



Heat flow estimation and quantification of geothermal reservoir of a basement terrain using geophysical and numerical techniques

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Abstract

The occurrence and manifestation of warm and hot springs gives a hint to the availability and abundance of geothermal resources in Nigeria. So for the first time we estimated and quantify the geothermal energy resource potentials in Ikogosi Warm Spring area (IKGWS) and environs using geophysical and Numerical methods. The results from heat flow computation from aeromagnetic investigations and volumetric estimation confirmed there are zones in the IKGWS with anomalous heat flow and great prospects of geothermal energy for direct and indirect applications. The heat flow estimated for the IKGWS and environs ranged from 75 to 127 mW/m² with an average value of 100 mW/m² while temperature gradient varied from 28 to 48 °C/Km with a mean value of 38 °C/Km. Also the Curie point depth (CPD) estimated ranged from 12 to 21 km with a mean value of 16 km. The power output of 2 MWe can be produced with 90% confidence and production greater than or equal to 3.7 MW with 5% confidence. The IKGWS isolated will produce 0.9 MWe if the recoverable heat is used for 25 years. The outcomes implied that IKGWS can primarily sustain a 0.9 MW power plant for a period of 25 years and likely extension will be subjected to further well-defined drilling and site data performance availability. The simulation results show that an estimated stored heat in-place of 0.65–1.95 × 10¹⁰ J can be expected from the inferred resource areas at 90% probability. This figure is equivalent to electric power generation potential of 3.2–9.6 MWe or annual electricity generation of 25–76 GWh at the same probability rate. Therefore Nigeria may appear on the global geothermal map by generating power and direct utilization of geothermal energy in IKGWS.

Keywords Ikogosi Warm Spring · Geothermal energy · Curie point depth · Quantification · Temperature gradient · Heat flow

Abbreviations

TG	Temp. Grad.
HF	Heat flow
IRT	Inferred resource thickness
RMT	Resource mean temp.
RSA	Resource surface area
RD	Rock density
RSHC	Rock specific heat capacity
UMS	Undifferentiated meta-sediments
UBC	Undifferentiated basement complex

Introduction

As Nigeria's population and industry grow, the energy demand will increase. Nigeria currently has an installed electricity generation capacity of less than 10,000 megawatts (MW) of FMPWH (2018), and peak demand is expected to rise 2.0% per annum over the coming decade, based on the medium economic outlook. To meet future base-load electricity demand, there is a need for new energy sources (NERC 2014).

However, the environmental impact of any new energy source must be considered; thus, a low emissions alternative to fossil fuels would be advantageous. Geothermal energy is a renewable energy which can generate power and as such has been identified as a potential future low emission energy resource. This is potentially a vast source of thermal energy that can be tapped by Engineered Geothermal System technology for power generation purposes (WEC 2014).

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Similarly an essential factor in a geothermal evaluation is the volume and size of the geothermal system. The volumetric approach is applied by assuming a box with volume and surface area A in a plane with thickness then the approximation of the operational or useable heat from the system will be gotten prior to volume evaluation of the system. For ease, temperature and heat capacity are uniform in the plane and dependent on thickness. There are no recorded studies to quantify the geothermal energy of the SW basement terrain but subsurface structural imaging within this region have been examined to give the structural settings of the subsurface and estimate its prospect for more energy utilization (Abraham et al. 2014; Lateef et al. 2019).

Globally, several researches toward this area is growing rapidly with research being carried out with respect to geothermal exploration, influence of fractures and faults on geothermal fluids, process, applications of geophysical systems for geothermal investigation (Ikeagwuani et al. 2015; Ragnarsson 2005; Ingebritsen et al. 2010; Lopez et al. 2010; Coumou 2008). In addition, the exploration and development of this geothermal area is continuing and much new data and technical evaluation are forthcoming (Kurowska and Schoeneich 2010).

The upward movement of fluid in permeable layers can produce high temperature that can be used for geothermal energy. This movement of fluid upward is critical in the exploration of geothermal energy and it is a better target for exploitation of geothermal energy. This is dependent on current geothermal gradient, thickness, permeability and transfer of heat between fluids in permeable layers and neighboring rock (Pasquale et al. 2013; Tournier et al. 2000; Murphy 1979).

Also temperature dataset analyses in Europe, America and even Africa have shown substantial geothermal irregularities situated in geothermal systems of sediment and layered basins which are consequences of convection of thermal fluid which have been connected to convective fluid flow (Garibaldi et al. 2010; Bonté et al. 2012; Pasquale et al. 2013; Guillou-Frottier et al. 2013; Ofor and Udensi 2014; UNFCCC 2012).

Different researches have demonstrated that thermal variances in sedimentary basins are intensely affected by fluid flow in porous medium and most of the investigations combined mathematical tools to link geological settings of the subsurface, deep temperatures and flow of fluid (Baillieux et al. 2013; Guillou-Frottier et al. 2013; Pasquale et al. 2013).

There has been new research interest in deeper formations in Nigeria which had led to the boring of several wells by oil and gas firms. However this is not always for research purposes but solely for oil exploration. Also from literatures there have been no recent works on the distribution of temperature in the subsurface that can reveal a thermal anomaly

even at 1 km depth in Nigeria except the deep wells in the Niger Delta region which could be described by thermal convection (Anomohanran 2004; Onuoha and Ekine 2009; Odumodu and Mode 2016; Emujakporue and Ekine 2014; Omokenu and Nwosu 2016; Anakwuba et al. 2016).

For the first time, this study attempted to quantify the heat flow and geothermal energy potential of a southwestern basement terrain using geophysical and numerical method and apply specific site values of rock, fluid properties and constants in the area of study by using a Python program for calculating possible by geothermal energy by applying volumetric technique in an aquifer reservoir.

Geology of Southwest Nigeria

The geology of southwestern part of Nigeria is of Precambrian basement rocks which are majorly made up of migmatite–gneissic, quartzite complex and from Archean to the early Proterozoic age (Oyinloye 2011; Adegbuyi et al. 1996; Adegbuyi and Abimbola 1997; Abraham et al. 2014). The Ikogosi area is underlain by south-western Nigeria's basement complex rocks. The basement complex is in places intruded and interspersed older granites which originated in the Pan-African orogeny. Basement complex rocks in Nigeria have been subjected to deformation of different intensities throughout the geological period. Consequently, fractures have developed. The warm spring issues near the foot of the eastern slope of the north–south trending ridge from a thin quartzite unit within a belt of quartzite which includes quartz-mica schist and granulitic migmatite east of Ilesha (Fig. 1). The issue of the springs is controlled by permeability developed within the quartzite as a result of intergranular pore spaces coupled with fracturing of the relatively competent quartzite (Rogers et al. 1969).

The study area is underlain by a group of slightly migmatized to non-migmatized para-schists and meta-igneous rocks. This group contains rocks which have been previously described as being younger or newer metasediments like the Effon Psammite formation and the associated epidiorite schist and amphibolite complex. The Effon Psammite formation (Caby and Boesse 2001) comprises quartzites, quartz schists and granulites which occur largely east of Ilesha and run for nearly 180 km in a NNE-SSW direction. There are three varieties of quartzite in the study area. These include massive quartzite, fissile quartzite and mica schist/quartz schist (Fig. 1).

Geological features such as faults and shear zones are concealed; however, fractures can be identified on a few outcrops along river valleys and on hill tops/slopes. The Southwestern region of Nigeria is one of the regions with presence of warm springs and the Ikogosi warm spring is the center point. There are research that have claimed that the IKGWS area is a prospect for geothermal energy exploration

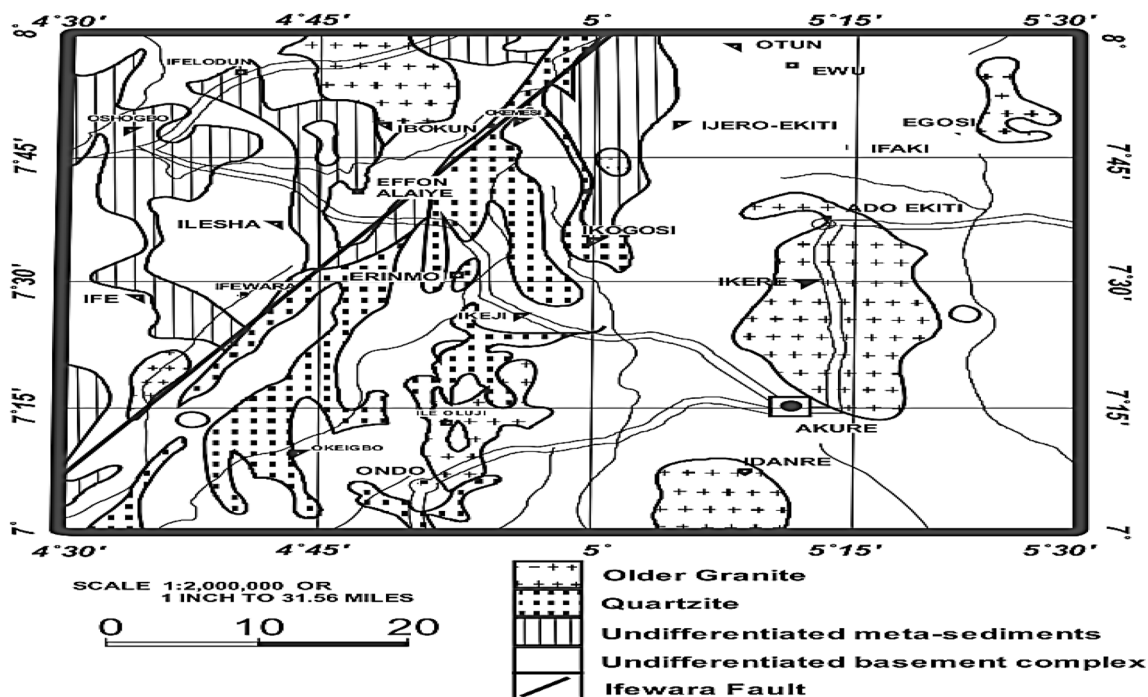


Fig. 1 Simplified Geological Map of IKGWS and environs (after Abraham et al. 2014)

founded on the tectonic lineaments of the IKGWS area but none have been able to quantify or classify and scale the geothermal prospect of the IKGWS area. The study area consists of rugged terrain with undulating hills and thick vegetation. The topographical elevation determined from topographic map varies from less than 473 m in the valleys to 549 m on the hills.

Methods

Air borne magnetic data acquisition and heat flow estimates

Four map sheets (Ilesa, Akure, Ado-Ekiti and Ile-Ife) of Aeromagnetic survey data was gotten from the Nigeria Geological Survey Agency (NGSA) on a map scale of 1:100,000 series. The data were merged and processed to a single dataset and gridded at 0.5 km which is transformed to a total field anomaly dataset. The magnetic field analysis used reduced to the pole data (RTP) and this RTP correction applied assumed a declination of -3° and an inclination of -10° for the region (southwestern Nigeria). The maps had the regional geomagnetic field and the effects of diurnal magnetic variations removed.

The Spectral Analysis Techniques (SAT) was applied to evaluate the Curie point depth (CPD) around Ilogosi area and environs within the southwest region. The SAT techniques

converted the spatial data into the frequency data domain using Forward Filtering Transform (FFT) filters and it also relates the depth to the top and bottom of the magnetic sources by the Eq. 1:

$$K_{max} = \frac{\log Z_b - \log Z_t}{Z_b - Z_t}, \tag{1}$$

where Z_t is the depth to top of the magnetic sources; Z_b (CPD) is the depth to bottom of the magnetic sources; K is the function of wave number expressed in radians per unit distance.

The main power spectrum was gotten by plotting a log of square root of power per absolute wave number versus absolute wave number. These parameters are linked by Eq. 2:

$$\ln \frac{\sqrt{P}}{|S|} = \ln A - (2\pi Z_o) |S|. \tag{2}$$

And in basic form of Eq. 3:

$$\ln Q = \ln A - (2\pi Z_o) X, \tag{3}$$

where, $Q = \frac{\sqrt{P}}{|S|}$; P is the power spectra of the anomaly; $X = |S|$ is the absolute wave number; A is the a constant.

Later a relationship between average power spectrum of the magnetic anomalies and depths to the corresponding sources is done as shown in Table 2.

The depth to the centroid Z_0 of the magnetic source was determined from the slope of the longest wavelength part of the power spectrum. A different power spectrum of logarithm of square root of power versus the wave number was plotted for the same profile (block). This is applied to all the twenty blocks and the variables for the spectrum are related by Eq. 4:

$$\ln \sqrt{P} = \ln B - (2\pi Z_0)X. \quad (4)$$

And in basic form gives Eq. 5:

$$\ln R = \ln B - (2\pi Z_t)X. \quad (5)$$

where B is the sum of constants independent of the wave number X .

Similarly the depth to the top of the magnetic sources boundary Z_t was obtained from the slope of the second longest wavelength of the spectral segment of the second spectrum. The basal depth Z_b which was assumed to be the Curie point depth was estimated for each profile (block) from Eq. 6:

$$Z_b = 2Z_0 - Z_t. \quad (6)$$

Therefore, the CPD obtained was used to calculate temperature gradients for each profile (block) by the supposition that rocks are dominated by magnetite and using the average thermal conductivity (TC) of 2.5 mWK^{-1} for igneous rock and a Curie temperature value of $580 \text{ }^\circ\text{C}$ (Tanaka et al. 1999). Consequently by dividing the temperature by depths, the estimated vertical temperature gradients along each block (profiles) with the average vertical temperature gradient for the whole area to be $37.69 \text{ }^\circ\text{C/km}$ and the results presented in Table 2. The radial power spectrum plot was generated from the transformed airborne magnetic data using Oasis Montag software which automatically calculates the depth corresponding to the power spectrum. The wave number value at maximum peak spectrum (due to deepest anomaly) K_{max} is usually determined on the generated log power spectrum. To get the value of the depth to the deepest anomaly, a least squared method is usually adopted to determine the slope at each peak of the log spectrum. The values of heat flow were determined using the thermal conductivity (TC) of rocks relating to the lithology of the region as expressed earlier (2.5 mWK^{-1}) by using Fourier's equation given in Eq. 7:

$$\text{Heat flow, } q = k \frac{dT}{dz}. \quad (7)$$

where: q is the heat flow and k is the thermal conductivity coefficient.

The flow of heat from the earth's interior is an important factor to consider when studying geothermal energy so it is very difficult to measure geothermal heat flow directly especially at high depth and as such we often rely on indirect geophysical measurements (computational, simulations

and modeling approach) to estimate heat flow on continental scale. There are some indirect methods by which heat flow can be determined when no borehole is available, such as from aeromagnetic data which is been done in this work which can also give a clearer position on geothermal energy exploration research in Nigeria.

An example of direct method is the Bottom hole temperature (BHT) technique though not applied in this work. In order to achieve the aim of this work, potential targets were identified based on the current understanding of the subsurface imaging and characteristics of the geothermal field of the region of study.

Thermal energy calculation

The Eqs. (8)–(13) applied for estimating the geothermal energy for a liquid-controlled reservoir is given below from Taylor and Glasstone (1942), Bridgman (1914), Beardsmore and Cull (2001) and Talebi et al. (2010, 2015):

$$Q_t = Q_r + Q_w \quad (8)$$

$$Q_r = Ah \times (\rho_r C_r \times (1 - \emptyset) \times (T_i - T_f)) \quad (9)$$

$$Q_w = Ah \times (\rho_w C_w \times \emptyset \times (T_i - T_f)), \quad (10)$$

where: Q_t is the thermal energy summation, kJ/kg; Q_r is the heat in the rock, kJ/kg; Q_w is the heat in water, kJ/kg; A is the reservoir area, m^2 ; h is the reservoir mean thickness, m; C_r is the specific heat of rock at reservoir conditions, kJ/kgK; C_w is the specific heat of water at reservoir conditions, kJ/kgK; \emptyset is the porosity; T_i is the reservoir mean temperature, $^\circ\text{C}$; T_f is the final temperature, $^\circ\text{C}$; ρ_r is the density of rock, kg/m^3 ; ρ_w is the water initial density, kg/m^3 .

These estimations are for the whole geothermal energy-in-place in the reservoir. To get the power that could be sustained by the reserve, these equations were further presented:

$$P = \frac{Q_t R_f C_e}{p_f t}, \quad (11)$$

where: P is the potential power (MWe), R_f is the recovery factor, C_e is the efficiency conversion, p_f is the plant factor; and t is the time in years (economic life), Q_t is the total thermal energy, kJ/kg.

For this research, the sampling is prepared over 10,000 iterations with uninterrupted calculation to get a good picture of the distribution. The input values are indicated in Table 1 for only Ikogosi warm spring area for the assessment of power energy generation by using volumetric method and Monte Carlo probabilistic analysis. The flow chart in Fig. 2 shows the process used for the numerical simulation. The algorithm used for the potential calculation of the

Table 1 Input file for the assessment of power energy generation by using volumetric method and Monte Carlo probabilistic analysis

Name place	Lat	Long	Reservoir properties	Symbol	Units	Min	Most likely	Max	Mean	SD	Distribution type
IKOGOSI	7.593	4.981	Reservoir area	A	km ²	6	8	10	0	0	T
			Thickness	h	m	1000	2000	3000	0	0	T
			Volume	v	km ³	6	16	30	0	0	None
			Reservoir temperature	Tr	°C	200	350	500	0	0	T
			Abandon temperature	Ta	°C	0	105.36	0	0	0	C
			Porosity	Phi	%	0	0.06	0	0.06	0.02	L
			Rock specific heat	Cr	kJ/kg-°C	0.85	0.85	0.9	0	0	T
			Water specific heat	Cf	kJ/kg-°C	0	4.16	0	0	0	C
			Rock density	rho_r	kg/m ³	2600	2500	2800	0	0	C
			Water density	rho_f	kg/m ³	0	1000	0	0	0	C
			Recovery factor	Rf	%	0.08	0.14	0.2	0	0	U
			Conversion efficiency	Ce	%	0	0.25	0	0	0	C
			Power factor	Pf	%	0.9	0.95	1	0	0	T
			Life span	t	years	10	25	35	0	0	C
			Rock thermal conductivity	λ	Wm ⁻¹ K ⁻¹	2.95	3.45	4.11		0.4	

geothermal energy using this model is given in Fig. 2. So the estimation of the reservoir power was done using a Python program that provides for a probabilistic approach of calculating uncertainty in the occurrence of events or unknown variables. In this study, to obtain a good representation of the distribution, sampling is done through 10,000 iterations with continuous calculation. This simulation was applied to get the recoverable heat for only Ikogosi area (Table 1) while the stored heat in-place and equivalent electric power was done for other areas within the region as shown in Table 2. This methodology of estimation of geothermal energy was used by some researchers for quantifying energy potential of the city of Queensland in Australia (Talebi et al. 2010, 2015).

Monte Carlo simulation (MCS)

The MCS is a tool for modeling possibility or improbability of a certain system and to test various outcome risks. In certainty, only one of the result options will play out in terms of possibility assessment. MCS helps drive the point that success and outcome is not the only measure of whether or not a choice was good. Due to limitations in data and large improbability connected with the expectations made, some cautions were taken into consideration in the estimates. This method accounts for a risk factor which can be computed with realistic calculation using the MCS. The dependability of the outcome from MCS depends on the volume, quality and kind of geophysical data which in turn is reliant on development of the target area. In general, the dependability rises as drilling is carried out in the target area until there is availability of in-situ measurements.

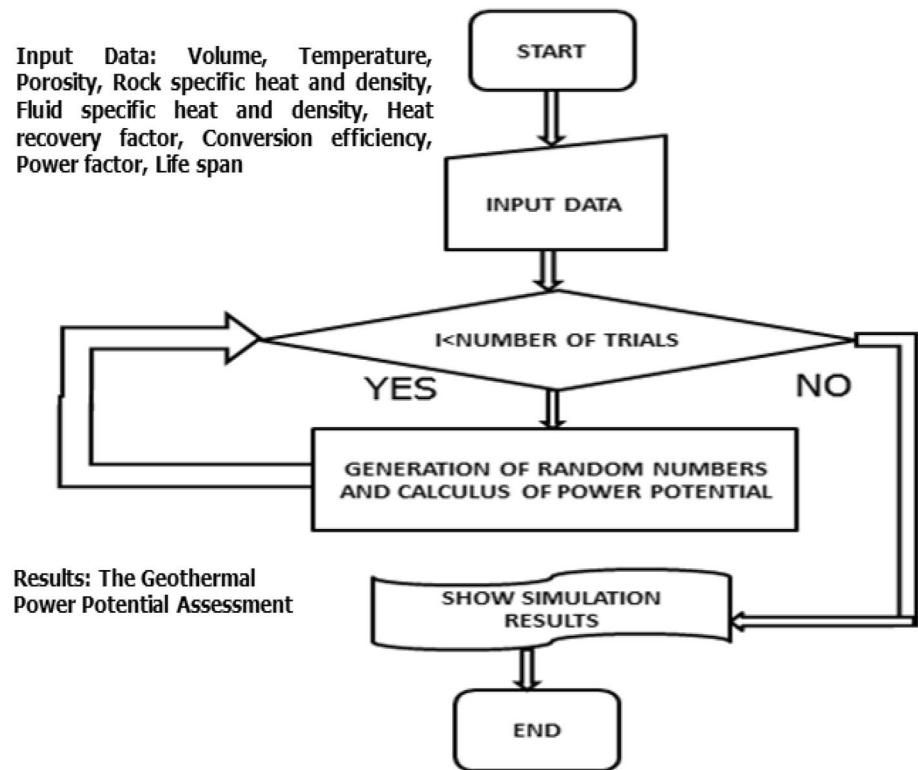
Heat flow modeling and temperature estimation to depth

Estimation of the temperature profile to 5 km is a very important factor in geothermal energy assessment of an area. This 5 km depth option is considered as a cut-off for commercialization and exploitation of geothermal energy (Chopra and Holgate 2005). In lieu of drilling and direct measurements in wells at depth, heat flow modeling provides a basis for reasonably accurate estimation of temperatures to depth. In a purely conductive heat regime, descending approximation and assessment of steady-state temperature to a depth z can be performed by:

$$T_z = T_o + q_o \int_0^z \frac{dz}{k_z}, \quad (12)$$

where: k_z is thermal conductivity of the interval, d_z is the interval thickness, q_o is the heat flow at the top of the interval T_o and T_z is the temperature at the top and bottom of the interval respectively. Equation (12) is an overview of a multifarious dynamic system and a first order calculation when there is no in-situ measurement at depth. These established thermal conductivity profiles and conductive modeled heat flow values were then used to estimate temperatures to 5 km using Eq. (12). The temperatures estimated at 5 km depth ranged between 110 and 250 °C. Based on the temperature estimations, the Ikogosi, Effon Alaye, Ikere, Ijero and Erinmo units were identified as high prospective units for geothermal energy which are towns within the region.

Fig. 2 Flow chart of reserves estimation for IKGWS area from simulation



Preliminary resource assessment

The desired technique for primary resource evaluation taking the Ikogosi area as a case study is the volumetric method. The total stored heat in-place in a geothermal system is given by: Total stored heat = Stored heat in rock + Stored heat in water + Stored heat in steam.

In the works of Sanyal and Sarmiento (2005), they confirmed that rocks heat is identified to intensely have control in the above equation especially porous rocks with fluid content. Moreover, the manifestation of fluid (water/steam) and porosity of rocks at depth are anonymous in the IKGWS area and surrounding area and therefore the resource rocks are presumed to have insignificant porosity and fluid content. A more basic equation was assumed for the stored heat in-place evaluation in the form of Eq. (13):

$$Q = \rho_r C_r V (T_R - T_r), \quad (13)$$

where: Q is the Stored heat in-place, Joule (J), ρ_r is the density of rock, kg/m^3 , C_r is the specific heat capacity of rock, $\text{J}/\text{kg}^\circ\text{C}$, V is the volume of Rock (resource), $\text{m}^3 (= AH)$ where A is the surface area of Rock (resource), m^2 , H is the thickness of Rock (resource), m ; T_R is the mean temperature of Rock (resource), $^\circ\text{C}$, T_r is the reference (base) temperature $^\circ\text{C}$.

Results and discussion

Energy estimation from numerical method

Using Eq. (13), stored heat in-place was calculated for the entire area and it ranged from 0.65×10^{18} to 1.95×10^{18} Joules (J). The estimated stored heat in-place was converted to equivalent electric power generation potential in megawatt (MW) and annual electricity generation potential in gigawatt-hour (GWh). Some rules were made when converting the stored heat in-place to electricity: Stored heat retrieval factor: 5%; thermal exchange efficiency of plant: 7%; capacity factor of plant: 90%; lifetime of plant: 25 years. The projected generation capabilities are only primary approximations centered on limits with substantial doubts. In IKGWS area for example a simulation assuming a small geothermal energy of 2.1 MWe installed power plant in few years. An estimation of the production from the recovered heat with cut-off heat of 120°C from the reservoir was considered. From these results, several statistical realities can be established like likely outcome, 90% confidence interval, median, standard deviation and mean of the results.

From the possibility distribution statistics, the volumetric approach expects that with 90% self-reliance, the production of output power is about 0.9 MWe for a 25 years period while the least energy production is projected to be 0.4 MWe. The highest energy production is estimated around

Table 2 Stored heat in place, electric power potential and annual electricity generation for IKGWS and environs

Tectonic unit	Locality	Zb (km)	TG (°C/km)	HF (mWm ⁻²)	IRT (km)	RMT (°C)	RSA (km ²)	RD (kg/m ³)	RSHC (J/kg°C)	Stored heat in-place (J) × E+18	Gross power generation potential (MWe)	Estimated annual electricity generation (GWh)
UBC	Ilesa	20.59	28.17	74.64	1	150	10	2800	1000	1.4	6.9	54.41
UBC	Ilesa	15.48	37.46	99.27	1	150	15	2600	1000	1.95	9.62	75.78
QUARTZITE	Erinmo	13.5	42.98	113.89	1	150	10	2800	1000	1.4	6.9	54.41
UBC/ QUARTZ- ITE/UBC	Effon Alaye	14.36	40.4	107.06	1	150	10	2800	1000	1.4	6.9	54.41
UBC/ QUARTZ- ITE/UBC	Effon Alaye	16.44	35.29	93.52	1	150	15	2600	1000	1.95	9.62	75.78
QUARTZITE	Ado-Ekiti	14.58	39.77	105.39	1	150	10	2800	1000	1.4	6.9	54.41
QUARTZITE	Ado-Ekiti	16.42	35.32	93.59	1	150	10	2600	1000	1.3	6.41	50.52
UBC	Ijero	13.48	43.02	114.01	1	150	10	2800	1000	1.4	6.9	54.41
UBC	Ijero	15.16	38.26	101.38	1	150	10	2600	1000	1.3	6.41	50.52
UBC	Akure	16.33	35.51	94.1	1	150	10	2800	1000	1.4	6.9	54.41
UBC	Akure	20.36	28.49	75.49	1	150	10	2800	1000	1.4	6.9	54.41
UMC	Ondo	16.17	35.88	95.08	1	150	10	2600	1000	1.3	6.41	50.52
UMC	Ondo	15.41	37.63	99.73	1	150	5	2800	1000	0.7	3.45	27.2
UBC/OLDER GRANITE	Ikere	17.5	33.14	87.82	1	150	5	2600	1000	0.65	3.21	25.26
UBC/OLDER GRANITE	Ikere	13.81	41.99	111.27	1	150	5	2800	1000	0.7	3.45	27.2
UMS/ QUARTZ- ITE	Ikogosi	12.13	47.82	126.71	1	150	6	2800	1000	0.84	4.14	32.64
UMS/ QUARTZ- ITE	Ikogosi	16.78	34.56	91.58	1	150	10	2600	1000	1.3	6.41	50.52
UBC	Ilesa	16.36	35.46	93.97	1	150	10	2800	1000	1.4	6.9	54.41
UMS	Osoobo	14.24	40.72	107.92	1	150	5	2800	1000	0.7	3.45	27.2
UMS	Osoobo	13.81	42	111.3	1	150	5	2600	1000	0.65	3.21	25.26

TG Temp. Grad., HF heat flow, IRT thickness of Inferred resource, RMT mean temp. of Resource, RSA surface area of Resource, RD = density of rock, RSHC specific heat capacity of rock, UMS undifferentiated meta-sediments, UBC undifferentiated basement complex

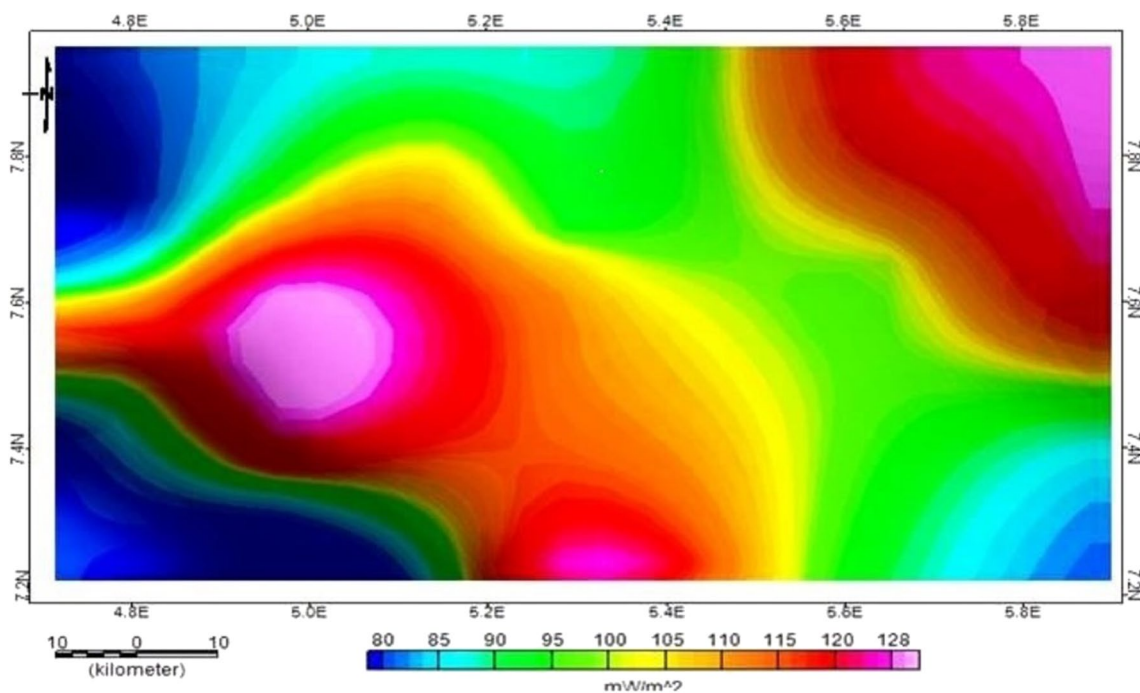


Fig. 3 Heat flow map of the whole area (Southwestern Nigeria)

5 MWe. This result is a reflection of the estimations from the python program and also reveals the ambiguity in the outcomes gotten from the volumetric technique. This is due to ambiguity in dimension, temperature and recovery factor for the thermal reservoir. The prospect that energy production will yield more than or equal to 4 MW is 5% (cumulative frequency) while possibility that the energy production will be larger than or equal to 0.9 MW is 90%. This means that site could primarily sustain a 0.9 MW power plant production for a period of 25 years and potential development will be a matter of additional defined boring, accessibility and accessibility of site performance data. The probability that the field could not sustain a 4 MW of energy production is equal to or less than 5%.

The simulation results show that the estimated stored heat in-place of $0.65\text{--}1.95 \times 10^{18}$ J can be expected from the inferred resource areas at 90% probability. This is equivalent to electric power generation potential of 3.2–9.6 MWe or annual electricity generation of 25.4–75.8 GWh at the same probability rate (Table 2).

Calculated heat flow from aeromagnetic data

Conventional heat flow data in Nigeria is very less especially in the southwest region which is the focus of this work. Only it is available in the works of Brigaud and Lucazeau (1985) from the West Africa Shield (Nigeria, Ghana and Liberia) with values ranging between 30 and 40 mWm^{-2} and Verheijen and Ajakaiye (1979) with average value of 38.5 mWm^{-2} .

No borehole data or well logging data were available in the southwest. The heat flow estimation in Southwest Nigeria have been through CPD estimation and assuming a constant Curie temperature and rock Thermal conductivity value. Hence most of heat flow data available around Nigeria were either acquired through aeromagnetic data or well logging. In the absence of conventional heat flow and thermal conductivity characteristics and description of the rocks in the above area, it is very difficult to arrive at the variations of reported heat flow from the actual heat flow of the regions.

The CPD estimated for the IKGWS area varied between 12 and 21 km and mean value of 16 km. Similarly the heat flow values for the area varied from 75 to 127 mW/m^2 with a mean value of 100 mW/m^2 while the temperature gradient varied from 28 to 48 $^{\circ}\text{C/Km}$ with a mean value of 38 $^{\circ}\text{C/Km}$. Figure 3 shows the heat flow map of the entire area and IKGWS area is located at the bottom right corner. So it is clear that no in-depth deductions can be gotten from a limited measurement so it is necessary to have measurements from Bottom hole temperatures from boreholes (temperature-depth data) in Ikogosi area.

Conclusion

With Nigeria's growing population and resource industries, there is a need for additional base-load electricity capacity. Due to this need, and to reduce environmental impact, the need for cleaner energy sources is an imperative. Amongst

all cleaner energy sources, geothermal energy is the best alternative to provide base-load electricity throughout the year with negligible greenhouse gas emissions. Geo-scientific data sets, including temperature and thermal conductivity data was collected from IKGWS area with the aim of expanding exploration opportunities and facilitating the reduction of risk for future explorers. Our data were used to define the heat flow of the area which is an important parameter for evaluating geothermal energy potential. The modeling process indicated that vertical conductive heat flow for the IKGWS and Environs ranged between 75 and 127 mW/m².

However, given the difficulty and heterogeneous nature of geological formations in almost all geothermal systems, 1D-modelling of heat flow and temperature has limitations since heat does not at all times flow straight up in areas where substantial lateral differences in thermal conductivity exist. A Python based evaluation on the obtainable data was used to estimate the electric power that can be gotten from the recoverable heat in IKGWS area and its environs. For more certainty and with 90% assurance, 0.9 MWe can be generated in IKGWS if the recoverable heat is used for a period of 25 years. The wide-ranging values of these estimates only reveal the ambiguity in dimension, temperature and recovery factor of the study area. Heat flow modeling in more than one-dimension, is required in prospective research to understand two- and three-dimensional distribution of the temperature field, so as to accurately describe the thermal state of the IKGWS targets. The Ikogosi, Effon Allaye have been identified as high prospective basins for geothermal energy highlighting. Using the volumetric approach, stored heat in-place of 0.65×10^{18} – 1.95×10^{18} J was estimated for the inferred resource areas accumulating to total amount of 24.54×10^{18} J.

The Monte Carlo simulations predicted a cumulative total stored heat in-place of 24.54×10^{18} J at 90% probability for the highlighted inferred resource areas. The estimated stored heat in-place is equivalent to gross electric-power-generation potential of 121 MWe which is sufficient to generate electricity to meet the demand over the next decade.

However, these estimates are purely hypothetical because of a lack of sufficient quantitative data. They will need to be reviewed after comprehensive investigation programs are commenced and direct field measurements at larger depths are acquired. The results from probability distribution from the simulation show that this area could primarily support an average of 5 MWe power plant for a 15 years period, with a possible expansion to 10 MWe.

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and take public responsibility for the research and have agreed to have our name listed as contributors.

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Declarations

Conflict of interest The authors declared that there is no competing interest and all authors approved the submission of the manuscript and that the manuscript has not been published elsewhere.

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