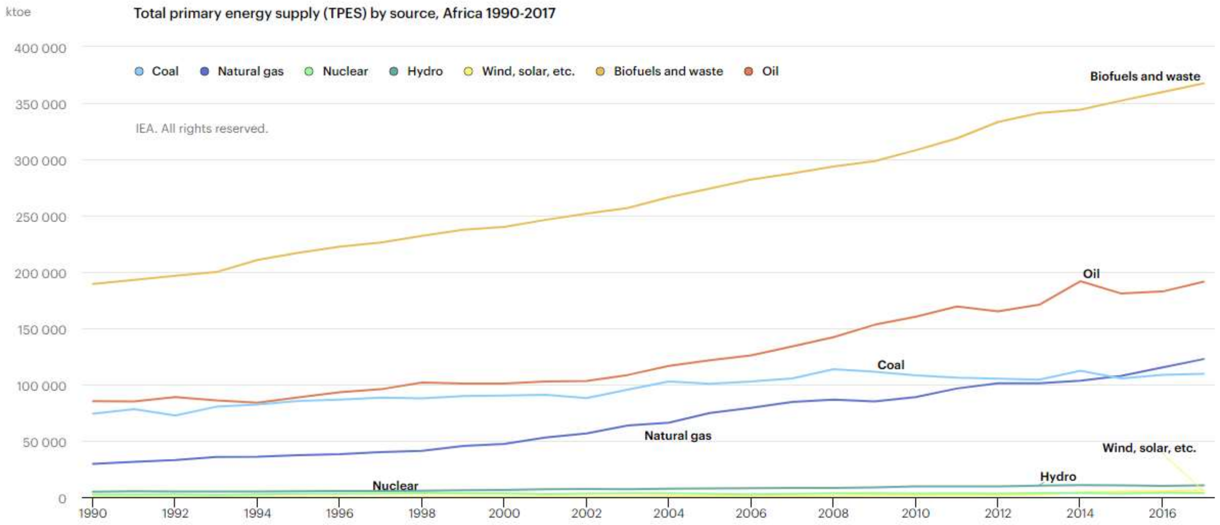


Figure 12. Total Primary Energy Supply (TPES) by source for Africa, from 1990 to 2017 (IEA, 2020a).

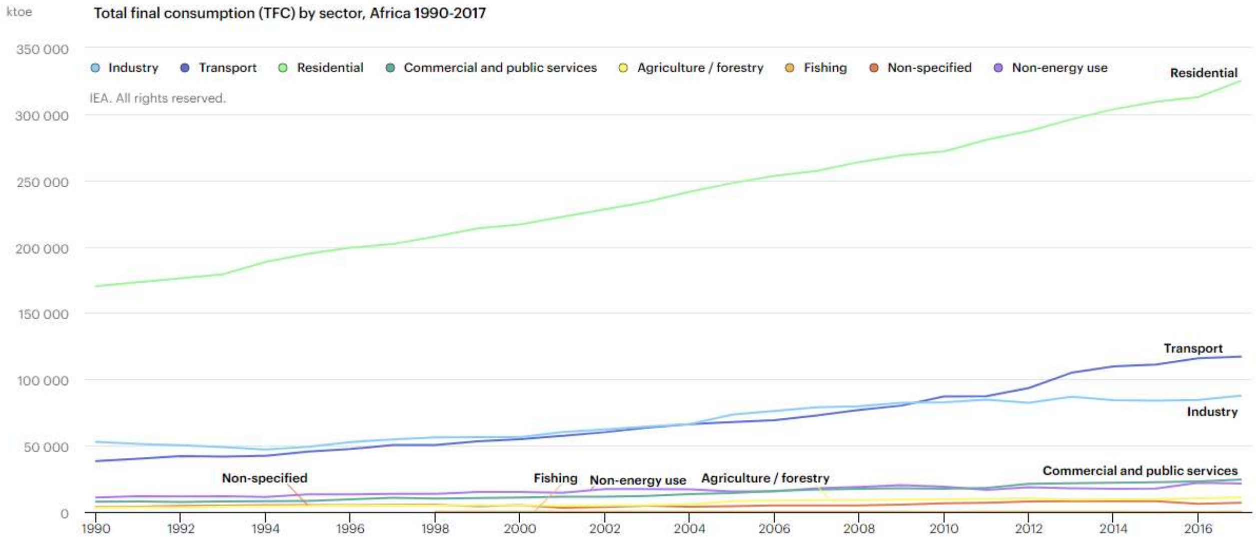


Figure 13. Total Final Consumption (TFC) by sector for Africa, from 1990 to 2017 (IEA, 2020a).

The TFC by source are indicating the evolution of the electricity market in Africa with respect to other sources. Figure 14 shows that the electricity was steadily increasing in the period with an acceleration around year 2002, but it still represents a minor fraction of final consumption uses dominated by Biofuels and Oil product. This may be explained by the limited access to electricity of most sub-Saharan countries and in particular in East Africa, as shown in Figure 15 (IEA, 2019). In 2000 the average access rate to electricity in East Africa was around 10% of the population, remaining around 22% till 2013 to raise to about 43% in 2018.

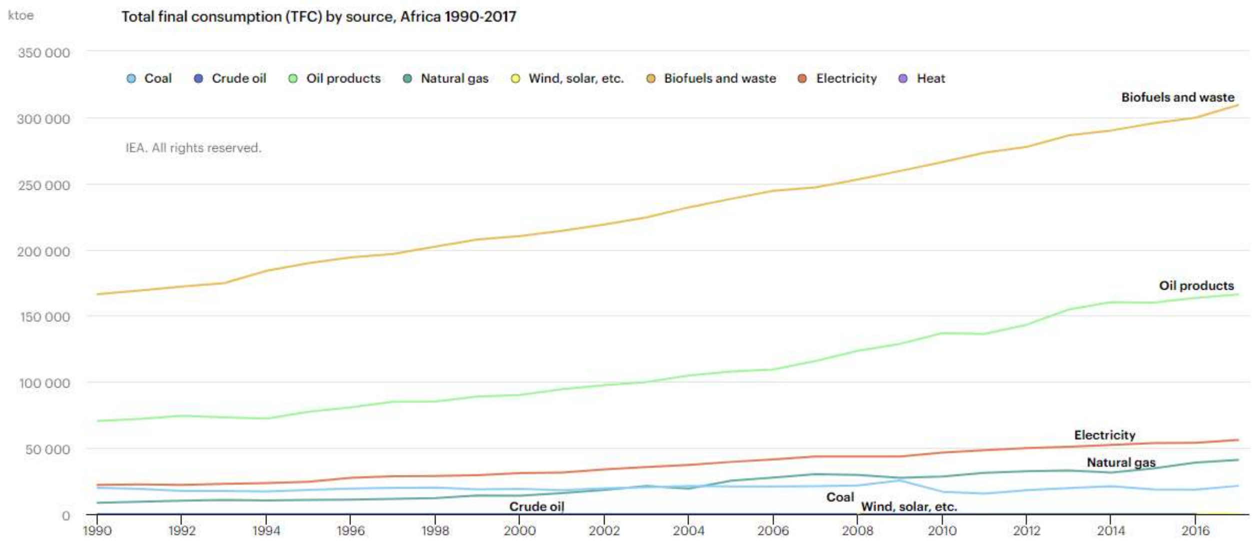


Figure 14. Total Final Consumption (TFC) by sector for Africa, from 1990 to 2017 (IEA, 2020a).

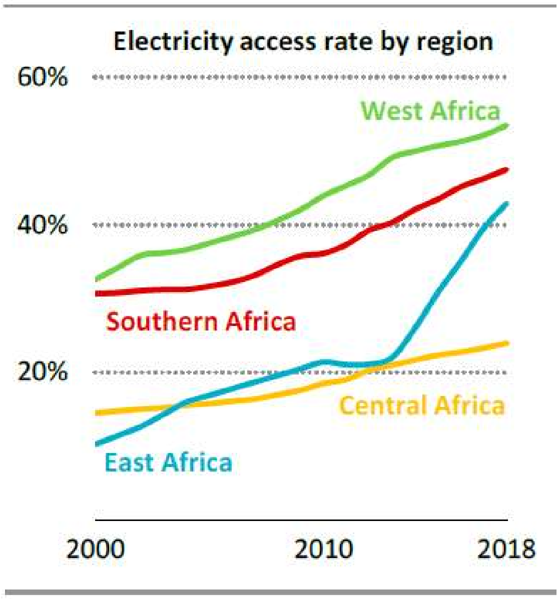


Figure 15. Electricity access progress in East Africa since 2000, showing an acceleration since 2013 (IEA, 2019).

As far as the expected development of electric market in sub-Saharan countries is concerned, Figure 16 shows how the IEA Sustainable Development Scenario for the 2010-2030 period plans to increase the access rate from about 45% in 2018 to about 100% in 2030. Considering the foreseen increment of population in sub-Saharan countries and the electricity consumption dominated by residential uses, the electricity consumption is expected to have a huge increment in East Africa, driving investments in electric power generation which will benefit also the geothermal industry.

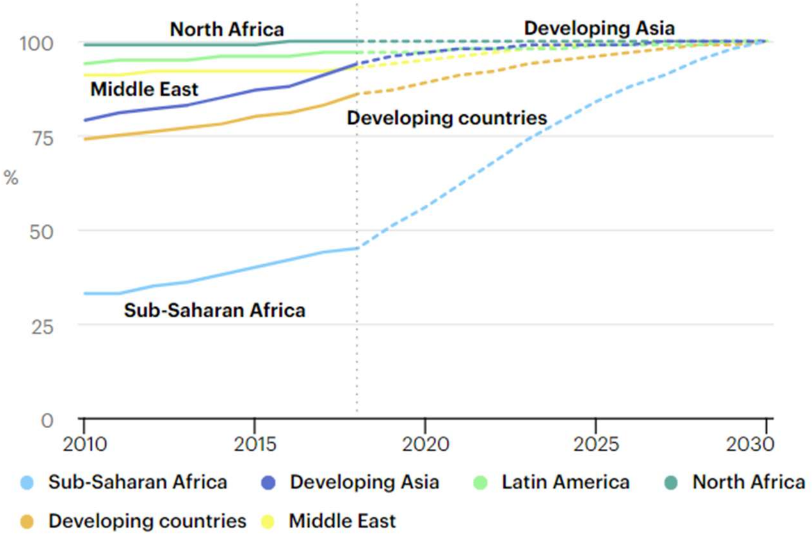


Figure 16. Access to electricity in the Sustainable Development Scenario, 2010-2030 (IEA, 2020b).

Table 2 lists some statistical data about the 5 countries analysed. All countries are characterized by a high trend of population increment and a high population density in Ethiopia and Kenya. Except Djibouti, where 2/3 of the population is concentrated in the capital city, all the countries have a very high percentage of population living in rural areas and employed in agricultural activities. Most of this people has no access to electricity and uses Biomass (wood and charcoal) as primary source of energy for food and heating, with an unsustainable impact on the ecosystems. All are low income countries, where the price of electricity may represent a huge obstacle for both private and commercial customers. Apart for Djibouti and Kenya, the access to electricity is lower than 50%. The global estimated geothermal potential for the 5 countries crossed by the Eastern Branch amounts to some 21,600 MW (approx. 95% of the whole EARS potential), but 20,000 MW are concentrated in Kenya and Ethiopia. Despite the small potential estimated for Eritrea, it represents a remarkable fraction (51%) of the present installed power, thus still representing an interesting option for the future energy mix of the country.

It is reminded that quite different figures about countries geothermal potential are found in published literature. While different evaluations made over time reflects the performance of new exploration activities, differences in resource potential estimates are mostly due to the application of variants of the heat stored method often based on limited data sets collected with reconnaissance and preliminary surface exploration studies.

Table 2. Miscellaneous statistical data about the 5 countries analysed in the present review

Country	Area (km^2)	Population (M, 2019)	Rural (% 2018)	GDP (B USD, 2019)	GDP/ capita (2019)	Installed Power (MW)	Reference year (power)	Annual electricity consumption (kWh/capita, 2016)	Access to electricity (%, 2017)	Geothermal potential (MW)
Eritrea	117600	3.497	64	6.5	1859	195	2017	59	48.4	100
Djibouti	23200	0.974	22	2.1	2105	123	2019	427	60.2	1000
Ethiopia	1104300	112.079	79	94.0	839	4522	2019	84	44.3	10000
Kenya	580000	52.574	73	89.0	1693	2997	2018	163	63.8	10000
Tanzania	945087	58.005	66	59.0	1017	1602	2019	103	32.8	500

(Population data https://www.populationpyramid.net, rural population and access to electricity https://www.macrotrends.net, GDP https://tradingeconomics.com/country-list/gdp, electricity consumption per capita https://photius.com/rankings/2019/energy/electricity_consumption_per_capita_2019_0.html,).

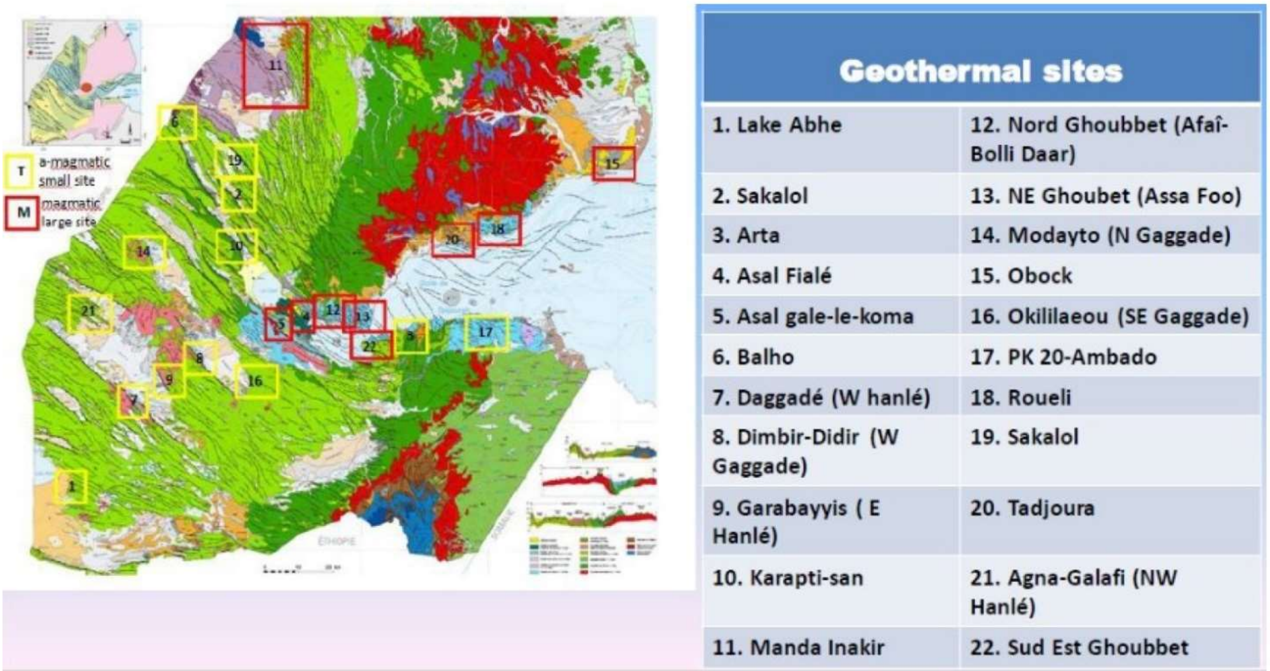
4.1 Eritrea

Eritrea (The State of Eritrea) is located at the extreme north of the EARS, along the coast of Red Sea. TPES in Eritrea is dominated by Biofuels and waste (wood and charcoal for basic cooking and heating needs) and Oil, totally imported, and used for transport and power production. Access rate to electricity was about 47% in 2017 with an extremely low electricity consumption of 70 kWh/capita sustained by a total installed power of 195 MW (Yohannes, 2020). The development of an indigenous energy resource such as geothermal energy would have clear benefits for the electric market in Eritrea totally depending on imported fuel oil. A 50 MW geothermal power plant would already be enough to supply most of the base load for the present average electric energy consumption.

The suitable tectonic environment of the Afar Depression characterized by a thinned crust and recent magmatic activity (Yohannes, 2015) favours a high heat flow on the upper zone of the crust. Geothermal exploration, started in early ‘70s (UNDP, 1973), has allowed to identify two main prospects: the Alid volcanic area and the Nabro-Dubbi volcanic complex, both characterized by important surface manifestations. While the latter prospect is still at a reconnaissance stage, the Alid prospect has been studied with surface exploration surveys performed from 1996 to 2009 followed by a prefeasibility study conducted under the Geothermal Exploration Project (GEP) jointly funded in 2013 by the Ministry for Foreign Affairs of Iceland and the Nordic Development Fund (NDF). Unfortunately, while mapping of surface manifestation and partial gravity measurements were conducted in 2015 (GOPA, 2019) the whole program was not implemented, failing to provide the well targeting for a possible drilling exploration phase. Despite GEP’s activity and other initiatives to support the geothermal exploration in Eritrea by UNEP, through the ARGeo facility for the preparation of an application to GRMF, and by the European Union, for preliminary studies and an exploration phase at Alid geothermal prospect, no further exploration activities have been apparently planned at Alid so far. The inferred geothermal potential for the Alid prospect has been reported at 70 MW and 100 MW by GOPA (2019) and the UN Environment Africa Geothermal Inventory Database managed by ARGeo (AGID, *http://agid.theargeo.org/newagid/eritrea.php*), respectively.

4.2 Djibouti

Djibouti (The Republic of Djibouti) is located at the north end of the EARS within the Afar Depression and is crossed by the Gulf of Aden ocean ridge (Figure 17). TPES in Djibouti is dominated by Oil and oil products (68%), which are totally imported, followed by Biomass (32%). This peculiar TPES is due to the fact that only about 22% of the population live in the extreme arid areas in the country side while most of the remaining people live in Djibouti city. Access rate to electricity was about 60% in 2017 with an electricity consumption of 472 kWh/capita sustained by a total installed power of 123 MW generated by thermal plants (Abdillahi et al., 2016). Electric energy is also imported from Ethiopia thanks to the interconnection completed in 2011, for an annual average potential of 42 MW. The development of an indigenous energy resource such as geothermal energy would have clear benefits for the electric market in Djibouti mostly depending on expensive imported fuel oil. A 50 MW geothermal power plant would already be enough to supply most of the base load for the present average electric energy consumption. In fact, consumption over the year is highly variable, as national grid demand is about 4 times greater in summer than in winter due to air conditioning. The Gov. of Djibouti is willing to develop wind power and solar PV in particular to extend electricity to the rural population and develop geothermal resources which are estimated between 800 and 1,000 MW based on very preliminary calculations (Abdillahi et al., 2016).



Geothermal sites	
1. Lake Abhe	12. Nord Ghoubbet (Afaî-Bolli Daar)
2. Sakalol	13. NE Ghoubet (Assa Foo)
3. Arta	14. Modayto (N Gaggade)
4. Asal Fialé	15. Obock
5. Asal gale-le-koma	16. Okililaeou (SE Gaggade)
6. Balho	17. PK 20-Ambado
7. Daggadé (W hanlé)	18. Roueli
8. Dimbir-Didir (W Gaggade)	19. Sakalol
9. Garabayyis (E Hanlé)	20. Tadjoura
10. Karapti-san	21. Agna-Galafi (NW Hanlé)
11. Manda Inakir	22. Sud Est Ghoubbet

Figure 17. Location of known geothermal sites in Djibouti (Awaleh et al., 2020).

Figure 17 shows the location of geothermal sites identified by reconnaissance surveys. Exploration drilling was performed in the ‘80s in the Hanlé plain and in the Asal Rift by drilling 2 and 6 deep wells, respectively. Wells A1, A3 and A6 found a highly saline liquid dominated reservoir with temperatures of 260-280°C on the western side of the Asal rift in the area known as Gale le Koma. Because of the severe scaling tendency, the reservoir was not exploited. Drilling at Gale le Koma found a shallow reservoir of lower salinity with temperatures in the order of 130-140°C which has been recently the target of the shallow well GLC-1 drilled by ODDEG with a drilling rig donated by the Turkish government. Additional funding for Gale le Koma exploration has been received in 2018 from KFAED and AFESD for the development of a 15 MW Geothermal Power Plant. The first phase of the project foreseen the drilling and testing of up to 8 production wells and 2 reinjection wells at depth interval of 400 – 1,200 m, to be drilled with a new fully equipped drilling rig with 250-ton capacity purchased by the Gov. of Djibouti.

Another exploration drilling phase has been performed by ODDEG within a multilateral funded project by drilling 3 deep exploratory wells in the Fialé caldera, in the middle of Asal rift close to well A5 drilled in the ‘80’. Preliminary results indicate that the three wells found static temperature up to 360°C, with two wells characterized by high enthalpy and low productivity. The project is going on with the execution of production tests, of feasibility study and the preparation of bidding document for an IPP tender (African Development Fund, 2019).

Detailed surface exploration studies have been performed in the following prospects:

- North-Ghoubet, with inferred reservoir temperatures in the range 170-220°C. Further investigations are planned by ODDEG to identify the exploration drilling sites.
- Arta, where an exploration study was performed in 2018 with a grant from GRMF.

- Lac Abhé, where a low enthalpy geothermal system with reservoir temperature of 110–150°C and a potential of about 14.5 MW using ORC plants (ODDEG-ISOR, 2016) has been inferred.
- Hanlè-Garabbayis, where two areas with deep temperature of 180°C and 260°C were inferred in a fault-controlled system between the Hanlé and Gaggadé plains.

Other prospects that have been the subject of reconnaissance studies and limited surface exploration surveys are: Ambado-PK20; Manda-Inakir; Obock; Sakalol-Harralol.

Djibouti has now a dedicated institution whose mission is the development of geothermal resources of the country (ODDEG, supported by CERD) and two drilling rigs (one for shallow and one for deep wells), likely allowing to lower the drilling costs with respect to international drilling contractors. The several surface exploration studies performed by ODDEG alone or in collaboration with foreign companies and institutions testify that considerable skills have been acquired by Djiboutian technicians. All the above are promising factors for the development of country geothermal resources, considering also the Gov. of Djibouti commitment to use the indigenous geothermal resources for the future base load of national electric network. In conclusion, at present no geothermal prospect exists with a completed positive feasibility study that would allow to go on with field development and the EPC of the power plant. Despite the willing and efforts of the Gov. of Djibouti to exploit the geothermal resources of the country, results achieved so far do not allow to expect that geothermal energy will be soon available to contribute to the national electric needs. On the other hand, if exploration will be finally successful, geothermal energy will be likely able to give a remarkable contribution to the limited base load requirements of national electric grid.

4.3 Ethiopia

Ethiopia (The Federal Republic of Ethiopia) is located at the north end of the EARS and includes the Afar Depression to the North and the Ethiopian Rift Valley to the South (Figure 18). About 79% of the people live between the highlands employed in subsistence agriculture and the extreme arid areas of Afar depression and Ogaden being mainly employed in nomadic cattle breeding. The access rate to electricity was 44.3% in 2017. TPES is dominated by Biomass (about 97% in 2017), with minor contributions from Hydro and Oil and Coal, the latter all imported. Power generation is dominated by Hydro with minor contribution from Wind.

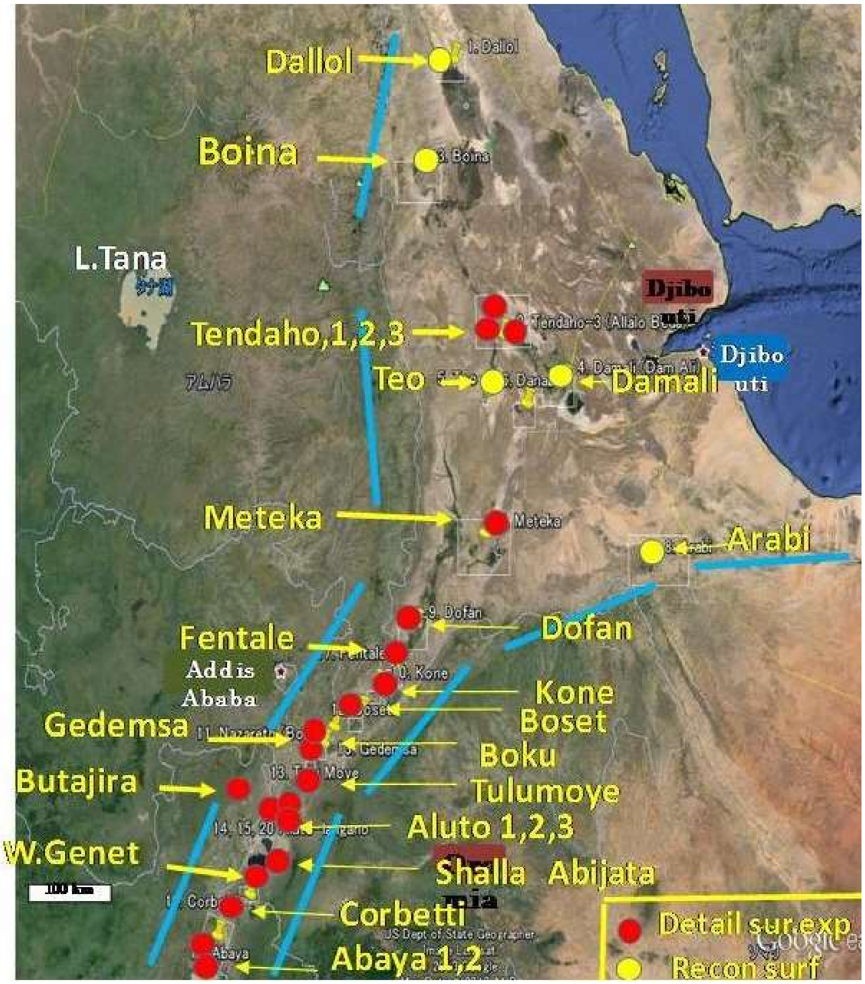


Figure 18. Location map of geothermal prospects in Ethiopia (detailed surface exploration and reconnaissance surveys) (Kebede et al., 2020).

The status of installed power in 2019 with that expected in 2020 is presented by Kebede et al. (2020) as shown in Table 3. Installed capacity in 2019 was 4,522 MW and that expected in 2020 is 4,742 MW, most coming from Hydro (4,077 MW). No contribution from geothermal energy is foreseen in 2020, while the 7.3 MW installed in 2019 refer to the Aluto Langano plant presently not in operation. Target total installed capacity in 2030 is 33,080 MW (Mekonnen, 2020), of which 20,200 MW from Hydro and 3,500 from geothermal energy, 3,000 from Solar and 2,500 MW from Wind.

Table 3. Existing capacity (2019) and planned production of electricity in Ethiopia at 2020 (modified after Kebede et al., 2020).

	Geothermal		**Fossil Fuels**		**Hydro**		**Other Renewables ***		**Total**	
	Capacity MW	Gross Prod. GWh/y	Capacity MW	Gross Prod. GWh/y	Capacity MW	Gross Prod. GWh/y	Capacity MW	Gross Prod. GWh/y	Capacity MW	Gross Prod. GWh/y
In operation in Dec. 2019	0	0	89	460	4,077	16,245	349	1,007	4,515	17,712
Under construction in Dec. 2019	70	520			10,390	30,207	220	770	10,680	31,497

Funds committed, but not yet under construction in Dec. 2019	1,640	8,549					100	210	1,740	8,759
Estimated total projected use by 2020	0	0	89	460	4,077	16,245	569	1,777	4,735	18,482

* Other renewables include: Wind, Solar and Waste to energy.

The geothermal potential of Ethiopia has been estimated in the range 4,200 – 10,800 MW as a result of 18 months of research and exploration by GSE and JICA (2015) who identified 22 areas with geothermal energy development potential in Ethiopia (Kebede, 2016). This figure has been recently confirmed at the upper value of 10,800 MW by Kebede et al. (2020). The attention of the Gov. of Ethiopia towards the geothermal sector is testified by the promulgation of the Proclamation No. 981/2016, and by the issue of the Geothermal Resource Development Council of Ministers Regulations No. 453/2019. The two documents regulate the activities of the operators in the geothermal sector by defining the geothermal resources grade, the type of different licenses to be applied for exploration, development and exploitation, the process of license management, the rights and duties of license owners. The documents also identify the EEA as the Government institution in charge of the management of permitting process and of the preparation of all necessary technical directives, while GSE is expected to collaborate with EEA in order to establish a process for geothermal resources data collection and management.

At present, 5 private companies hold 8 geothermal licenses, as listed in Table 4 (Mekonnen, 2020), all awarded before the issue of the Regulations No. 453/2019. Only 2 companies have already signed the PPA and IA: Tulu Moye Geothermal Operation Plc and Corbetti Geothermal Plc. The others are in the process of PPA negotiation and surface exploration activity. Table 3 also list the planned potential according to Kebede et al. (2020) for a total of 1940 MW. Different figures are given by other sources, probably reflecting the review stage of prospect development plans. For the Abaya prospect, with inferred reservoir temperature in excess of 230°C, two development phases are planned of 50 and 250 MW each (VSO, 2019). The Corbetti prospect, with inferred reservoir temperature in excess of 250°C, will be developed in two phases of 50 and 100 MW each. The Fentale prospect, with inferred temperature of 250°C, is planned to be developed in 4 phases for a total of 400 MW (Elliot et al., 2020). Tulu Moye, with estimated temperatures in excess of 230°C, will be developed in 2 phases of 50 and 150 MW, respectively (Guðbrandsson et al., 2020). About the 4 prospects owns by OrPower 12 Inc., 3 related to medium temperature deep circulation systems, the following potentials are reported by GRMF (2018a): Dofan 60 MW; Boku 70 MW; Shashemene 150 MW; Duguno 50 MW. From the above figures, more related to the operators, the total potential of the 8 prospects is 1,380 MW

Table 4. Active Geothermal License areas (awarded before the new Geothermal Resource Development Council of Ministers Regulations No. 453/2019). (After Mekonnen, 2020. Planned potential from Kebede et al., 2020).

No.	**Company**	**Location**	**Issue date**	**License area (km^2)**	**Status**	**Planned (MW)**
1	Reykjavik Geothermal Co.	Abaya	Dec. 11, 2009	513	Active	300
2	Corbetti Geothermal Plc	Corbetti	Dec. 11, 2009	735	PPA & IA signed	520

3	Cluff Geothermal Ltd	Fentale	July 15, 2015	1,255	Active PPA negotiation	150
4	OrPower 12 Inc	Boku	April 20, 2015	342	Active PPA negotiation	100
5	OrPower 12 Inc	Shashemene	April 20, 2015	1,005	Active PPA negotiation	100
6	OrPower 12 Inc	Duguno	April 20, 2015	1,249	Active PPA negotiation	150
7	OrPower 12 Inc	Dofan	April 20, 2015	1,255	Active PPA negotiation	100
8	Tulu Moye Geothermal Operation Plc	Tulu Moye	Aug. 29, 2018	588	PPA & IA signed	520

Other prospects are explored and developed by EEP, the state-owned electric power company, namely: the Aluto-Langano prospect in the Rift Valley, Dubti (also known as Tendaho) and Alalobad prospects in the Tendaho graben located in the Afar Depression. The Aluto caldera hosts a liquid-dominated reservoir with temperature reaching 330°C and low deliverability wells discharging a high enthalpy mixture. Ten wells have been drilled, of which 8 within the caldera. Five wells were connected in 1998 to a combined power plant with gross capacity of 8 MW. Plant operation was discontinuous due to problems linked to well production decline, scaling in production wells, brine pipelines and plant equipment failures. Because of that the plant was shut in 2008. A field development project is presently under way within the Geothermal Sector Development Project (GSDP) financed by the World Bank and the Gov. of Ethiopia. Two complete drilling rigs have been procured to drill up to 10 wells in both the old Aluto sector and the Bobessa area located to the East of Aluto main wellfield. The total potential for the caldera has been estimated at about 70 MW summing the Aluto (WestJEC, 2016) and Bobessa (ELC-Electroconsult, 2016a) contributions.

The Dubti drilling project, jointly funded by AFD and EU for the development of the shallow reservoir found at depth of 250-500 m with temperatures between 220 and 250°C (Pasqua et al., 2014), has the final goal to produce the feasibility study for the EPC of a power plant of about 10 MW capacity. The project is at present undergoing a review phase. The Alalobad drilling project, developed within the GSDP with funds from the World Bank, is aimed at drilling and testing up to 4 exploratory wells in the Alalobad prospect in order to produce a feasibility study for the further field development and the EPC of the power plant, being the potential of the liquid-dominated reservoir, with temperature in the order of 200-220°C, preliminary estimated at about 30 MW (ELC-Electroconsult, 2016b). The project is at present undergoing a review phase.

Despite an important geothermal potential estimated at some 10, 000 MW and exploration activities started in the early ‘70s, no geothermal power plants are presently active in Ethiopia. The promulgation of the Proclamation No. 981/2016, and in particular, of the Geothermal Resource Development Regulations No. 453/2019 should facilitate substantially the activity of geothermal operators and in particular of the private ones that were already owing 8 different licenses. The operators of Tulu Moye and Corbetti licenses have signed in March 2020 updated PPA and IA for the development of the two prospects. Drilling operations were also started in March 2020 at Tulu Moye for the drilling of the first exploratory well. It seems that geothermal resource development by international IPP might now proceed faster than in the past. Reconnaissance surveys, as that performed in 2014-15 by GMS in collaboration with JICA on more than 20 prospects, as well as surface exploration surveys performed by GSM, may be extremely useful to identify the most promising prospects for which exploration licenses can be awarded on a competitive basis to both national and international operators as already foreseen by the Regulations No. 453/2019. This approach would follow that customarily used in mature geothermal industrial markets.

4.4 Kenya

Kenya (The Republic of Kenya) is crossed N-S by the Rift Valley (Figure 19). About 72% of the people still live in rural areas employed in subsistence agriculture and cattle breeding. Because of that, TPES is still dominated by Biomass with a minor contribution from Oil, used both for transport and electric generation in thermal plants, followed by renewables. About the electricity generation (by source), Hydro gave historically an important contribution, with trends reflecting the variable climatic conditions in different years. Since about 1996 Oil was increasingly used to generate electricity, but its use is declining since about 2009. Generation from geothermal resources had a first important increment in 2003 and a remarkable increment in 2013, to become in 2017 the primary source for electric generation in Kenya. The access rate to electricity reached a remarkable 63.8% in 2017. The interconnected installed capacity in 2018 was 2,997 MW, out of which geothermal contributed for about 865 MW, Hydro for 837 MW, thermal for 807 MW, Solar for 92.5 MW and Wind for 336 MW. Additionally, Kenya has an off-grid installed capacity amounting to 31.1 MW comprising thermal at 26.3 MW, Wind at 0.55 MW, Solar at 0.64 MW and geothermal at 3.6 MW (Mangi, 2018).

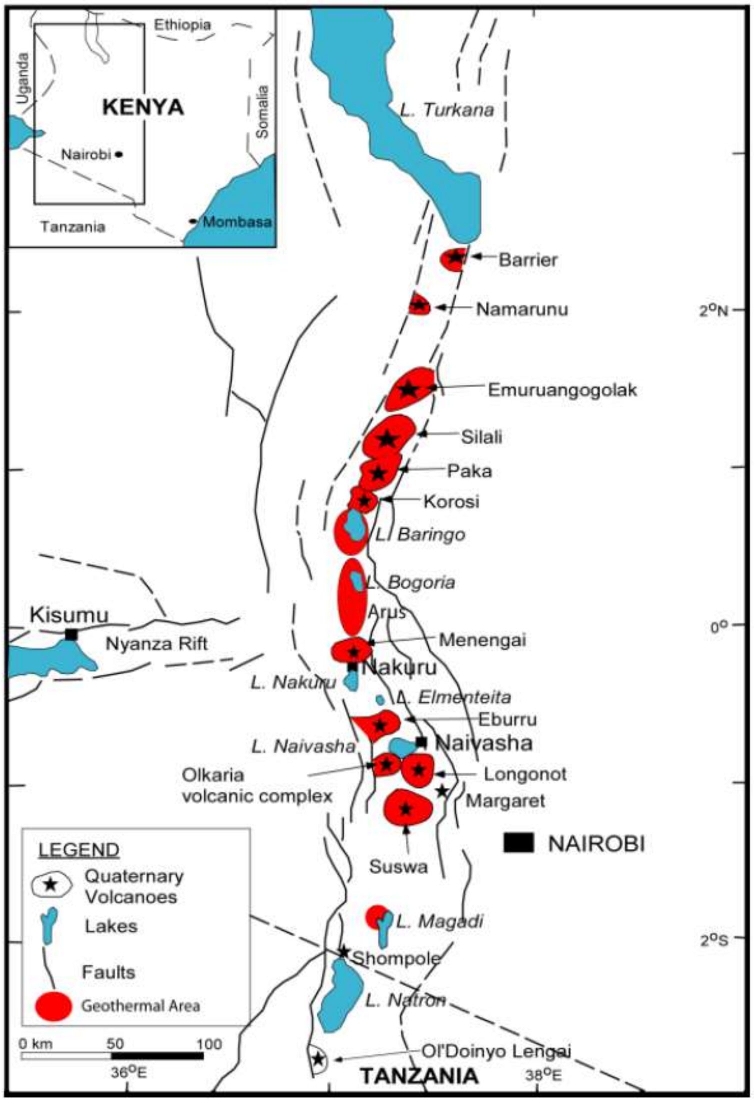


Figure 19. Location map of geothermal areas in Kenya (Omenda et al., 2020).

Kenya is the leading country in Africa in terms of geothermal power generation and 9th in global ranking of geothermal producing countries (Omenda et al., 2020), with an estimated potential of up to 10,000 MW (Omenda, 2018b). The installed geothermal capacity in 2019 comprises 706.8 MW by KenGen, 155 MW by OrPower 4 Inc. and 3.6 MW by Oserian Development Company Ltd. (Omenda et al., 2020). Olkaria geothermal field is so far the largest producing site with current installed capacity of 689.7 MW, while Eburru field has an installed capacity of 2.52 MW. Installed capacity for direct utilization of geothermal energy is about 18.5 MW. The existing plants and those under construction or planned, for a total power of 328 MW, at Olkaria, Eburru and Menengai are listed in Table 5.

Table 5. Power plants at Greater Olkaria, Eburru and Menengai fields as of December 31, 2019 (in operation, construction or planned) (Omenda et al., 2020).

Locality	Plant name	Year Commissioned	N. of units	Status	Type of unit	Cpacity MW
Olkaria	Okaria I Unit 1	1981	1	Operating	SF	15
Olkaria	Okaria I Unit 2	1982	1	Operating	SF	15
Olkaria	Okaria I Unit 3	1985	1	Operating	SF	15
Olkaria	Olkaria II Unit 1&2	2003	2	Operating	SF	70
Olkaria	Olkaria II Unit 3	2010	1	Operating	SF	35
Eburru	Eburru	2010	1	Operating	ORC	2.52
Oserian	Oserian	2004 & 2006	2	Operating	ORC	3.6
Olkaria	Olkaria Wellhead	2013	1	Operating	SF	5
Olkaria	Olkaria Wellheads	2014	4	Operating	SF	12.8
Olkaria	OrPower 4 Unit I	2000	4	Operating	ORC	52.8
Olkaria	OrPower 4 Unit II	2008	4	Operating	ORC	39.6
Olkaria	OrPower 4 Unit III	2014	1	Operating	ORC	17.6
Olkaria	Olkaria IV Unit 1	2014	1	Operating	SF	75
Olkaria	Olkaria IV Unit 2	2014	1	Operating	SF	75
Olkaria	Olkaria I Unit 4	2014	1	Operating	SF	75
Olkaria	Olkaria Wellheads	2014	6	Operating	SF	32.8
Olkaria	Olkaria wellheads	2014	5	Operating	SF	30.5
Olkaria	Olkaria I Unit 5	2014	1	Operating	SF	75
Olkaria	OrPower 4	2015-18		Operating	ORC	45
Olkaria	Olkaria V	2019	2	Operating	SF	173.2
Olkaria	Olkaria I Unit 6	2020	2	Construction	SF	83.3
Olkaria	Olkaria PPP	2022	2	Planned	SF	140
Menengai	Menengai	2021	3	Construction	SF	105
Total			47			1,193

SF = Single Flash. ORC = Organic Rankine Cycle.

The Greater Olkaria geothermal field, where the first well was drilled in 1973 and power generation began in 1981, has been developed by KenGen (and its predecessor), which since 1998 has the mandate to undertake grid electricity generation functions now accomplished with the operation of Hydro, geothermal, thermal, Solar and Wind power plants. KenGen drilled over 300 wells in Olkaria using both international drilling contractors as well as its own drilling rigs operated by KenGen personnel. In addition, KenGen is capable to provide with its personnel all specialized services related to drilling including mud engineering, cementing engineering, aerated drilling, directional drilling, geological site assistance, well logging and testing. After the power sector reforms of 1996, geothermal exploration and generation was opened to private operators. ORMAT international was licensed by the Gov. of Kenya to explore and generate power from the Olkaria South-West field in 1997.

GDC, the other public company in charge of geothermal development, has developed the Menengai caldera field with 3 power plants of 35 MW each under construction by different IPPs. GDC has also started exploration surveys at Suswa (Haizlip et al., 2020), Korosi, and Baringo-Silali-Paka (Lichoro, 2020) prospects, with exploration drilling already performed at Paka.

Having recognized the potential role that could be played by private investors, the Gov. of Kenya has so far licensed 13 IPPs to undertake greenfield projects at Barrier (http://www.olsuswaenergy.com), Longonot (Alexander and Ussher, 2011), Akiira (http://www.akiiraone.com/), Elementaita, Homa Hills (http://capitalpower.co.ke/), Menengai North, Lake Magadi, Arus (http://arusenergy.com/), Lake Baringo, Emuruangogolak, Namarunu, and Emuruapoli prospects (Omenda et al., 2020). According to licensing conditions, the IPPs are required to drill exploration wells within three years of license issuance. The Gov. of Kenya is continuing with its ambitious plan to increase the geothermal installed capacity to 5,000 MW by year 2030.

The institutional setup on Kenya energy sector, with specific reference to the geothermal energy sector, is summarized in Figure 20 (Omenda et al., 2020). The geothermal steam development is mainly devoted to GDC which shall deliver the produced steam to KenGen (as in Olkaria) or to IPPs, as is the case of the Menengai caldera field development. Actually, licenses for field exploration and development have been already assigned to private operators, such as Olsuswa Energy Ltd, Africa Geothermal International Ltd, Capital Power Ltd, Arus Energy Ltd and Akiira Geothermal Ltd. In the developed Kenyan geothermal energy sector Public Private Partnerships (PPP) models have become increasingly important drivers of promoting renewable energy growth over the last decade with Gov. of Kenya facing increasingly constraint budgets (Kiptanui and Kipyiego, 2020). These PPP models are now gaining traction in Kenya's geothermal resource development with geothermal projects of over 2,000 MW already approved for implementation and with 245 MW at advanced stages of implementation by GDC and KenGen, which intend to sell the steam under PPP steam supply contracts, a separate business from steam conversion to electricity.

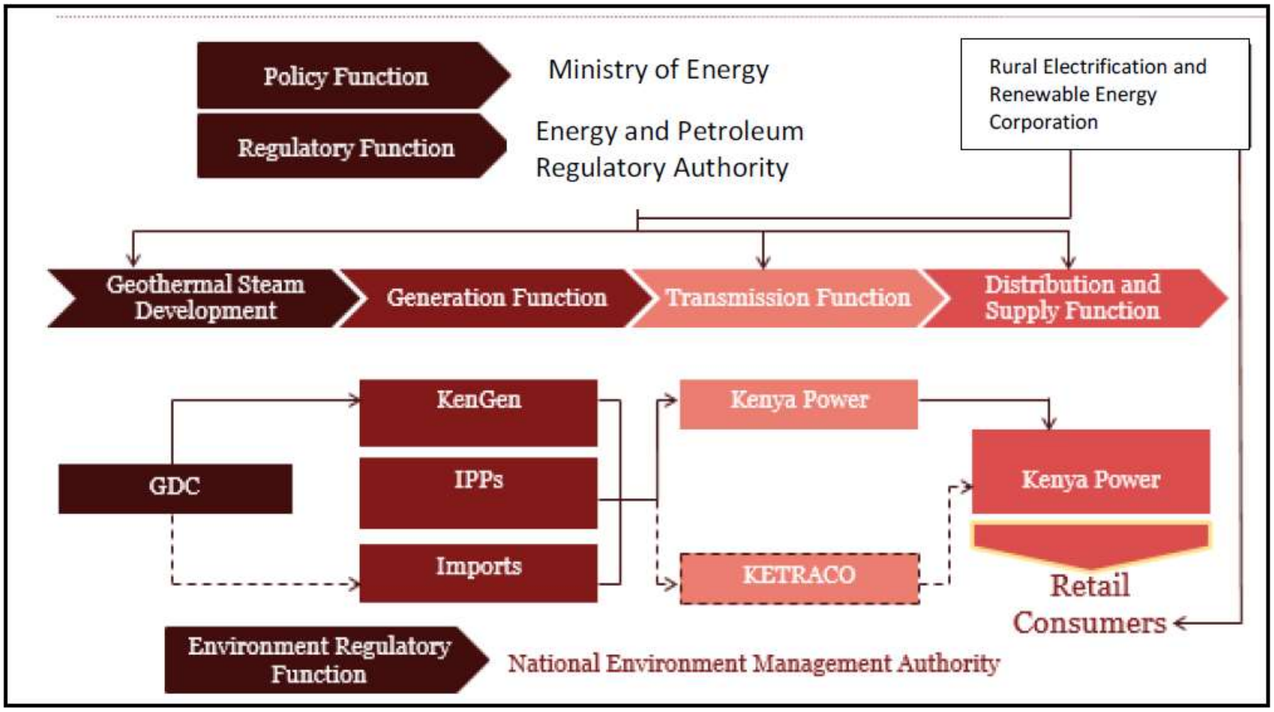


Figure 20. Kenya Energy sector Institutional setup, with specific reference to the geothermal sector (Omenda et al., 2020).

The PPP Act No.15 of 2013 recognizes various schemes with variable involvement and assumption of risks by the private sector. Ten geothermal power projects with a cumulative capacity of 2,455 MW have been approved under the PPP Act and are at various stages of development as shown in Table 6.

Table 6. PPP approved geothermal projects (Source: PPP Unit website) (Kiptanui and Kipyiego, 2020).

No.	Project	Contracting Authority	Project Cost (M $)	PPP Model & duration	Status
1	50 MW Olkaria Wellheads Geothermal Project	KenGen	-	Built, lease, operate & maintain	Operational
2	35 MW Sosian Menengai Geothermal Power Plant Project	GDC	79.15	BOO (25 y)	Commercial/Financial close
3	35 MW Quantum Menengai Geothermal Power Plant Project		79.15	BOO (25 y)	Commercial/Financial close
4	35 MW OrPower Menengai Geothermal Power Plant Project		82.00	BOO (25 y)	Commercial/Financial close
5	140 MW Olkaria Geothermal PPP Project – Phase 1	Kengen	2,000	BOOT (25 y)	Procurement
6	420 MW Olkaria Geothermal PPP Project – Phase 1			TBD	Proposal stage
7	280 MW Olkaria VII & VIII		-	TBD	Drilling stage
8	360 MW Menengai Phase 2	GDC	-	TBD	Drilling stage
9	800 MW Baringo-Silali Phase 2		-	TBD	Drilling stage
10	300 MW Suswa Geothermal Plant		-	TBD	Preliminary stages

BOO= Build-Own-Operate. BOOT: Build-Own-Operate-Transfer. TBD: To be determined.

Kenya is therefore the leading country in Africa as far as the development and exploitation of geothermal resources is concerned. The development of the Greater Olkaria Field is a success story witnessing the capabilities acquired by KenGen in all the different phases of resource development, from surface exploration and deep drilling to plant construction and field exploitation. Such capabilities are now used by KenGen to provide technical services to other operators inside and outside Kenya such as exploration surveys performed in Bayuda (Sudan), Karisimbi (Rwanda), Kapisya and Chinyunyu (Zambia), and those performed in Comoros, Uganda, and Djibouti, and drilling operations conducted at Akiira field (Kenya) and Tulu Moye field (Ethiopia).
GDC also developed in over 10 years of activity strong experiences and capabilities in surface exploration and well drilling, in particular at the Menengai caldera field, with on-going and future drilling projects at Paka, Suswa, Korosi and Silali. GDC too is providing exploration services outside Kenya in other East Africa countries and is starting to bid for geothermal drilling projects outside Kenya.

The geothermal market in Kenya is the most developed, with a clear institutional set-up allowing the active participation of both public and private operators with provisions for public-private collaborations with different PPP models. Concessions have been assigned to several Kenyan and international operators with already planned developments in the order of more than 2,000 MW to be installed. The Kenyan success story is for sure an example for all the other East Africa countries willing to utilize their geothermal resources.

4.5 Tanzania

Tanzania (The United Republic of Tanzania) is interested by the south end of the Eastern Branch and by the Western Branch of EARS. TPES by source is dominated by Biomass (wood and charcoal), used for basic cooking and heating of the 66% of people still living in rural areas mainly employed in agriculture, followed by Oil (all imported) and since 2005 natural gas. (about 50% produced in Tanzania). Hydro power generation represents an important fraction of about 30% while the remaining is supplied by Oil (about 18%, all imported) and mostly by natural gas (about 52%, produced from national gas reserves). Hydro generation is subject to strong variations depending on drought periods, which are compensated since year 2005 by generation with O&G. Access to electricity was 32.8% in 2017. As of May 2019 (Kajugus et al., 2020), the total installed generation capacity was 1,601.9 MW, of which 36.2 MW off-grid. Hydropower accounted for 573.7 MW (36.6%), natural gas power plants for 892.7 MW (57.2%), liquid fuel power for 88.8 MW (5.7%), and biomass for 10.5 MW (0.6%). Currently, there is no contribution from geothermal generation, however, geothermal energy is expected to contribute, as a short-term target, 200 MW to the ambitious national grid electricity target of 10,000 MW by 2025 (Kajugus et al., 2020).

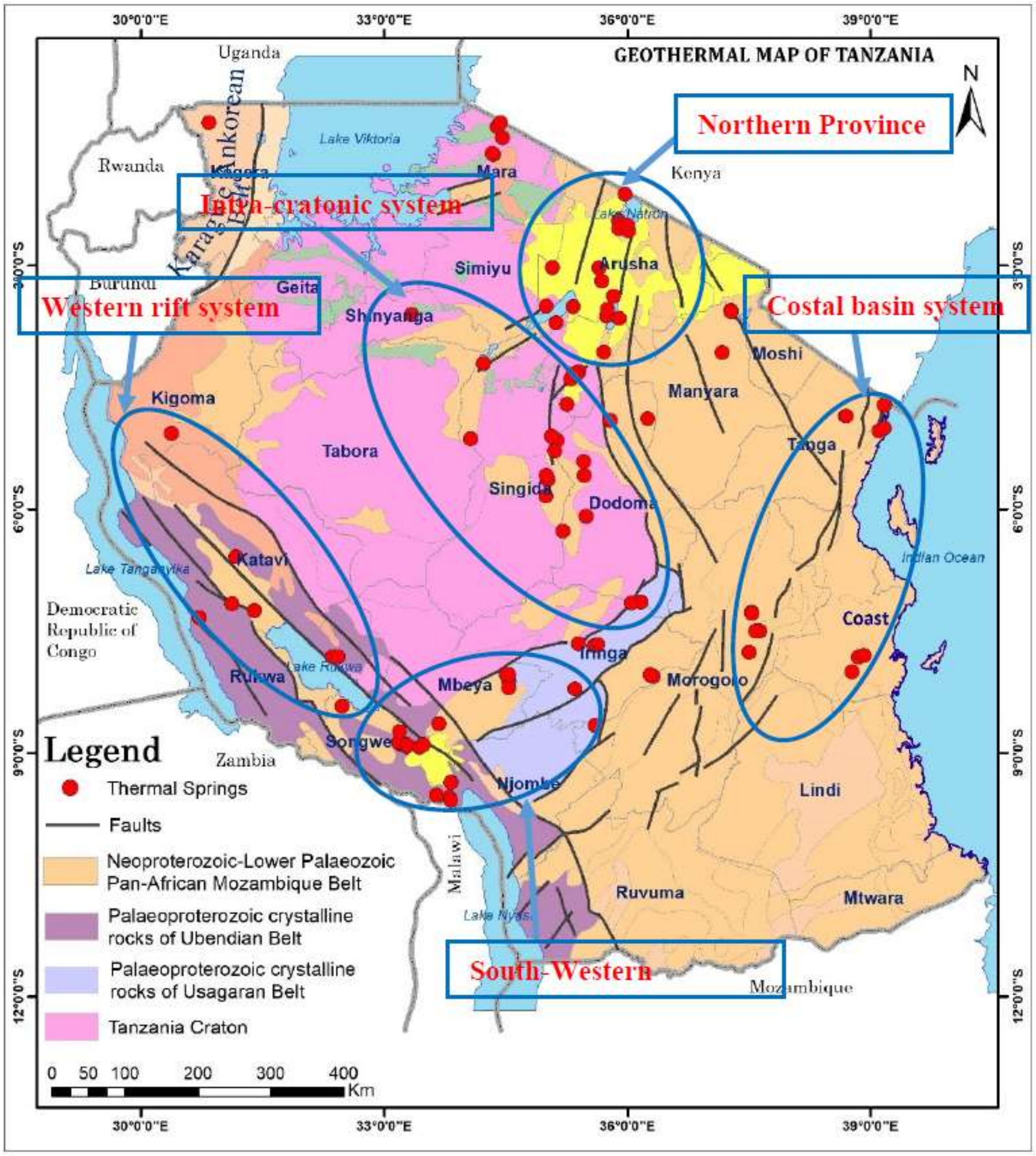


Figure 21. Simplified geological map of Tanzania with geothermal regions and location of major thermal springs (Kajugus et al., 2020).

Geothermal potential of Tanzania has been estimated, from surface exploration data only, up to 5,000 MW by Kajugus et al. (2020) and, more realistically, at over 500 MW by Omenda (2018b). The Gov of Tanzania has set up short and long-term targets that has to be attained in 5 and 25 years respectively. The former, entrusted to TGDC, is to add 200 MW capacity from geothermal resources by 2025. In order to accomplish the above target, TGDC is implementing 4 flagship projects, namely: Ngozi, Songwe, Kiejo-Mbaka and Luhoi.

Ngozi prospect is located in SW Tanzania within the Rungwe Volcanic Province, at rift intersection of the Western and Eastern Branches of the EARS (Kajugus et al., 2020). Surface exploration studies, the las concluded in 2016, suggested that an inferred liquid dominated geothermal reservoir is located beneath Ngozi crater, with an estimated temperature of about 230°C and an estimated potential of 30 MW (Alexander et al., 2016b). The study indicated 5 possible well locations, 3 of which were chosen for an exploratory drilling project partially financed by a grant from GRMF. The project was stopped in early 2019 during the planning phase.

Kiejo-Mbaka prospect is located in the Southern part of the Rungwe Volcanic Province (Kajugus et al., 2020). Surface exploration performed concluded that Kiejo-Mbaka is a medium temperature geothermal system with estimated reservoir temperature around 140°C (ELC-Electroconsult, 2017a). TGDC planned to drill 3 slim holes and 1 full size well. GRMF grant support under the 5th Application Round has been awarded to the project which will be co-financed by the Gov. of Tanzania.

Songwe prospect is located just North West of Ngozi prospect. Exploration studies performed concluded that the prospect occupies a pull-apart basin along a strike-slip fault system with reservoir temperature in the order of 110°C (Heat et al., 2018; EAGER, 2018; Hinz et al., 2018). On the basis of a pre-feasibility study for direct uses applications, TGDC concluded that direct uses of geothermal energy for agri-processing and touristic exploitation were the most suited utilisation of Songwe prospect.

Luhoi prospect is located within the Coastal basin system, about 150 km from Dar es Salaam (Kajugus et al., 2020). A detailed surface study conducted by ELC-Electroconsult (2017a) indicates that Luhoi prospect hosts a medium temperature geothermal system (95-145°C), suitable for direct uses and/or power generation using ORC plants. TGDC secured also a grant from the 5th Application Round of GRMF for a surface exploration study at Natron prospect located in the Northern Province.

Thus, 3 of the 4 flagship prospects, namely Kiejo-Mbaka, Songwe and Luhoi, are inferred to host geothermal reservoirs with low to medium temperatures for which a limited potential can be reasonably exploited using ORC plants. Ngozi, the most promising prospect hosted in a volcanic environment, is still at the stage of exploratory drilling and testing. All that considered, it seems reasonable to conclude that the fulfilment of the short-term target of 200 MW to be installed before 2025 will be hardly accomplished.

5. DISCUSSION

You have no Discussion section, this is necessary, what are the contrasts/lessons learned from the work, what are your opinions. Some of the narrative in the Conclusion could be inserted in the Discussion,
I recommend that you provide a few sentences on the limitations of the work in the discussion section and point out or list future work required,

Eritrea has basically a single explored site, Alid volcanic complex, with reported potential of 70-100 MW. Despite the acquired knowledge is still insufficient to target exploration wells, further activities aimed at completing the surface exploration and target exploratory drillings seem worth to be performed, as the installation of a 50 MW geothermal plant in Eritrea would already cover most of its national base load.

Surface and drilling exploration in Djibouti dates back to late ‘70s, with several prospects recently explored with surface surveys and new exploratory wells drilled in 2 prospects within the Asal rift area at Gale le Koma and Fialé caldera. The latter found high temperatures and apparently limited well deliverability, subject to confirmation by a well testing program. In Djibouti too the installation of a geothermal power plant of some 50 MW would cover most if its electric network base load, consistently reducing the use of imported oil. ODDEG is the public institute in charge of surface exploration and field development which is managing all the initiatives under way focusing all the national efforts and international contributions.

Ethiopia has a large inferred potential in the order of 10,000 MW, but despite exploration activities started in the ‘70s and exploration drilling performed since mid ‘80s, only a 7.5 MW power plant was installed at Aluto caldera, now not in operations. Licenses assigned to private operators since 2009 have led only to surface exploration activities, with the performance of more expensive exploratory drillings hindered by a not clear regulation framework. The situation has recently changed thanks to a new geothermal proclamation and regulations issued in 2016 and 2019, respectively. This facilitated the signing of new PPA and IA for the Tulu Moye and Corbetti caldera in march 2020, with drilling activities started in Tulu Moye. Other operators, most of which have obtained grants from the GRMF for both surface surveys and exploratory drillings, will likely go on on the other 6 already licensed prospects. EPP, the public electric utility in Ethiopia, is the operator for the Aluto Langano field development project aimed at providing the steam for a new power plant. Within the same project, funded by the World Bank, EEP is purchasing 2 complete drilling rigs which are planned to be used for future drilling exploration activities after the completion of Aluto field development. Geothermal development in Ethiopia will face the competition with cheaper renewables, such as the huge hydropower resources presently developed by EEP and the large estimated solar and wind resources.

Kenya is the leading country as far as the geothermal development in East Africa. It’s a success story characterized by the development of the great Olkaria geothermal field by a public electric utility, KenGen, now able to explore, drill and operate the field and the power plants with its own personnel, equipment and facilities. GDC has been entrusted by the Gov. of Kenya of the development of national resources by performing surface surveys and prospect development to eventually select IPP for the construction and operation of the power plants. Following this approach, GDC is going to complete the development of Menengai field with 3x35 MW power plants, while is actively exploring other interesting prospects. Opening to private operators and to PPP models, allowed a faster development of the Great Olkaria field where the private operator OrPower 4 is already approved PPP projects for ready generating 155 MW. Other operators are actively exploring other prospects along the Rift Valley, with more than 2,000 MW planned. Kenyan experience is taken as a successful example of geothermal industry, with both KenGen and GDC providing consultancies and services to neighboring countries. Kenya has been also chosen as the location of the Africa geothermal Centre of Excellence operated by GDC in collaboration with KenGen.

Tanzania has deployed several efforts in last years both with the creation in 2011 of TGDC, the state-owned company with the main mission to develop the national geothermal sector, as well as on the exploration of the most promising prospects. Despite these efforts, fueled by large inferred potential estimates of some 5,000 MW, results so far acquired on 3 out of 4 flagship prospects indicate mostly low to medium temperature reservoirs of limited potential which can be exploited using ORC plants. These results obtained in prospects located on the Western Branch of EARS, in some way similar to those obtained in other countries crossed by the Western Branch, are linked to the different geological and vulcanological features which allows the evolution of medium temperature fault controlled geothermal systems rather than volcanic hosted high temperature systems preferentially found in the Eastern Branch. The potential has been recently conservatively estimated in 500 MW. When compared to the planned electric power development in Tanzania, it is clear that geothermal energy will play a minor role in the future energy mix, unless additional exploration activities will identify new promising prospects.

6. CONCLUSIONS

The conclusion typically summarises the paper and also identifies/provide guidance/lessons learned/ knowledge gaps and advice for stakeholders, industry and also research gaps.

A review of the status of geothermal industry in 11 East African countries crossed by the EARS has been conducted in the framework of the project “The African Networks of Centres of Excellence on Water Sciences PHASE II” implemented by JRC in partnership with UNESCO. The review has been based on public available documents and news and was focused on geothermal resource development for electric power generation. The peculiar characteristics of geothermal energy and the obstacles to their wider use has been analyzed in the contest of the conditions of East Africa, while the analysis of the country status was here limited to 5 countries crossed by the Eastern Branch of EARS, namely Eritrea, Djibouti, Ethiopia, Kenya and Tanzania, where approximately 95% of the EARS estimated geothermal potential, amounting to some 21,600 MW, is concentrated. In addition, some 20,000 MW are inferred to be located in Ethiopia and Kenya. Despite that, until know only Kenya was able to develop a fraction of its resources by installing 865 MW by the end of 2019. The reasons for such a delay after decades of surface exploration are known, being related to: the high costs of exploration drilling with associated mining risks which are difficult to be afforded by financing institutions; the lack of professionals and expertise necessary for project planning, execution and management; the lack of a coherent legislative and regulation framework for geothermal operations; the competition with other renewables, such as solar PV and hydro, not affected by mining risks and characterized by lower LCOE. Both national governments and international stakeholders are actively working to overcome the above obstacles.

In conclusion, thanks to the efforts of both national governments and international stakeholders, the geothermal energy in Eastern Branch countries of EARS seems to be at a turning point in particular in Ethiopia and Djibouti, with Kenya going on in an accelerated way along an already established successful path.

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