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An evaluation for harnessing low-enthalpy geothermal energy in the Limpopo Province, South Africa

South Africa generates most of its energy requirements from coal, and is now the leading carbon emitter in Africa, and has one of the highest rates of emissions of all nations in the world. In an attempt to decrease its CO_2 emissions, South Africa continues to research and develop alternative forms of energy, expand on the development of nuclear and has began to explore potentially vast shale gas reserves. In this mix, geothermal has not been considered to date as an alternative energy source. This omission appears to stem largely from the popular belief that South Africa is tectonically too stable. In this study, we investigated low-enthalpy geothermal energy from one of a number of anomalously elevated heat flow regions in South Africa. Here, we consider a 75-MW enhanced geothermal systems plant in the Limpopo Province, sustainable over a 30-year period. All parameters were inculcated within a levelised cost of electricity model that calculates the single unit cost of electricity and tests its viability and potential impact toward South Africa's future energy security and CO_2 reduction. The cost of electricity produced is estimated at 14 USc/KWh, almost double that of coal-generated energy. However, a USD25/MWh renewable energy tax incentive has the potential of making enhanced geothermal systems comparable with other renewable energy sources. It also has the potential of CO_2 mitigation by up to 1.5 gCO_2/KWh. Considering the aggressive nature of the global climate change combat and South Africa's need for a larger renewable energy base, low-enthalpy geothermal energy could potentially form another energy option in South Africa's alternative energy basket.

Introduction

As the leading carbon emissive nation in Africa, South Africa joined several developing nations with the aim to decrease their greenhouse gas (GHG) emissions. Previously, only developed nations had stringent environmental policies toward decreasing their GHG emissions; however, this situation will change as the rate of GHG emissions from developing nations are predicted to surpass that of developed nations before 2020.[1] Whilst the Kyoto Protocol proposed financial penalties on ratified developed nations, developing nations were given temporary exemption. However, newer planned international legislation is expected to penalise developing nations for failing to meet millennium GHG reduction targets. This legislation was decreed under the Bali Action Plan in which key mitigation scenarios were outlined for developing nations at the COP17 summit held in Durban, South Africa.[2]

Having ratified the Kyoto Protocol, the South African government affirmed its commitment to reduce CO_2 emissions by introducing environmental legislation that includes the *Environmental Act, 1998*[3] and the White Paper on Renewable Energy, 2003[4]. These policy documents highlight the plan to reduce GHG emissions by 40% by 2050 through the development and implementation of a basket of renewable energy sources, including wind, hydro, bio and extensive solar projects. However, with continuous pressure on the South African energy sector to meet immediate and an ever-increasing energy demand, the development of two large-scale coal-fired power plants was commissioned. These plants will not only double the country's energy capacity, but also increase South Africa's overall GHG emissions. Therefore, the current renewable energy scheme will not be sufficient to adequately decrease South Africa's overall GHG emissions without severe market penalties and trade solutions. The National Treasury therefore proposed the introduction of a carbon tax from 2015[5] which, it has been argued, will be potentially damaging to the national economy and forego socio-economic benefits and increasing unemployment[6]. In order to achieve millennium targets and reach a sustainable future, South Africa will need to expand the current renewable energy research protocol and consider other possible alternative energy sources.

Geologically, South Africa is largely underlain by the Archean-aged (greater than 2.5 billion years old) Kaapvaal Craton. This craton comprises a crust of some of the oldest rocks on Earth that formed a nucleus for later continental growth by accreting to it younger rock formations, predominantly between ca. 1–2 billion years old (known as the Namaqua-Natal Mobile Belt).[7,8] The unique stability of the Kaapvaal Craton is because its crust is underlain by an equally old, exceptionally thick and chemically depleted mantle lithosphere with low heat conductivity. This mantle keel reaches depths of ca. 250–300 km,[9-11] and is relatively immune to melting. Together with its overlying crust, this unusually thick and stable lithosphere essentially acts as an insulator, deflecting most of the heat from the underlying convective mantle away from the craton toward younger surrounding regions with less depleted and thinner mantle lithosphere (<120 km).[12,13] These cratonic aspects of the South African geology are the fundamental cause of the low heat flow values measured at the surface in much of the central parts of the country, resulting in low geothermal gradients, which in turn are the fundamental reasons why geothermal energy is not being considered in South Africa as a viable option.[14] Globally, there are a number of countries with similar geological profiles to South Africa (e.g. Canada, Russia and Australia) that have dismissed the geothermal energy potential on their cratonic regions. However, recent experience has shown that these areas may still have capacity to yield energy from relatively low temperatures of 100–200 °C at a depth ranging from 2 km to 3 km[15] – conditions that are met in other parts of South Africa. These areas then provide potential for sustainable low-enthalpy geothermal energy extraction.

We investigated low-enthalpy geothermal energy as a viable alternative energy source in South Africa, by considering a hypothetical geothermal energy plant in the Makuleni Village within the Limpopo Belt. This target area reveals the presence of a suitable heat flow profile, as witnessed by hot springs with surface temperatures of up to 70 °C.[16-18] We present a model that considers the development of a 75-MW enhanced geothermal systems plant, sustainable over a period of 30 years in this area. Attaining an economic viability indication is achieved through levelised cost of electricity (LCOE) model calculations. This model considers all financial and economic parameters associated with the building and maintenance of such a plant, weighed against all geological and engineering parameters associated with harnessing the energy. Because there are other regions in South Africa (notably in the Northern Cape) that have similarly high heat flow profiles, the results of this study should generate recommendations for the consideration of geothermal energy in South Africa's shift toward long-term renewable energy production.

Enhanced geothermal systems

Enhanced geothermal systems (EGS) are unlike hydrothermal or volcanic-fuelled systems that derive heat directly from the Earth's convective mantle. An EGS exploits latent heat encapsulated in deep crustal rocks. These crustal rocks are predominately granitic in composition and have high concentrations of heat producing elements that emit heat during their radioactive decay. These elements include U, Th and K.[19] High heat producing granites located at the Cooper Basin EGS project, South Australia, exhibit values of ca. 30 ppm U and 144 ppm Th, giving rise to temperatures between ca. 250 °C and 350 °C at depths of ca. 4–5 km.[20] This project indicates the possibility of harnessing EGS in South Africa where similar concentrations of heat-producing elements are present in the Namaqualand, Northern Cape and the Limpopo Province.

An EGS system functions by pumping a 'working fluid' (mainly water) into a geothermal reservoir and allowing it to interact with the surrounding hot rocks and heat up substantially. The heated fluid is then pumped back to the surface and used in a binary generation system (Figure 1). The binary system has a second organic-based fluid with a much lower boiling point, which flashes to steam upon exposure to the heated geothermal fluid. The organic steam is then used to run a generator and produce electricity.[21] EGS is also being proposed as a mechanism for simultaneous carbon sequestration, which is thought to be possible by incorporating CO_2 into the working fluid. The CO_2 would theoretically be trapped and stored in the reservoir before the working fluid returns up the production wells.[22]

A successful EGS plant requires an appropriate crustal lithology that contains a relatively high concentration of radioactive heat-producing
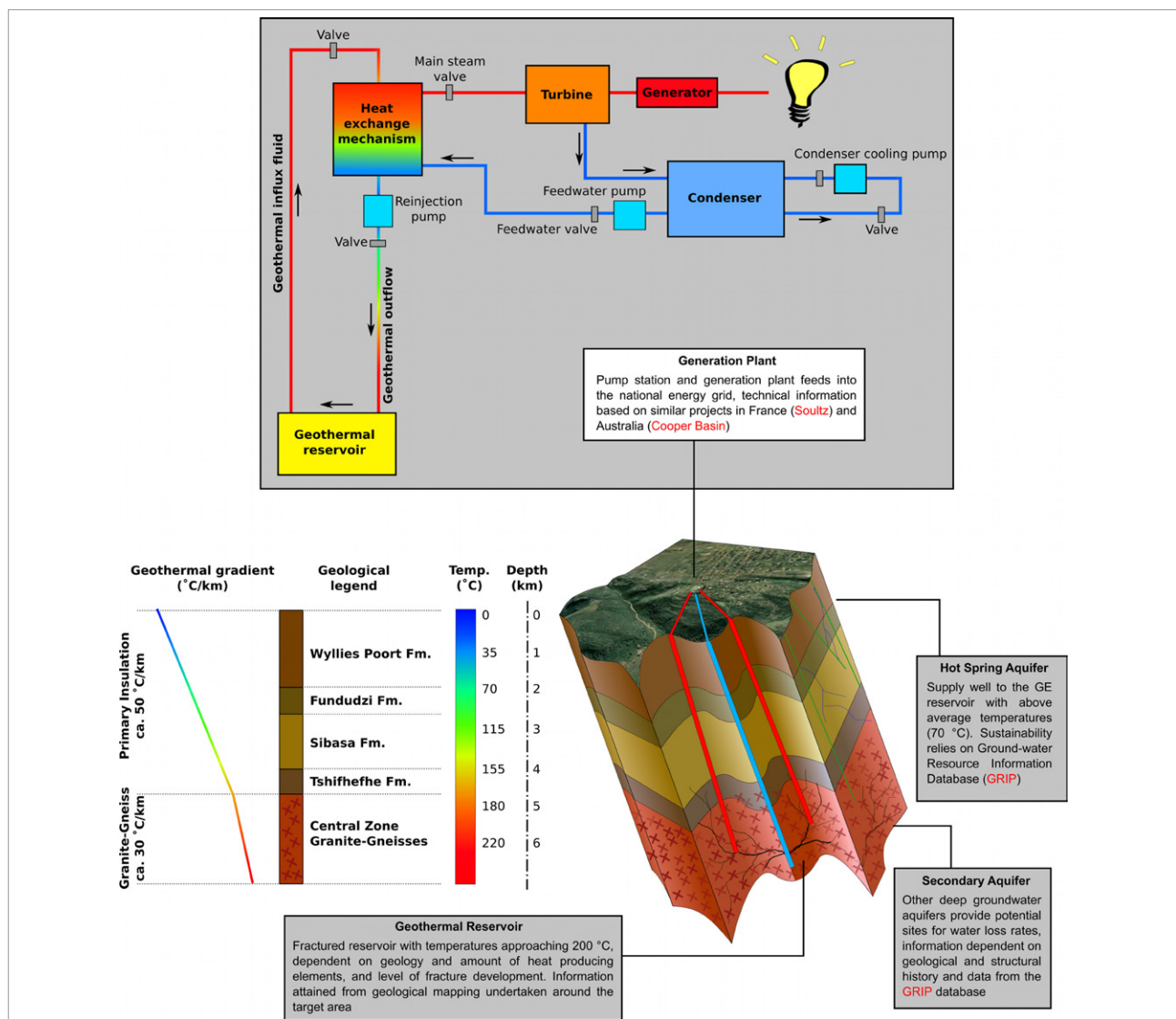

Figure 1: Schematic illustration of the hypothetical enhanced geothermal system plant in the Limpopo Province. The blue line indicates the influx well and the red line indicates the outflow/production wells. Also shown is the depth, geological profile, geothermal gradient and detailed binary production system.

elements. This lithology also needs to attain an appropriate thickness and depth and have a relatively homogenous mineral composition. The crustal lithology will also need to be effectively insulated, by an adequately thick overlying sedimentary sequence. In order to maintain efficient flow between the inflow and outflow systems, a sufficiently porous geothermal reservoir is needed. Therefore, the crustal lithology should have a uniform fracture network that can be manipulated through hydraulic fracturing. Manipulation includes increasing the porosity of the fracture network and creating a sizable geothermal reservoir. Knowledge of the geological mineral chemistry is important to avoid possible decreases in the reservoir porosity as a result of secondary mineral precipitation.

Finding a target area in South Africa

Early heat flow measurements in South Africa have indicated the presence of a relatively low heat flow profile.[23-25] However, these measurements were made within the central part of the Kaapvaal Craton, across the Witwatersrand Basin of the Gauteng region, and reflect the thermal insulating effects of the underlying depleted mantle keel. When heat flow measurements were extended beyond the Witwatersrand Basin, off the Kaapvaal Craton and across the surrounding Proterozoic mobile belts, the heat flow profile increased markedly.[26,27] Measurements show that the heat flow increased from ca. 45 MW/m² on the Kaapvaal Craton to ca. 80 MW/m² along the Namaqua Natal Mobile Belt.[28,29] This finding suggests that the mantle heat deflected by the cratonic keel may be concentrated beneath thinner neighbouring Proterozoic mobile belts.[12] The higher heat flow evident along the Proterozoic mobile belts can also be attributed to the difference in geology between these terrains. Archean-aged granites are predominantly tonalitic in composition and lack very high concentrations of the heat-producing elements that are found within the younger Proterozoic granites. Figure 2 illustrates a map of South Africa compounding all available heat flow measurements. This map best illustrates the effect of the Kaapvaal Craton with low heat flow

signatures and the surrounding Proterozoic mobile belts, which display much higher signatures. This observation suggests that while the Kaapvaal Craton has a very low geothermal potential, the surrounding Kalahari Shield, which includes Proterozoic mobile belts, has a much higher potential.

An important factor in locating a possible EGS target site is the consideration of the concentration of heat-producing elements. Andreoli et al.[30] investigated the gamma ray exposure signatures across South Africa. These signatures highlight regions of South Africa with high concentrations of U and Th (and K), such as in the Proterozoic granites. Many of these signatures correspond to Proterozoic mobile belts of the Kalahari Shield, including the Namaqua Natal and Limpopo Belts.

Careful consideration must also be given to the effect on the surrounding groundwater supply, because EGS uses a substantially larger volume of water than other renewable energy sources. Controlling the amount of groundwater required can be addressed by attempting to create an ideally sealed geothermal reservoir; creation and modification of a fractured reservoir, in turn, necessitates very precise hydraulic fracturing. Early EGS projects in Japan experienced water loss rates of up to 50% because of imprecise fracture modelling and uncontrollable reservoir growth.[31]

A target site in the Limpopo Belt

Given the abovementioned constraints, we considered a target site close to the Makuleni Village within the largely rural Vhembe District of the Limpopo Province (Figure 3). Makuleni and its neighbouring villages have the additional benefit of being located on the national energy grid and included in Eskom's (South Africa's public electricity utility) basic free energy policy, which allocates each household 50 KWh of free electricity a month.
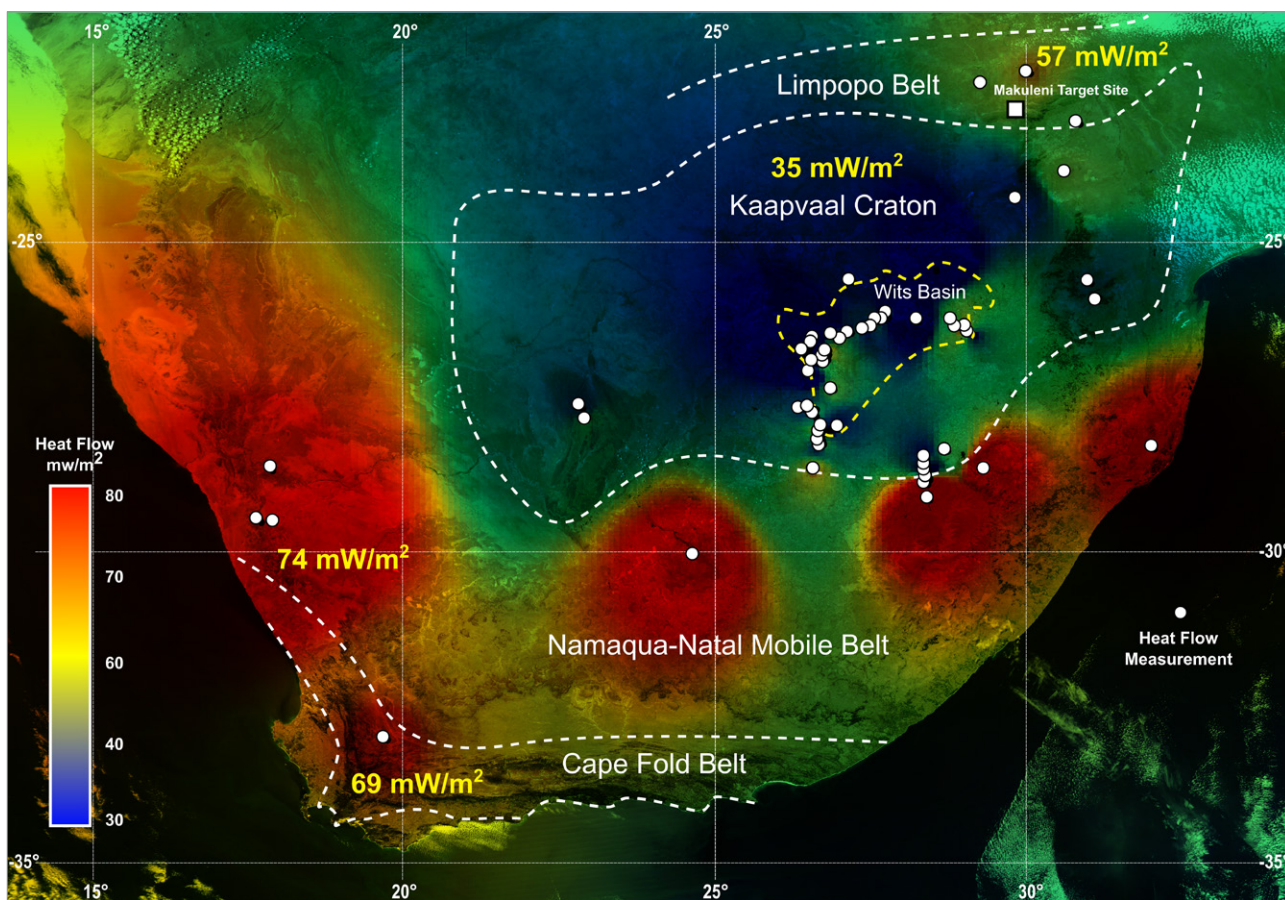

Figure 2: Geothermal potential map produced using available heat flow data created using inverse distance weighting within Quantum GIS. Major tectonic boundaries and geological features are highlighted.
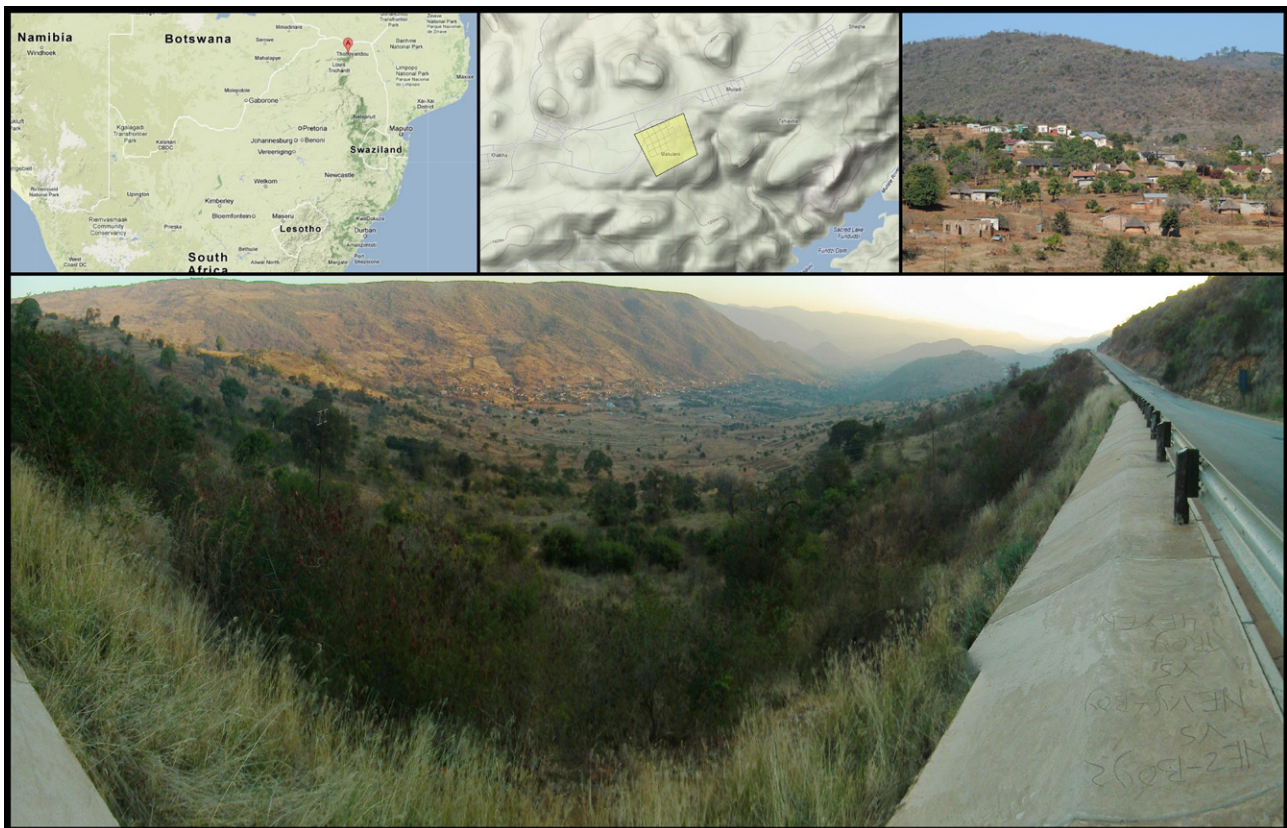
Figure 3: Overview of the Siloam Valley and Makuleni Village: the site of the hypothetical enhanced geothermal system.

The target site is located within the Limpopo Belt, a ca. 150-km long orogenic belt formed during the amalgamation of the Kaapvaal and Zimbabwe cratons. This major period of continental collision began ca. 3.2 Ga, reaching its maximum compressional regime at ca. 2.0 Ga.[32] Outpouring of granites rich in heat-producing elements are evident of this period, providing much of the high heat flow signatures observed.[30,33] The Limpopo Belt is separated into three discrete zones: the northern and southern marginal zones and the central zone, each of which is bounded by major shear features. The marginal zones are largely composed of fragments of their respective adjacent cratons (Zimbabwe and Kaapvaal cratonic fragments in the northern and southern marginal zones, respectively), while the central zone has a unique lithological array.

The Makuleni village is located near the boundary between the central and southern marginal zones, ca. 20 km north of the Kaapvaal Craton boundary. The target site sits on the 1.85 Ga volcano-sedimentary Soutpansberg Group[34,35], which covers the tectonic boundary between the Limpopo Belt and the Kaapvaal Craton and unconformably overlies Limpopo Archean and Palaeoproterozoic granitic rocks[7,36-38]. The Soutpansberg Group was deposited as a syn-rift sequence, in a half-graben basin structure with alternating phases of sedimentary deposition and volcanic outpourings.[39-41] This deposition occurred during a late-stage period of regional extension, following the collision of the Kaapvaal and Zimbabwe cratons.[42] The Soutpansberg Group displays a complex network of normal faults and numerous dolerite dykes and sills that characterise the area with many fault-controlled hot springs. These hot springs further illustrate the higher heat flow of this region. The highest recorded hot spring is found near the Makuleni target site, and reaches a surface temperature of 70 °C, after circulating to a maximum depth of 2 km (based on geological investigations). A possible basal reservoir temperature capable of sustaining low-enthalpy EGS production could be attained at greater depths.

Model development for determining EGS viability

To determine the possible economic viability of harnessing low-enthalpy geothermal energy in the Limpopo region, a LCOE model was developed

(Figure 4).[43] This model considers all economic and financial factors associated with building a geothermal energy plant in the Makuleni Village. These factors are then weighed against the total possible energy capable of being generated from the geothermal energy plant. The hypothetical EGS plant in the Makuleni Village is modelled based on similar plants in France[44] and Australia[45].

Model calculations

Levelised cost of electricity

The LCOE model calculations append all cost factors with the potential energy factors to estimate a unit cost of electricity. This calculation is commonly used in most energy producing technologies.[46] This is the final calculation within the model sequence and is expressed as:

$$LCOE = \frac{TC}{TE}$$

Equation 1

where TC is the total cost and TE is the total energy.

Generation cost

The generation cost considers the total capital cost associated with an EGS plant in the Limpopo Province. This calculation includes the cost of generating turbines and grid parity for feeding back into the national energy grid. Deep drilling and hydraulic fracturing costs have also been incorporated. The calculation is:

$$C(MW) = \frac{C}{N}$$

Equation 2

where C(MW) is the capital cost per MW of electricity produced, C is the total capital cost and N is the nameplate plant size.
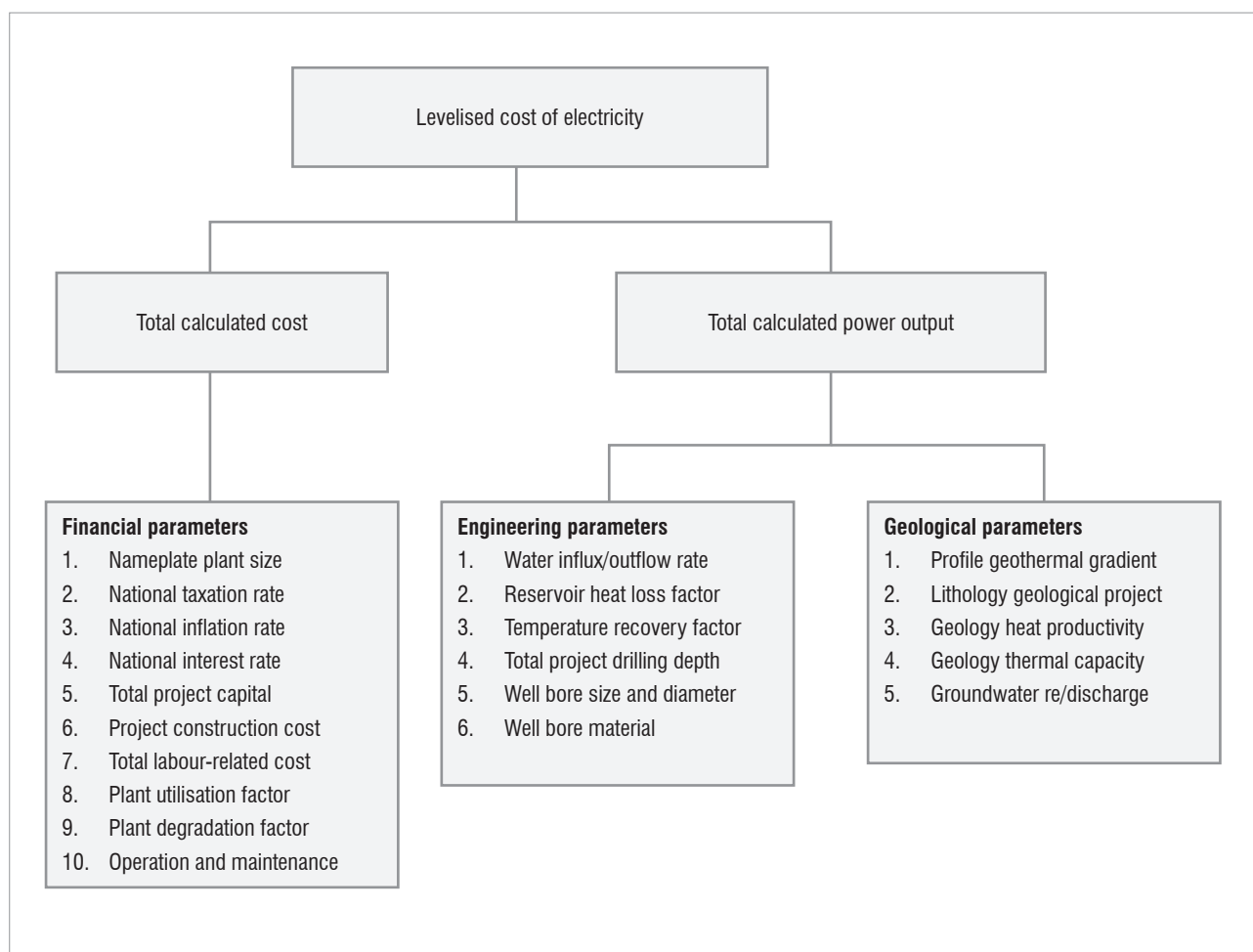
Figure 4: Flow diagram of the economic model developed within this study for the hypothetical enhanced geothermal system.

Operating and maintenance costs

The operating and maintenance costs relate to the various parameters associated with all maintenance-related events. This amount is calculated using a defined operational and maintenance cost per year, weighed against the total energy production of that same year. Both South African tax and inflation rates are included.

$$OM = \sum_{t=2}^{t=n} OM(t) * (1 + i) * P(t) * (1 - T)$$

Equation 3

OM is the overall operational and maintenance costs, *t* is the year; *n* is the lifetime of the plant, OM(*t*) is the defined operational and maintenance value per MWh, *i* is the South African annual inflation rate, P(*t*) is the annual electricity production and *T* is the South African tax rate.

Renewable energy production incentive factor

Renewable energy feed-in tariff (REFIT) is a mechanism used to accelerate the development and implementation of renewable energy. Various industrialised countries have successfully introduced REFIT schemes to assist in the production of renewable energy. Similarly, the National Energy Regulator of South Africa introduced a REFIT scheme that supports various renewable energy projects. While this scheme does not include geothermal energy, this model will consider a geothermal REFIT as follows:

$$PTC = PTC(t) * E(t) * 1000$$

Equation 4

where PTC is the overall production tax credit, PTC(t) is the defined yearly production tax credit and E(t) is the yearly electricity production.

Geological parameters

The geological parameters are used together with the engineering parameters to determine the most probable energy production. The geology is dependent on the lithological profile underlying the target site and extends until the maximum basal reservoir depth. This parameter determines the variability in heat productivity, conductivity and the overall geothermal gradient along the well length. This calculation is expressed as follows:

$$Tb = \sum_{t=2}^{t=n} \frac{(G * t)}{d} * (1 - L)$$

Equation 5

where *Tb* is the expected basal reservoir temperature, I is the lithology, *n* is the number of lithological units, *G* is the geothermal gradient, *t* is the thickness of the lithological unit, *d* is the well depth and *L* is the thermal loss coefficient.

Engineering parameters

The engineering parameters are used to consider the amount of heat available for exploitation and to estimate the total amount of electricity capable of being harnessed. These parameters include the initial and final temperature of the working fluid, together with the heat capacity and overall flow rate within the system. Variation in the composition of the working fluid can play a major role in the overall energy production.

Here the model assumes the use of water as the main geothermal working fluid. Experiments do suggest that supercritical CO_2 has a lower boiling point and could increase the system efficiency, while allowing for simultaneous carbon sequestration. These factors are equated as follows:

$$Energy = [R * 1000 * C((Tb * (1 - Rf)) - Ti)] * 0.001$$

<div align="right">Equation 6</div>

where R is the system flow rate, C is the heat capacity factor, Ti is the input temperature of the working fluid, Tb is the reservoir temperature and Rf is the final recovery factor.

Groundwater sustainability

The process by which geothermal energy is harnessed requires a large volume of water for operation. Failure to create an adequately sealed reservoir can result in poor water recovery rates, which will require the continuous addition of water. The model estimates the value of water required to run the proposed EGS plant and weighs the estimate against the current local exploitation values, together with the natural recharge and discharge rates. A population coefficient is also taken into account and considers an increase in the surrounding population size. An additional coefficient is also equated for any possible water loss. These parameters are equated as follows:

$$W = \sum_{t=1}^{t=n} [Rn - Ry - Gl - Dn - (Dp *) 1 + ip))]$$

<div align="right">Equation 6</div>

where W is estimated required water supply, t is the year of n years, n is the lifetime of the plant, Rn is the natural recharge rate, Ry is the yearly plant water flow rate required, Gl is the geothermal water loss coefficient, Dn is the human population required discharge and ip is the human population increase factor over the lifetime of the plant.

Results

Levelised cost of electricity

Modelled results compared against other models

The LCOE modelled results of a proposed EGS plant within the Makuleni target site are shown in Figure 5 and are compared with the LCOE of other international EGS projects. The first result, LCOE, is the modelled result for a scenario excluding any REFIT. This scenario would best simulate an EGS plant under the current energy scheme in South Africa that lacks any financial incentives for geothermal energy. LCOE (+REFIT) follows the same parameters, but includes a REFIT of USD25/MWh. This amount is an upper-level accepted geothermal energy incentive used in many international countries.
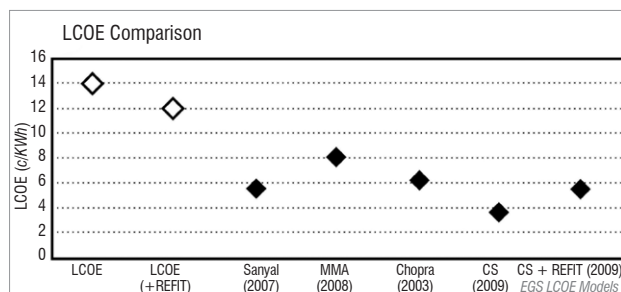

Figure 5: Graph comparing the calculated levelised cost of electricity (LCOE) of this study (white points) with the LCOE of other enhanced geothermal systems (black points).

In Figure 5, Sanyal (2007)[47] represents the modelled LCOE results from the Desert Peak EGS plant in Nevada, USA; MMA (2008)[48] represents the modelled calculations performed by MacLennan Megasanik Associates

for the viability of the developing EGS plants in Australia; and Chopra (2003)[49] represents the results as determined for the first successful EGS project in the Cooper Basin, South Australia. The final two points illustrated are modelled results determined by a Credit Suisse report on renewable energy; the first point excludes and the final point includes a REFIT and carbon tax credit.[46] These points had the benefit of actual field data from EGS test sites. This study, however, estimates a much higher LCOE, primarily as a result of the use of conservative data assumptions where actual data is not available.

Calculated energy potential versus other renewable sources

The calculated LCOE and energy capacity of the hypothetical plant were compared with other energy options, including renewable and non-renewable energy (Figure 6). The white points in Figure 6 represent the LCOE of each form of energy, while the corresponding black points represent the total energy capacity of each energy source. Non-renewable sources are clearly more viable, with a greater capacity and lower cost. EGS has the second largest capacity, after concentrated solar power, but it also has the highest cost of all renewable energy sources.
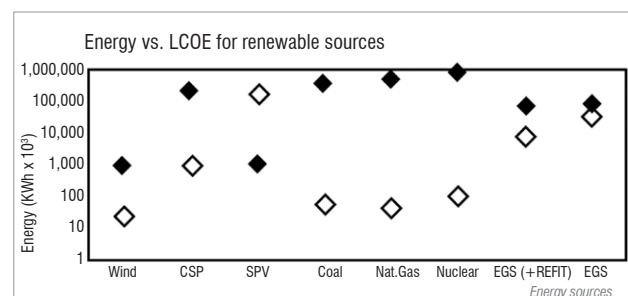
CSP, concentrated solar power; SPV, solar photovoltaic.

Figure 6: Graph comparing the levelised cost of electricity (LCOE) of enhanced geothermal systems (EGS) with those of other renewable energy sources. Black points correspond to the energy capacity and the white points correspond to the LCOE.

Sensitivity analysis

Energy potential versus depth

The change in the LCOE with an increasing basal reservoir temperature and the consequential increase in the overall energy capacity of the system are shown in Figure 7. The dashed curve represents the scenario excluding any REFIT, while the black curve illustrates a scenario including a USD25/MWh REFIT. This calculation restricts the drilling depth to a maximum of 6 km. The temperature range best estimates the expected basal reservoir temperature as determined within the model calculation.
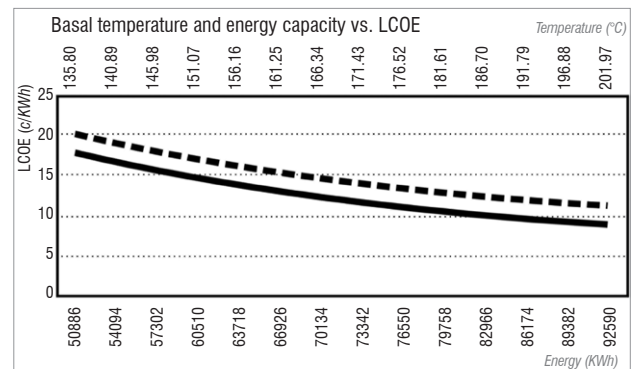

Figure 7: Graph illustrating the effect of an increasing basal reservoir temperature and consequential energy capacity on the levelised cost of electricity (LCOE). The dashed curve represents a scenario excluding a renewable energy feed-in tariff (REFIT), while the solid curve includes a USD25/MWh REFIT.

Cost versus incentives

Renewable energy is an expensive alternative source of energy that relies heavily on governmental incentives to be deemed significantly viable. The effect of a REFIT on the LCOE is shown in Figure 8. The REFIT represents the absolute value of the incentive the government is willing to pay for the production of renewable energy. With no current concession provided for geothermal energy, the effect of an added REFIT ranges from 0 to USD30/MWh of energy produced. The steep decline in the LCOE highlights the need for government-driven renewable energy production incentives.
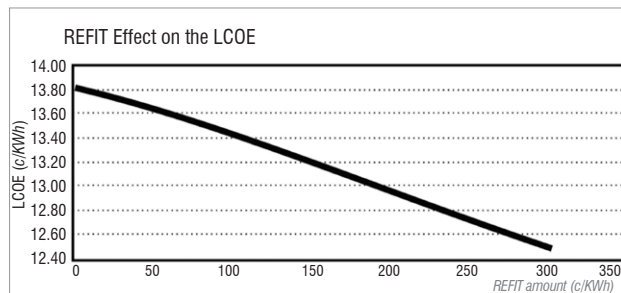

Figure 8: Graph illustrating the effect of an added renewable energy feed-in tariff (REFIT) on the levelised cost of electricity (LCOE) for a hypothetical enhanced geothermal system.

Cost versus drilling depth

The effect of an increasing drilling depth on the LCOE is shown in Figure 9. This scenario considers increasing drilling costs with depth as determined from Augustine[50]. These values are compounded with current and previous inflation rates to obtain a comparable evaluation over the time period specified. This evaluation excludes the additional cost of deep hydraulic fracturing, which is controlled by the geology and fracture transmissivity.
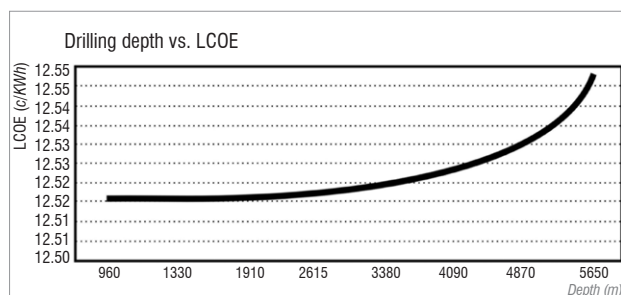

Figure 9: Graph illustrating the effect of an increasing drilling depth on the levelised cost of electricity (LCOE) for a hypothetical enhanced geothermal system.

Sustainability of enhanced geothermal systems

The model calculates the total energy capable of being produced from any production well, at any depth with a corresponding basal reservoir temperature. However, over the lifetime of the plant a thermal drawdown in the basal temperature could result in a decrease in the total energy production. Figure 10 shows the calculated result for the total reduction in heat as indicated by the dashed curve, against the consequential decrease in the overall energy production, indicated by the black curve. The thermal drawdown rate is estimated according to the age and heat productivity of the Limpopo rocks and further appended against those of other EGS granites.

Groundwater sustainability

Water forms the main constituent of the working fluid within the proposed EGS plant system and therefore is an important component within the model. The Makuleni target site is situated where one of the main potable water sources is groundwater. The overall effect of an EGS plant on the

groundwater volume is displayed in Figure 11. A large concentration of the water exploited for human disposal is attained from groundwater aquifers stored within fracture zones and incorporated below surface sediment layers. Using data from the Department of Water Affairs of South Africa and the Groundwater Resource Information Project, which monitors several thousand boreholes throughout the Limpopo Province,[51] the model calculates the overall amount of water exploited for human and industrial consumption, and weighs this against the overall recharge rates. Periods of both drought and flooding are also considered. These calculations are forecasted over the lifetime of the EGS plant and are appended with the inclusion of a coefficient for human population size increase associated with further social development within the Limpopo Province. The dashed curve in Figure 11 illustrates the result of this forecast, while the black curve illustrates water consumption of the EGS plant. Based on these results, the idealised closed system of the EGS plant will be sustainable over its lifetime of 30 years.
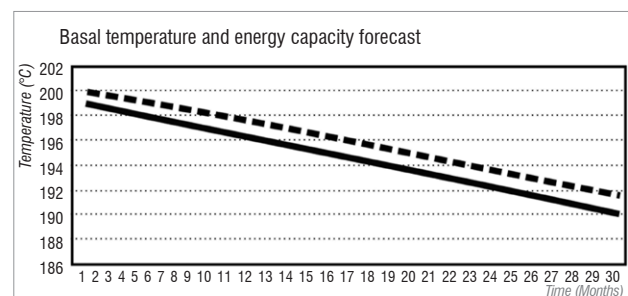

Figure 10: Graph forecasting the decrease in basal reservoir temperature (dashed curve) and the consequential decrease in energy production (solid curve) of a hypothetical enhanced geothermal system.
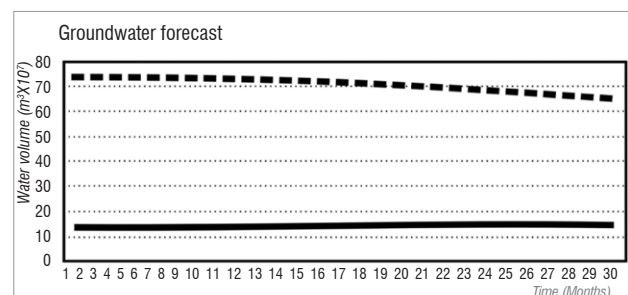

Figure 11: Graph forecasting the groundwater requirements of the hypothetical enhanced geothermal system (solid curve) and the average natural recharge rate (dashed curve).

Discussion

Excluding any REFIT incentive, the EGS LCOE determined the cost of geothermal energy to be greater than 14 USc/KWh in South Africa. This figure is about 7 USc/KWh more than the cost of coal-generated electricity that currently comprises more than 90% of South African electricity. However, under the same circumstances, with an added REFIT of USD25/MWh, the LCOE decreases to approximately 12 USc/KWh. This figure is more comparable with other renewable energy options: about 1 USc/KWh more than solar photovoltaic, although with up to a 25-MW lower energy capacity. When comparing these results against those of other models for similar EGS plants, the results are comparable with the calculated case scenario, deviating no more than 4 USc/KWh from other model projections. As the global and local combat against CO_2 emissions intensifies, nations will face stringent penalties for failing to meet GHG reduction targets. The legal implementation of GHG reduction is becoming more aggressive following the COP18 summit, especially considering the amendment made to the Kyoto Protocol that extends it for another 8-year commitment period. This amendment transpires in addition to a newer climate change agreement expected to be resolved in 2015. The 2015 resolution is expected to have legal implementations that are likely to result in financial penalties for big GHG emitters, like

South Africa. Changes are already present in South Africa with the introduction of the Carbon Tax Policy.[5] This policy aims to reduce GHG emission through the introduction of carbon taxing for large CO_2 emitters in South Africa. Policies like the carbon tax form an integral part of the reduction of South Africa's carbon footprint; however, these policies may potentially have a negative impact on foreign business investment.[6]

The high cost of the EGS plant calculated in this model assumes the prospect of an EGS plant in an area with a predicted lower heat production and heat flow rate than other international target sites. Many of these sites boast some of the highest heat flows in areas lacking active volcanism and/or tectonism. With the lower heat flow rate estimated within the target area, the model is based on the calculations assuming a drilling depth of 5–6 km. Deeper drilling would likely cause a substantial increase to the overall project cost. The model suggests that a continued increase in the drilling depth below 2 km would result in a steeply increasing LCOE, but only of 1–2 USc/KWh, excluding additional hydraulic fracturing costs. Hydraulic fracturing is an additional cost to the deep drilling.

Previous EGS plants in the UK and Japan experienced great fluid losses associated with extended hydraulic fracturing programmes. Hydraulic fracturing was applied in an attempt to control the growth of the reservoir, which often closed because of low fluid flow rates or the accumulation of mineral precipitates. These reports highlight the importance of accurately assessing the orientation and scale of the fractured reservoir and the mineral chemistry of the targeted lithology prior to undertaking hydraulic fracturing. In addition, hydraulic fracturing has the potential to cause irregular surface seismic events. EGS projects in Basal, Switzerland and Landau, Germany were forced to stop following induced seismicity associated with hydraulic fracturing.[52] This further highlights the need for an active seismic-monitoring system during any hydraulic fracturing.

The total energy capable of being produced from an EGS plant within the Limpopo Belt depends predominantly on the basal reservoir temperature encountered. With a shortage of heat flow data, the model relies on information gathered on the surrounding hot springs and granites enriched in radiogenic elements to attain predictions of reservoir temperatures against depth. The calculated basal reservoir temperature illustrates that EGS will be viable and sustainable for a lifespan of 30 years at the Makuleni target site if a basal temperature of 150–200 °C is attained at a depth of 5–6 km. South Africa is well endowed with granites that exhibit large concentrations of heat-producing elements, similar to those in the Cooper Basin, Australia. Considering the high basal reservoir temperatures achieved at the Cooper Basin EGS project, South Africa could have the potential to reach the expected basal reservoir temperatures considered within the model, in a number of regions, notably the rural areas of the North West Province, and likely parts of the Eastern Cape and KwaZulu-Natal Provinces.

Based on the data from the Department of Water Affairs and the Groundwater Resource Information Project in the Limpopo Province, the average rate of aquifer recharge is adequate to sustain an EGS plant in the Makuleni village. Furthermore, the model, based on the average recharge and discharge rates as experienced during possible periods of drought, appended with a coefficient for the increase in demand for groundwater supply over the lifetime of the plant, shows favourable results for sustaining an EGS plant, while having a low impact on the surrounding communities. Assuming a regular thermal decrease in the basal reservoir temperature, the model predicts that there would not be a great drop in the overall production temperature over a period of 30 years, and this drop would amount to less than a 1 MWh decrease in the total energy production.

Conclusion

While geothermal is not currently under consideration by the National Energy Regulator of South Africa, a provision is in place for its inclusion subject to commercial application. Globally, the development of renewable energy is becoming aggressive and the technology of low-enthalpy EGS is advancing toward the use of low-temperature resources. With certain types of organic fluid compositions and specific fluid flow rates, EGS plants can become economically viable at temperatures as low as 100 °C. These conditions could make EGS more viable in many areas around the world.

Several key conclusions and recommendations can be drawn from this work. Firstly, EGS in conjunction with a binary generation system can generate energy from low-enthalpy sources, and has the additional possibility of simultaneously sequestering CO_2. This technology could assist in South Africa's shift toward renewable energy security. Secondly, EGS is a costly form of renewable energy and will rely heavily on governmental tax incentives to achieve viability. Thirdly, South Africa's geology in general, and that of the Kaapvaal Craton in particular, has a relatively low heat flow because of a thick underlying mantle keel. However, there are zones in the broader Kalahari Shield where high heat producing granite-gneisses occur that give rise to much higher heat flow signatures. These areas could form the ideal locations for low-enthalpy EGS exploitation and also correlate with rural communities that could benefit from such development. Finally, if geothermal energy is to be realised in South Africa, further research, especially data acquisition, is required to adequately delineate and design any prospective low-enthalpy EGS plant.

Authors' contributions

T.D. was the primary researcher with this work forming the basis of his MSc degree at the Nelson Mandela Metropolitan University (NMMU), with a large portion of the work completed at the International Institute for Applied Systems Analysis (IIASA). M.d.W. and A.P. provided supervision and review at NMMU and IIASA, respectively.

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