UNITED NATIONS
UNIVERSITY

GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensasvegur 9,
IS-108 Reykjavik, Iceland

Reports 2011
Number 34

THE POTENTIAL OF GEOTHERMAL ENERGY RESOURCES IN SRI LANKA

P.S. Mangala S. Wijetilake
Sri Lanka Sustainable Energy Authority
3G-17, BMICH, Colombo-07
SRI LANKA
mangalawijetilake@gmail.com

ABSTRACT

The Sri Lanka geology is characterised by 350 km long N-S striking contacts of the igneous Highland and Vijayan complexes. Microseismicity and a gravity low accompany this contact. Based on available chemistry of the ten thermal springs that follow the Highland and Vijayan contact in eastern Sri Lanka, chemical geothermometers indicate the reservoir temperature is in the range of 100-140°C. This line of thermal springs can be conceptualised as a continuous geothermal belt hosting geothermal reservoirs within steep faults and fractures. The temperature of 100-140°C is an indication of a commercial low-temperature resource.

Presuming a 100-140°C resource temperature, a reservoir length of 350 km, width of 2-4 km and thickness of 1-3 km, a volumetric assessment indicates a raw heat generating capacity ranging between 17 and 33 GW over a 50-100 year lifetime. Incorporating the various uncertainties under Monte Carlo style assessment, a power generating potential of 700-1300 MWe was estimated. This simple analysis shows that a geothermal resource could contribute significantly to Sri Lanka's energy mix. However, more field studies are needed to take the geothermal potential from possible to proven. As a first step in the development, a USD 10 M investment would cover a site selection study, surface exploration at the most promising site followed by deep drilling, and commissioning of a 2 MW binary power plant if the wells are successful.

1. INTRODUCTION

Sri Lanka is an island in the Indian Ocean, approximately 880 km north of the equator, between 5°55' and 9°55' north latitudes and between 79°42' and 81°52' longitudes. It lies on the Indo-Australian plate, seemingly far away from any of the tectonic plate boundaries shown in Figure 1. Sri Lanka is in close proximity to India with an area of 65,610 km^2 and a population of about 21 million. The government is run by the Democratic Socialist Republic of Sri Lanka. The main industries of the island are manufacturing, based on textiles & apparel and tea. Mineral resources currently developed in Sri Lanka are limestone, graphite, mineral sands, gems and phosphate.

In Sri Lanka the composition of power generation is currently made up of 42% hydro, 51% thermal and 7% other renewable sources comprised of mini hydro, wind and agriculture waste plants. The country does not possess any fossil fuel resources of oil, coal or natural gas. A sizeable fraction of the land area of the island is well endowed with good average rainfall and surface water resources. More than half of the hydropower potential, in the form of major hydropower plants, has been harnessed (Susewhewa et al., 2004). However, in the dry years, hydroelectricity is unreliable and the grid supply has to depend on imported fossil fuels. The demand for electricity increases 8% per year; for this reason, the country has to use more foreign exchange for oil and coal. To reduce this expenditure, the government has attempted to add non-conventional renewable energy to the system. In this context, Sri Lanka Sustainable Energy Authority (SLSEA) has taken several measures to promote renewable energy within the country. As a result of these measures, the renewable energy component has increased up to 7% of the total electricity generation.

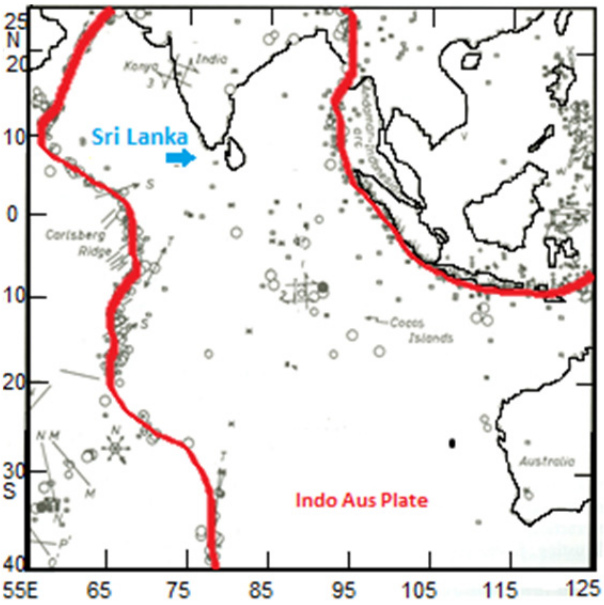

FIGURE 1: Location of Sri Lanka relative to plate boundaries (bold lines); seismic epicentres shown by dots (modified from Dissanayake and Jayasena, 1988)

One of the potential renewable energy sources still to be developed in Sri Lanka is geothermal. Ten hot springs have already been found in the country and SLSEA envisages drawing up a resource assessment programme prior to future exploration of the geothermal resource. This report should be regarded as a part of that effort. It is constructed such that available data sources on the Sri Lanka geothermal potential are reviewed; seismicity, gravity, a ground magnetic survey and the geothermal gradient will be discussed. A chemical analysis of spring water samples will be explained. Determination of the reservoir temperature is the most important factor for assessing the generating capacity. For this, chemical geothermometers were used. Based on the chemical analyses, the water samples were plotted in a Cl-SO_4-HCO_3 ternary diagram for classification of their behaviour, and reservoir temperatures plotted on the Na-K-Mg diagram, clarifying their suitability for chemical geothermometers. Also, the reliability of the determined temperatures from the samples could be checked by this diagram. Based on the geology, seismicity, gravity and ground magnetic surveys, a conceptual model of the geothermal belt was defined. Afterwards, several principal physical parameters were estimated for the geothermal belt. The raw heat generating capacity was estimated by volumetric assessment. The generating capacity of electricity was also assessed by the Monte Carlo simulation. The report concludes with a discussion on the way forward and conclusions drawn.

2. DATA SOURCES

2.1 Geology

According to the theory of plate tectonics, the base rocks forming Sri Lanka and most of south India were part of a single southern landmass called Gondwanaland. Beginning about 200 million years ago, forces within the Earth's mantle began to separate the lands of the Southern Hemisphere, and a crustal plate supporting both India and Sri Lanka moved northeast. About 45 million years ago, the Indian Plate collided with the Asian landmass, raising the Himalayas in northern India and continuing to advance slowly to the present time (US Library of Congress, 1988).

More than 90 percent of Sri Lanka's surface lies on Precambrian strata, some dating back 2000 million years. Figure 2 shows a simplified geological map of Sri Lanka. Granulite facies rocks make up most of the island, divided into a Highland Complex (HC) as the largest and oldest rock unit (2,000 million years) and the northern subdivision known as the Wanni Complex (WC), dated 1100 million years (Kroner et al., 1987; Holzl and Kohler, 1989). Amphibolite facies rocks (Vijayan Complex, VC) occur in the eastern and southern lowlands, dated similar to WC. Jurassic sediments (140-190 million years old) are present in very small areas near the northwest coast while Miocene limestone (5-20 million years old) underlies the northwest part of the country and extends south in a relatively narrow belt along the west coast.

The smallest lithotectonic unit is the Kadugannawa Complex (KC), aged 1,400-1,600 million years (Milisenda et al., 1988; Kroner et al., 1991) and is composed of biotite-hornblende and biotite gneisses, amphibolite, quartzofeldspathic gneisses, pelitic gneisses, quartzites and granitic gneisses.

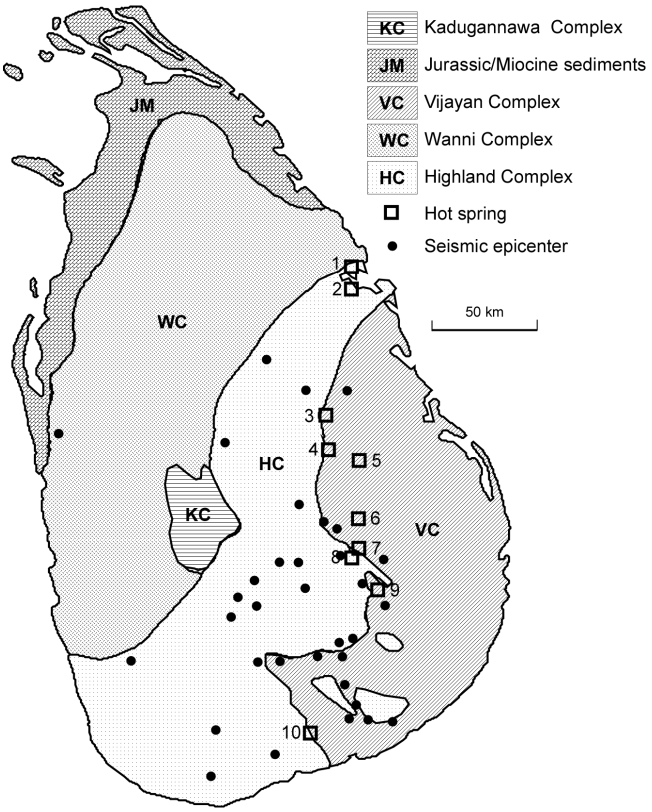

FIGURE 2: The four main lithological units found in Sri Lanka, locations of hot springs (boxes) and microseismic locations (dots) (modified from Dissanayake and Jayasena, 1988)

2.1.1 Geological settings of hot springs

Even though Sri Lanka is not an active volcanic region or situated within the proximity of an active plate margin, the country has some geothermal resources with possible potential for development as a renewable energy source. Geothermal surface manifestations have been recorded from ancient times. Table 1 lists ten thermal springs identified in the country. The location of the manifestations is shown on Figure 2, where it can been seen that a N-S trending belt of hot springs line up with the lithological boundary of the Highland Complex in the west and the Vijayan Complex in the east. The boundary is one of the widely attracted and more controversial geological features in Sri Lanka. It is also considered to be a mineralized belt (Dissanayake, 1985), a convergent plate boundary (Munasinghe and Dissanayake, 1980; Dissanayake and Munasinghe, 1984) and a thrust contact (Vitanage, 1985; Kroner et al., 1991; Kleinschrodt, 1994). Associated with the entire length of the 350 km HC-VC boundary are:

TABLE 1: Thermal springs identified in Sri Lanka

No.	Hot spring	Temperature (°C)	Lithological unit
1	Rankihiriya	-	Highland complex
2	Kanniya	42	Highland complex
3	Nelumwewa/Galwewa	61	Vijayan complex
4	Mutugalwela	-	Vijayan complex
5	Kapurella	55	Vijayan complex
6	Maha Oya	54	Vijayan complex
7	Marangala	48	Vijayan complex
8	Embilinne	-	Vijayan complex
9	Kivulegama	34	Vijayan complex
10	Mahapelessa	44	Vijayan complex

- A line of hot springs;
- Serpentine bodies (Dissanayake, 1985);
- Massive Cu-Fe rich sulphides (Jayawardena, 1982);
- Native sulphur occurrences (Wickramaratne, 1985);
- Diamond occurrences (Dissanayake and Rupasinghe, 1986);
- Groundwater fluoride anomalies (Dissanayake and Weerasooriya, 1986);
- Gravity anomalies along the HC-VC boundary zone (Hatherton et al., 1975) and (Buchel, 1994).

2.2 Geophysics

Several geophysical surveys have been carried out including monitoring of seismicity, gravity and the thermal gradient. Below is a short summary on the available studies.

2.2.1 Seismicity

Sri Lanka is located far away from the boundaries of the Indoaustralian tectonic plate. The nearest active plate boundaries to Sri Lanka are the Sumatra subduction zone to the east and the extensional/transform fault structures of the Central Ridge to the west (Figure 1). The above zones are located approximately 2000 km away from Sri Lanka, hence, any earthquakes in these structures are unlikely to be of geothermal significance in the island.

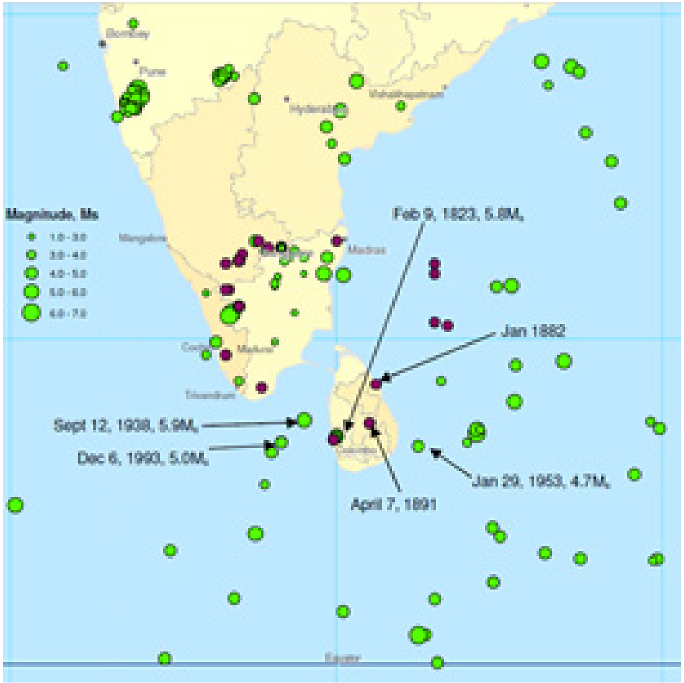

FIGURE 3: Combined earthquake catalogue (Peiris, 2007)

Although numerous large earthquakes have occurred in the past within the South Asian region, few of them were reported within Sri Lanka. An earthquake catalogue was compiled for an area bounded by latitudes 0°N to 20°N and longitudes 70°E to 90°E based on historical and instrumental data since 1819 AD and in terms of surface wave magnitudes, M_S. The catalogue is based on earthquake data compiled by Abayakoon (1995) and the ANSS (2006) earthquake database. Abayakoon's (1995) catalogue was based on data from USGS and from the Institute of Geological Sciences, Edinburgh, UK, extracted from Fernando and Kulasinghe (1986). Figure 3 plots the catalogue, where the location of earthquakes without a magnitude is shown (Peiris, 2007). Based on the earthquake catalogue, selected earthquakes reported in Sri Lanka are listed in Table 2.

Fernando (1983) suggested that slow vertical movements of the Sri Lanka highlands were responsible for the observed seismicity (Figure 2) in the studies he carried out on micro seismicity. An earthquake of significant proportions (>4 in the Richter scale) with its epicentre near Bandarawela was noted and was presumed to have been the result of a major dislocation in the crustal block. The seismicity of the Indian Ocean was described by Sykes (1970) and could also be an influence on micro seismicity in Sri Lanka. Special notice should be given to a cluster of seismicity points at the Highland-eastern contact in the Badarawela-Rakwana area which indicates a thermal anomaly.

TABLE 2: Earthquakes reported in Sri Lanka (Peiris, 2007)

Date	Magnitude	Location	Reference	Damage
April 1615	6.5 M_L	Fort Colombo	Vitanage,1995; Abayakoon, 1995;	2000 deaths 200 houses collapsed
Feb 1823	5.8 Ms	15 km NE of Colombo	Abayakoon, 1995	No damage reported
1857	2.6 Ms	Same	-	-
1866	2.6 Ms	Same	-	-
1882	-	Trincomalee	-	-
April 1891	-	Mahiyangana	-	-

M_L - Richter scale magnitude; M_s - Surface wave magnitude; M_b - Body wave magnitude

2.2.2 Gravity

Figure 4 shows the Bouguer gravity anomaly map of Sri Lanka. Along the boundary of the Highland-Vijayan complexes, a negative anomaly within the Bibile-Mahaoya region is observed. One of the models put forward (Hatherton et al., 1975) to explain the gravity anomaly is a graben or a crustal downwarp associated with deep normal faults linking the download faulted crust to the surface. The hot springs are near the eastern flanks of the graben while the Mahaweli River and the topographic channel through Badulla and Ella flank the western side of the graben. Based on the presence of deuterium (D), oxygen-18 and tritium, it was established that the hot spring waters were meteoric in origin (Dharmasiri and Basnayake, 1986). If the aforesaid deep normal faults are interconnected, the graben waters could enter the western graben and return upward along the eastern graben via interconnected paths. Groundwaters would be driven topographically by a regional contrast in elevation while heating would occur as a result of the normal or above normal temperature gradient of the earth (Perry et al., 1979). A geothermal temperature gradient and heat flow data in this part of Sri Lanka are not available (Fonseka, 1995).

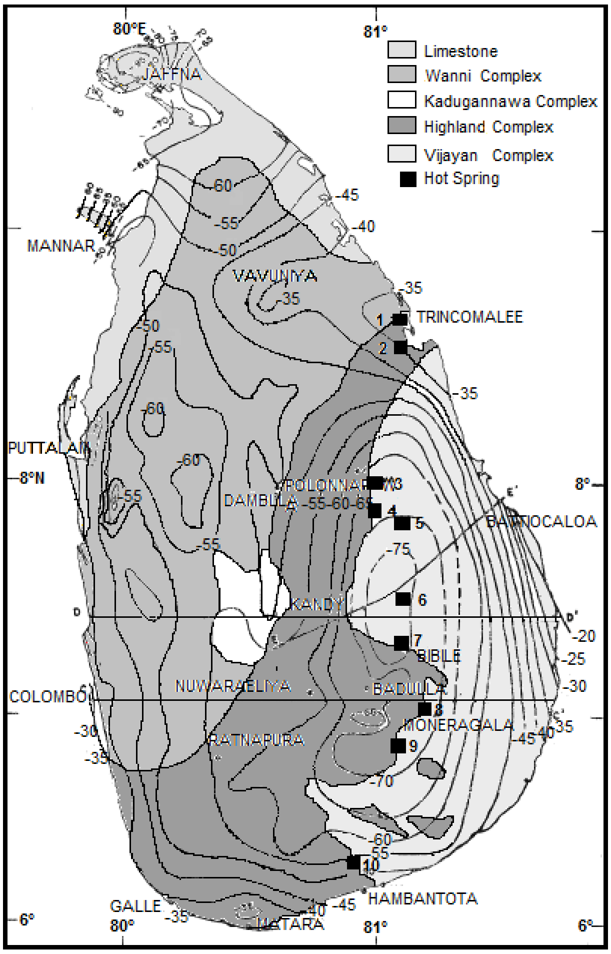

FIGURE 4: A Bouguer gravity map of Sri Lanka (modified from Fonseka, 1995)

The hottest thermal springs lie close to or within the region bounded by the -75 to -55 mGal eastern gravity low (Figure 4). Tectonic features also favour heat production in this region (Fonseka, 1994; Dissanayake and Jayasena, 1988).

2.2.3 Ground magnetic surveys

Even though all the hot spring areas have not been examined with geophysical surveys, a ground magnetic survey was carried out in the area of the Mahapelessa hot springs (Figure 5) of southern Sri Lanka (Taylor, 1997). Figure 6 shows one of the survey lines. Approximately 20 km^2 area centred on two hot springs in the village of Mahapelessa was covered by the survey. The survey was carried out mainly on the roads and tracks surrounding the springs with the central crossroads being the origin of the reference frame. Some extra magnetic traverses were carried out through the jungle and paddy fields where possible in the immediate vicinity of the springs.

The data collected by the survey were interpreted and a geological model was created by it with the observed cross-section. The observed and a calculated magnetic profile based on the model, along one of the survey lines, are shown in Figure 6.

According to the magnetic survey conducted around the Mahapelessa hot springs, a wide fracture zone is directly underneath the hot springs sites. This fracture zone dips about 45°NNW, and is several kilometres wide. The survey concluded that this fracture zone is a segment of the western flank of a graben, with water rising along it from deep within the crust.

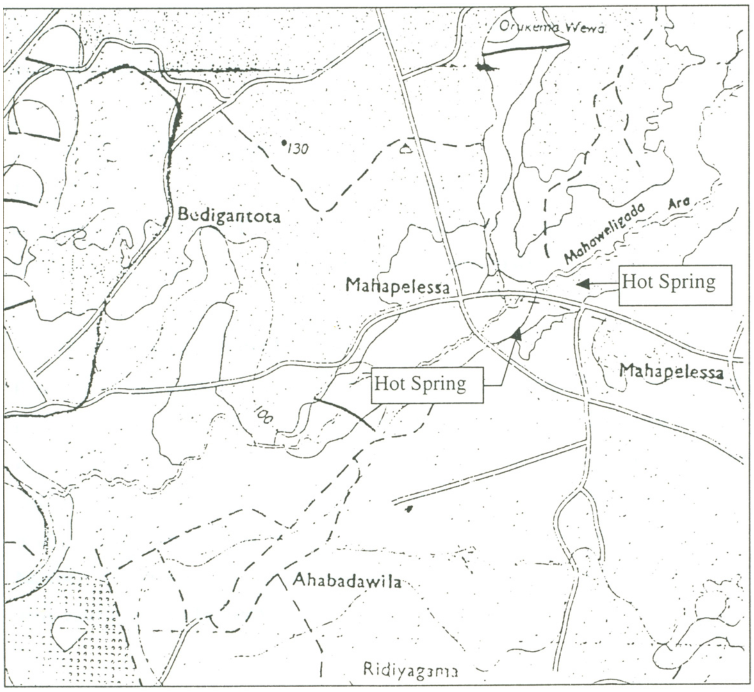

FIGURE 5: Map of Mahapelessa hot springs area (Taylor, 1997)

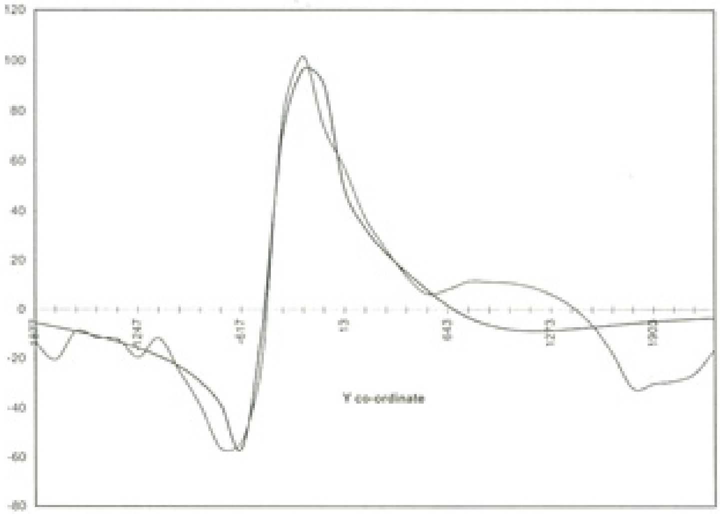

FIGURE 6: Comparison between the observed and calculated magnetic anomaly (Taylor, 1997)

2.2.4 Geothermal gradient

The geothermal gradient is the rate of change of temperature (ΔT) with depth (ΔZ), in the earth. The usual measuring unit is °C/km. In geothermal terms, the measurement of T is associated with heat flow, Q, through the simple relation: $Q=K\Delta T/\Delta Z$, where K is the thermal conductivity of the rock.

The rate of increase with depth (geothermal gradient) varies considerably with both tectonic setting and the thermal properties of the rock. Away from tectonic plate boundaries, it is 25-30°C/km at depth in most of the world. Higher gradients up to 200°C/km are observed along the oceanic spreading centres and along island arcs. The high gradients are due to molten volcanics (magma) rising to the surface. Low gradients are observed in tectonic subduction zones because of thrusting, cold, water-filled sediments beneath an existing crust. The tectonically stable shield areas and sedimentary basins have average gradients that typically vary from 15 to 30°C/km (Stacey, 2008).

Geothermal gradient and heat flow data along the boundary of the Highland-Vijayan complexes (thermal spring belt) of Sri Lanka are still not available. However, a 2.5 km deep borehole on Mannar Island indicates an above normal geothermal gradient of 34.2°C/km (Fonseka, 1994).

2.3 Geochemistry

Of the ten locations in which thermal springs have been found in Sri Lanka (Figure 2, Table 1), the chemistry of Kanniya, Kapurella, Maha Oya, Kivulegama, and Mahapelessa geothermal areas has been studied (Fonseka et al., 1963). The chemical analyses of 7 hot springs are shown in Table 3.

TABLE 3: Chemical composition of geothermal waters from 7 hot springs

Constituents	**Kanniya** # Δ	**Kapurella** Δ	**Maha Oya** ## Δ	**Marangala** *	**Kiulegama** Δ	**Mahapelessa** Δ	**N/Galwewa** +
Temperature (°C)	42	55	54	48	34	44	61
pH	6.4	7.6	7.6	7.6	6.9	7.7	7.75
Conductivity (mSm^{-1})	250.0	1600.0	1500.0	900.0	650.0	7100.0	1350.0
Total solids	220.0	870.0	990.0	662.0	550.0	5490.0	-
Free CO_2	80.0	b.d.l.	b.d.l.	n.d.	14.5	5.3	-
Free NH_3	0.01	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.73
HCO_3^-	4.0	52.1	92.2	4.0	153.6	16.1	-
Cl^-	16.8	286.0	75.9	b.d.l.	34.7	2630.0	-
SO_4^{2-}	b.d.l.	164.0	210.0	30.0	194.2	200.0	200.0
NO_3^-	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	9.0
PO_4^-	55.0	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	1.19
SiO_2	55.0	110.0	110.0	7.0	110.0	90.0	-
Ca^{2+}	38.0	22.4	53.9	18.0	62.8	545.1	32
Mg^{2+}	8.3	0.6	2.7	0.12	8.7	2.7	-
Na^+	11.3	247.3	106.8	16.2	92.0	1157.6	-
K^+	6.5	12.0	14.7	n.d.	4.0	34.8	-
Li^+	b.d.l.	0.6	0.6	n.d.	0.2	5.0	-
Fe^{2+}	0.03	b.d.l.	b.d.l.	0.03	100.0	b.d.l.	1.85

n.d. = Not detected; b.d.l. = Below detection level;
Δ Data obtained from (Fonseka et al., 1963);
* Data obtained from Overseas Technical Cooperation Agency (1966);
# Represents average analysis of waters from seven springs;
Represents average analysis of waters from six springs;
+ Data obtained from Gunarathne (2004).

3. GEOCHEMICAL METHODOLOGY

Chemical geothermometry is a basic tool used to determine subsurface temperatures of geothermal reservoirs. The input parameters for the geothermometer are the chemical analyses of the water samples of hot springs. Hence, the accuracy of the subsurface temperatures determined by the chemical geothermometers depends upon the accuracy of the chemical analyses. One way to evaluate the quality of the analytical work is to calculate the ionic balance of the measured constituents. Naturally the sum of negative ionic charges (the anions) balances the sum of positive charges (the cations). As a rule of thumb, a chemical analysis is acceptable if the calculated ionic balance is:

$$-10\% < Ionic\ Balance < +10\%$$

If the calculated ionic balance lies outside this margin, it is either due to inaccurate analytical results of one or more constituents or because some major element or elements are missing from the analyses. Such samples have to be used provisionally in any interpretation or even excluded.

3.1 Classification of geothermal waters using the Cl-SO_4-HCO_3 ternary diagram

Different chemical compositions of geothermal water affect geothermometers in different ways; hence, classification can give an idea of the reliability of different geothermometers in each case. A widely used classification of geothermal waters was established in terms of the major anions Cl^-, $SO4^{-2}$ and HCO_3^- (Giggenbach, 1991). The three groups are bicarbonate spring waters which are likely to be found at the peripheries of hydrothermal systems; the origins of the bicarbonate are atmospheric CO_2, chlorite water which is likely to represent well equilibrated fluids from major up flow zones, and high sulphate waters which may be formed as a result of the absorption of magmatic gases in groundwater in volcanic areas (Giggenbach, 1991). Other sources of sulphate in non-volcanic areas such as Sri Lanka can be old marine sediments or other rock formations with SO_4-rich minerals.

This classification of geothermal waters is best shown using the Cl-SO_4-HCO_3 ternary diagram (Figure 7). The likelihood of equilibrium between water and rock is higher where waters plot high in the chlorite corner rather than as bicarbonate or sulphate waters. Sub-surface temperatures calculated from chloride type waters are, therefore, more likely to show reliable results than other types of waters.

3.2 Geothermometers

Geothermometers are based on the assumption that specific temperature dependent mineral/solute equilibria are attained in geothermal reservoirs. For a particular geothermometer this only involves a few of the chemical components usually analysed in geothermal water. When different geothermometers are applied to the same fluid, different geothermometer temperatures are obtained in some cases. This could be due to a lack of equilibrium between respective solutes and hydrothermal minerals or due to reactions or mixing with water during upflow, causing modification of geothermal fluid chemical composition.

In 1984, Reed and Spycher proposed that the best way to estimate reservoir temperature is to consider simultaneously the state of equilibrium between a specific solution and many hydrothermal minerals as a function of time. The equilibrium constant is affected by temperature and pressure. However, the pressure in geothermal systems is in the range 0-200 bar and has little effect on the equilibrium constant. Equilibrium constants vary widely with minerals. Hence, the temperature of convergence for a group of minerals in a log (Q_m/K_m) vs. temperature plot will likely be the temperature of the geothermal reservoir. For a reaction:

$$\Delta G_m = +\Delta G^0_{m,r} + RTlog\, Q_m/K_m$$

where K_m is the equilibrium constant, ΔG is free energy, and Q_m is the activity coefficient.

3.2.1 Silica geothermometers

The solubility of silica minerals depends on temperature; it decreases significantly at temperatures below 340°C. Variations in hydrostatic pressure have little effect on the solubilities of quartz and amorphous silica (Fournier and Potter, 1982). Salt influences concentrations greater than 2-3 wt% (Fournier, 1985; Fournier and Marshall, 1983); however, small changes in pressure and salinity have greater effects at temperatures above 300°C. The solubility of silica is also affected by changes in pH. Water rock interactions fix the pH of reservoir fluids at between 5.0 and 7.5. Hence, dissolved silica in hydrothermal solutions can be used with near neutral pH. It is one of the most reliable geothermometers for waters with known steam fractions when this has been corrected for (Fournier, 1991). Equations 1-6 are different expressions for the quartz geothermometer. Temperatures in the range 20-250°C can be calculated using the concentration of silica in mg/kg (S):

Quartz:

$$t°\mathrm{C} = \frac{1309}{5.19 - \log S} - 273.15 \tag{1}$$

Quartz after adiabatic boiling to 100°C:

$$t°\mathrm{C} = \frac{1552}{5.75 - logS} - 273.15 \tag{2}$$

Chalcedony:

$$t°\mathrm{C} = \frac{1032}{4.69 - logS} - 273.15 \tag{3}$$

The other polymorphs of silica used as geothermometers include cristobalite (α-christobalite), opal-CT (β-christobalite) and amorphous silica, obeying Equations 4, 5 and 6, respectively:

α-cristobalite:

$$t°\mathrm{C} = \frac{1000}{4.78 - \log S} - 273.15 \tag{4}$$

Opal-Ct (β-christobalite)

$$t°\mathrm{C} = \frac{781}{4.51 - logS} - 273.15 \tag{5}$$

Amorphous silica:

$$t°\mathrm{C} = \frac{731}{4.52 - logS} - 273.15 \tag{6}$$

The results discussed in this project were calculated using chalcedony and quartz silica geothermometers.

3.2.2 Cation geothermometers

Cation geothermometers depend on ion exchange reactions which are temperature dependent. The geothermometers used include the Na-K geothermometer, the Na-K-Ca geothermometer and the K-Mg geothermometer. They are based on the temperature dependence of the following two reactions (Fournier and Truesdell, 1973):

$$K - feldspar + Na^{+} = Na - feldspar + K^{+}$$

$$2.8\,K - feldspar + 1.6\,water + Mg^{2+} = 0.8\,K - mica + 0.2\,chlorite + 5.4\,silica + 2K^{+}$$

From which the following two geothermometers are derived:

$$t_{kn} = 933/(0.993 - L_{kn}) - 273.15 \tag{7}$$

$$t_{km} = 4410/(1.75 - L_{km}) - 273.15 \tag{8}$$

where $L_{kn} = \log\left(\frac{C_K}{C_{Na}}\right)$; and $L_{km} = \log(C_K^2/C_{Mg})$ and C is in mg/kg.

The Na-K geothermometer

The Na-K geothermometer uses a reaction that involves simultaneous equilibrium between Na^{+} and K^{+} in solution and pure albite and K-feldspar that is expressed by the following equation (D'Amore and Arnórsson, 2000; Fournier, 1991):

$$NaAlSi_3O_3 + K^+ = KAlSi_3O_3 + Na^+ \tag{9}$$

And with an equilibrium constant of:

$$K_{eq} = \frac{[Na^+]}{[K^+]}$$

K_{eq} is the equilibrium constant, and feldspar and albite are almost pure minerals with activity approximating one.

Equation 10 was used for the temperature calculations of this project (Giggenbach, 1988):

$$t°\text{C} = \frac{1390}{1.750 + \log(^{Na}/_{K})} - 273.15 \tag{10}$$

The Na-K-Ca geothermometer

This geothermometer is based on the exchange reaction between Na^+ , K^+ and Ca^{2+} with mineral solids. The following equation was proposed for it (Fournier and Truesdell, 1973):

$$t°\text{C} = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \log(\frac{Ca^{0.5}}{Na}) + 2.24} - 273.15 \tag{11}$$

Concentrations are in mol/kg;

β=4/3 for temperatures <100°C and 1/3 for temperatures > 100°C and for log ($Ca^{0.5}$/Na) < 0;

β=1/3 for water equilibrating above 100°C and 4/3 for water equilibrating below 100°C.

The value β=1/3 should be used when the temperature of the water is less than 100°C when log Ca^{+2}/Na is negative with concentrations expressed in molality units. However, when the geothermometer is applied to waters in which the partial pressure of CO_2 in the aquifer is above 10^{-4} atm, a correction factor I is subtracted from the right hand side of Equation 11, where:

$$I = -1.36 - 0.253 log P_{CO_2} \tag{12}$$

K-Mg geothermometer

Giggenbach (1988) proposed the following equation for a K-Mg geothermometer:

$$t°\text{C} = \frac{4410}{14.0 + \log(\frac{K^2}{Mg})} - 273.15 \tag{13}$$

4. ESTIMATING DEEP RESERVOIR TEMPERATURES

Early studies of the hot springs in Sri Lanka were made by Parsons in 1907, Daniel in 1908 and Chanmugam in 1951 (see Fonseka et al., 1963) and later by Fonseka et al. (1963) where the chemical analysis and physical properties of five hot springs were discussed in detail. The data from Fonseka et al. (1963) were also used for the current project. The thermal springs in question are Kanniya, Kapurella, Maha Oya, Kiulegama and Mahapelessa. In this report, analyses from 8 geothermal locations were evaluated. The analyses are listed in Table 3, and the sources of the data are discussed in the table's caption.

Figure 7 shows the Cl-SO_4-HCO_3 triangular diagram classification of the geothermal fluids collected in Sri Lanka (Table 3). The Mahapelessa site plots close to the chloride corner and is, therefore, classified as mature neutral chloride water. This spring likely formed from discharge from a geothermal reservoir associated with neutral chloride and represents equilibrated fluid from an up flow, and makes this sample suitable for further interpretation. Kapurella also plots in the chloride region, but not as high as Mahapelessa. The Kiulegama and Maha Oya sites plotted in the SO_4 region. The origin of sulphate is not clear but may be due to buried rocks of a marine sediment origin in the region or other high-sulphide mineral assemblages of the host rock. These samples are less suitable for geothermometry.

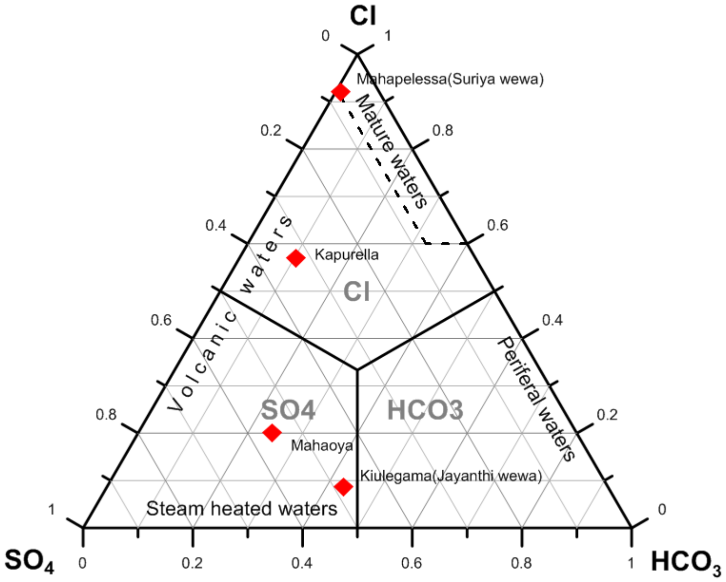

FIGURE 7: Cl-SO_4-HCO_3 classification of hot springs in Sri Lanka

Figure 8 shows the Na-K-Mg ternary diagram for the geothermal fluids listed in Table 3. They can be classified as immature, partial equilibrated and fully equilibrated waters. The diagram shows which fluids are suitable for geothermometry: partially and fully equilibrated fluids. The graph confirms the above observation that the Mahapelessa and Kapurella waters are well suited for further interpretation as they plotted near the full equilibrium curve. The Maha Oya water sample plotted close to the partial equilibrium line. The other samples, Marangala, Kiulegama and Kanniya, plotted in the Mg corner of the diagram, indicating non-equilibrium.

Calculated subsurface temperatures of the hot springs are shown in Table 4, based on the silica and Na/K geothermometers. Based on the above results, Kapurella, Mahaoya and Mahapelessa samples qualify for interpretation. Other samples are less likely to give reliable information because of poor analytical quality (poor ionic balance).

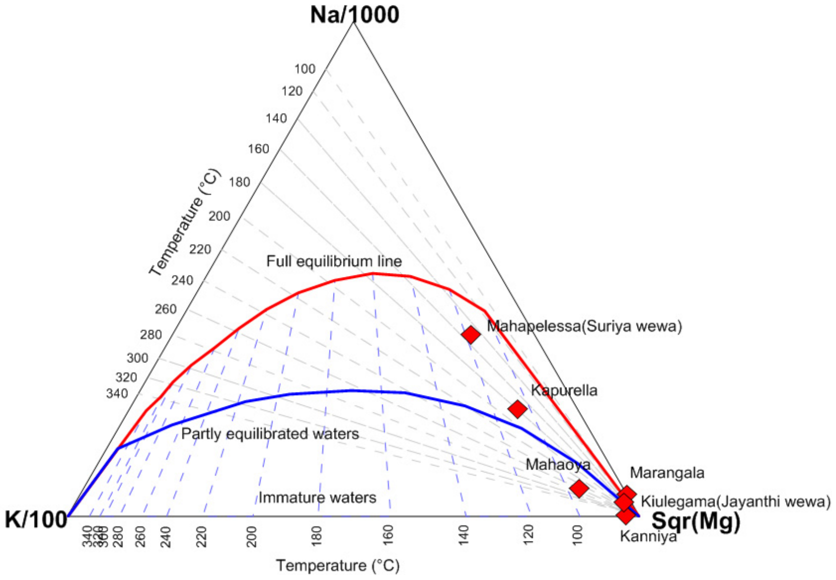

FIGURE 8: Na-K-Mg diagram for Mahapelessa, Kapurella Maha Oya, Marangala, Kiulegama and Kanniya hot springs

Interpretation of the chemical data indicates a possible subsurface temperature of 100-140°C. But it was not possible to find a correlation between the hot springs with the results obtained from the above analysis. More detailed analyses of all the hot springs with quality samples will help to improve the findings by using geochemical interpretations, including whether or not there might be a correlation between the hot springs.

TABLE 4: Subsurface temperatures of hot springs based on chemical geothermometers

Location	**Date**	**Sampling temperature (°C)**	**Ion balance (%)**	**Geothermometers**		
				SiO_2q (°C)	**SiO_2c (°C)**	**Na/K (°C)**
Kanniya	1963	42	-40.7	107	76	
Kapurella	*1963*	*55*	*-0.6*	*143*	*113*	*136*
Maha Oya	*1963*	*54*	*-0.4*	*143*	*113*	*245*
Marangala	1966	48	80.5	25		
Kiulegama	1963	34	45.4	143	114	126
Mahapelessa	*1963*	*44*	*-0.1*	*132*	*101*	*100*
Nelumwewa	2004	61	-90.9			
Wahawa	2011	54				

5. CONCEPTUAL RESERVOIR MODEL – COUNTRY SCALE

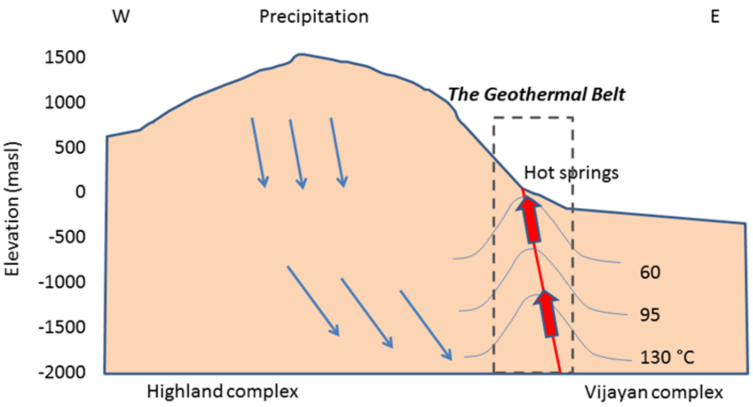

FIGURE 9: A conceptual reservoir model for geothermal systems in Sri Lanka

Based on the above mentioned information on tectonics, geophysics, seismicity and geochemical reactions, a conceptual reservoir model was put forward (Figure 9). Most thermal manifestations (hot springs) were seen to be in close proximity to the boundary of the Highland and Vijayan Complex. This boundary zone can be interpreted as a geothermal belt. Based on these manifestations, we can imagine that there is most likely a fault zone located along the Highland-Vijayan boundary. Precipitation in the highlands goes through the ground to deep high-temperature rocks. Here the already observed 35°C/km is assumed to be the thermal gradient of the hot springs belt. In turn, the water is heated and emerges on the surface as manifestations of the reduced density of heated water in the faults.

6. VOLUMETRIC GENERATING CAPACITY ASSESSMENT

In this study, most of the field data was based on geochemistry, coupled with geological and geophysical observations. Production history and well data were not available. In order to estimate a green field generating capacity without downhole data, there are three main methods available. These methods are volumetric modelling, lumped parameter modelling and distributed parameter modelling (numerical simulation). For this project, volumetric modelling was used to coarsely estimate the generating capacity of Sri Lanka.

The stored heat method assumes that we extract the heat from a specific volume of the geothermal belt, cooling it down from an initial temperature (T) to a base temperature (T_0). For this purpose, we need to define a volume for heat extraction as shown in Figure 10. Based on the subsurface

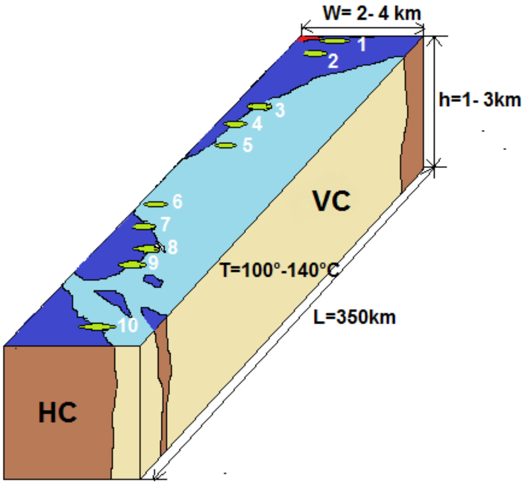

FIGURE 10: Volume of the Sri Lanka geothermal belt; L = Length of the geothermal belt (km); h = Thickness of the geothermal belt (km); w = Width of the geothermal belt (km); T = Initial temperature of the geothermal belt (°C); VC = Vijayan complex; HC = Highland complex

temperatures determined by the chemical geothermometers (Table 4), a reservoir temperature ranging from 100-140°C was found. Assuming that the reservoir is liquid dominated and a governing equation has been selected, its basic input parameters can be estimated for the volumetric method's governing equation. For such a reservoir, the stored heat is denoted by 'Q', calculated using the following equations (Halldórsdóttir et al., 2010):

$$Q = Q_r + Q_w \tag{14}$$

$$Q = Ah(1-\emptyset)C_r\rho_r(T-T_0) + Ah\emptyset C_w\rho_w(T-T_0) \tag{15}$$

where Q_r = Stored heat of the geothermal belt rocks (J);
Q_w = Stored heat of the water (J);
A = Surface area of the geothermal belt (m^2);
h = Thickness of the geothermal belt (m);
C_r = Specific heat of the geothermal belt (J/kg°C);
ρ_r = Density of the geothermal belt (kg/m^3);
T = Initial temperature of the geothermal belt (°C);
T_0 = Base temperature of the geothermal belt (°C);
Φ = Porosity;
C_w = Specific heat of water (J/kg°C);
ρ_w = Density of water (kg/m^3).

Now it can be assumed that the available heat defined by Equation 15 is extracted at a steady rate over a given time and at a given conversion efficiency and recovery factor. This results in a formula like:

$$P = \frac{nRQ}{t} \tag{16}$$

where P = Power (W_e);
n = Electrical utilization constant;
R = Recovery factor;
t = Utilization time, here chosen 50 and 100 years.

According to Equation 15, the most likely amount of raw heat stored in the geothermal resource is:

$$Q = Ah(1-\emptyset)C_r\rho_r(T-T_0) + Ah\emptyset C_w\rho_w(T-T_0)$$

or

$$\begin{aligned} Q &= 1000 \times 10^6 \times 2 \times 10^3 \times (1-0.1) \times 900 \times 2750 \times (120-80) + \\ &\quad 1000 \times 10^6 \times 2 \times 10^3 \times 0.1 \times 4185 \times 926 \times (120-80) \\ &= \mathbf{209{,}203 \times 10^6 GJ} \end{aligned}$$

Raw heat could be recovered from the resource as

$$Q = R \times 209203 \times 10^6 GJ$$

or

$$Q = 0.25 \times 209203 \times 10^6 GJ \ = \mathbf{52,300 \times 10^6 GJ}$$

Thermal energy that could be utilised constantly within 50 years as:

$$P \ = \frac{52300 \times 10^6 GJ}{50 \times 365 \times 24 \times 60 \times 60S} \quad = \mathbf{33\ GW_t}$$

Thermal energy that could be utilised constantly within 100 years as:

$$P = \frac{78740 \times 10^6 GJ}{100 \times 365 \times 24 \times 60 \times 60S} = \mathbf{17\ GW_t}$$

where A = 1000 km^2 (most likely value);
h = 2000 m;
ϕ = 10%;
C_r = 900 J/kg°C;
ρ_r = 2750 kg/m3;
C_w = 4185 J/kg°C;
ρ_w = 926 kg/m^3;
T = 120°C (most likely);
T_0 = 80°C
R = 0.25.

From this calculated thermal energy , 5% could be utilised for power generation and 25% could be used for air conditioning. The rest could be utilised for other industries. The capacities of thermal power and utilization could be summarised as in Table 5.

TABLE 5: Summary of the potential of thermal power in Sri Lanka

Utilisation time period (years)	50	100
Available total thermal potential (GW_t)	33	17
Potential for power generation - 5% (GW_t)	1.65	0.85
Potential for air conditioning - 25% (GW_t)	8.25	4.25
Potential for other industries - 70% (GW_t)	23.1	11.9

7. MONTE CARLO VOLUMETRIC ASSESSMENT APPROACH

With the governing equation stated above, the Monte Carlo method (Thorgilsson, 2008) was applied using the most appropriate values or range of values. The key parameters required to estimate the electrical power potential in this project were found to be: the surface area of the geothermal belt, thickness of the belt, temperature distribution in the belt, porosity of the belt, the physical characteristics of the belt and water, the recovery factor, the cut-off temperature, the conversion efficiency factor of heat to electricity, and the production time. The basis for the assumptions made for each of the underlying parameters is explained such that the rationality for the figures used becomes more realistic.

7.1 Selecting principal parameters

- In Sri Lanka, most of the thermal springs are located within the 350 km belt on the eastern side, in close proximity to the Highland Vijayan boundary line. The width of the geothermal belt was considered to be 2-4 km across the boundary line. The minimum value of the area should be 700 km^2 and the maximum value should be 1400 km^2. The most likely value is 1000 km^2.

- Subsurface temperatures determined by the geothermometers reached at 1-3 km of depth (also based on a thermal gradient of 35°C/km). Hence, 1, 2 and 3km values were considered as the minimum, best value and maximum values of the reservoir thickness for the Monte Carlo simulation.
- Volcanic rocks were considered to be basaltic and, accordingly, the porosity was assumed to be between 5 and 10%.
- Specific heat of belt and water were selected according to the temperatures of rock and water at 120°C.
- Densities of rock and water were also selected based on their temperature at 120°C.
- The temperature of the upper depth was selected as 120°C (most likely value) based on geothermometry.
- According to the subsurface temperatures obtained by the analysis, the maximum temperature may be near 140°C. Here, 120°C was considered the most likely temperature of the reservoir. 80°C was the cut off temperature for the simulation.
- Based on the porosity (5-10%), the recovery factor selected was 25% (Muffler, 1979).
- For the simulation, it was assumed that the boiling curve ratio was 1.
- Because it is a low-temperature field, conversion efficiency was considered to be 5% for electrical power.

A Monte Carlo simulation was done to assess the electricity potential of the geothermal resource in the country for 50 and 100 year time periods.

7.2 Monte Carlo volumetric assessment for 50 years electricity production

Data used for a volumetric assessment under conservative conditions for 50 years are in Table 6.

TABLE 6: Input data for the Monte Carlo volumetric assessment for 50 years

Data	Minimum	Most likely	Maximum	Distribution
Number of runs		10000		Fixed
Number of histogram bins		30		Fixed
Max depth of boil curve (m)		0		Fixed
Upper depth of reservoir (m)		0		Fixed
Lower depth of reservoir (m)	1000	2000	3000	Triangular
Area (km^2)	700	1000	1400	Triangular
Temperature of upper depth (°C)	100	120	140	Triangular
Cut off temperature (°C)		80		Fixed
Porosity (%)	5		10	Constant
Specific heat of rock (J/kg°c)		900		Fixed
Density of rock (kg/m^3)		2750		Fixed
Specific heat of water (J/kg°c)		4185		Fixed
Density of water (kg/m^3)		926		Fixed
Boil curve ratio (%)		1		Fixed
Linear water heat grad.(°C/km)		0		Fixed
Latent heat of lava (J/kg)		0		Fixed
Recovery factor (%)		25		Fixed
Conversion efficiency (%)		5		Fixed
Accessibility (%)		100		Fixed

Parameter values in Table 6 were applied to the Monte Carlo simulation and the results are shown in Table 7. The results in Table 6 point out that the volumetric assessment predicts with a 90% probability that the reservoir could produce 715-2515 MWe for 50 years. The probability distribution for a simple power curve and the probability distribution for a cumulative power curve are shown in Figures 11 and 12, respectively.

TABLE 7: Volumetric generating capacity for 50 years of electricity production

Parameters	**Power (MWe) for 50 years**	
	Normal distribution	**Cumulative distribution**
Most probable value (at least 9% probability)	1335	450
90% probability interval	715-2515	0-970
Mean	1550	1540
Median	1480	1480
Standard deviation	505	503

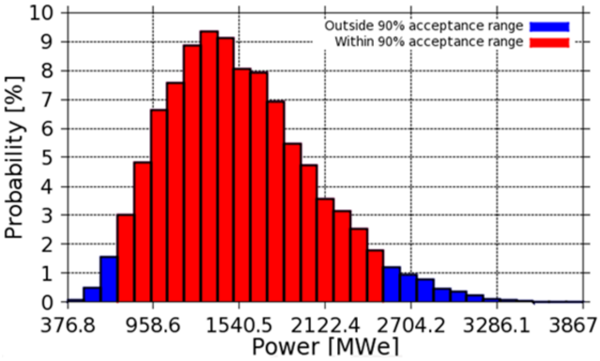

FIGURE 11: Probability distribution of power for 50 years production, assuming a 1000 km^2 reservoir area

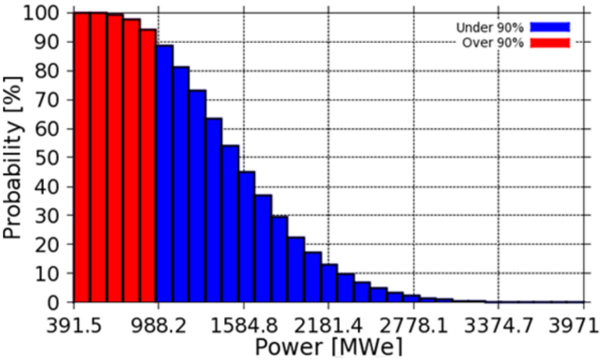

FIGURE 12: Probability distribution of cumulative power for 50 years production, assuming a 1000 km^2 reservoir area

7.3 Monte Carlo volumetric assessment for 100 years electricity production

The above assessment was also done for a 100 year time period using the same input data. The results are shown in Table 8.

TABLE 8: Volumetric generating capacity for 100 years of production

Parameters	**Power (MWe) for 100 years**	
	Normal distribution	**Cumulative distribution**
Most probable value (at least 9% probability)	723	225
90% probability interval	385- 1250	0-475
Mean	775	770
Median	750	740
Standard deviation	250	250

According to Table 8, the volumetric assessment predicts with a 90% probability that the reservoir could produce 385-1250 MWe for 100 years. The probability distribution for a simple power curve and the probability distribution for a cumulative power curve are shown in Figures 13 and 14, respectively.

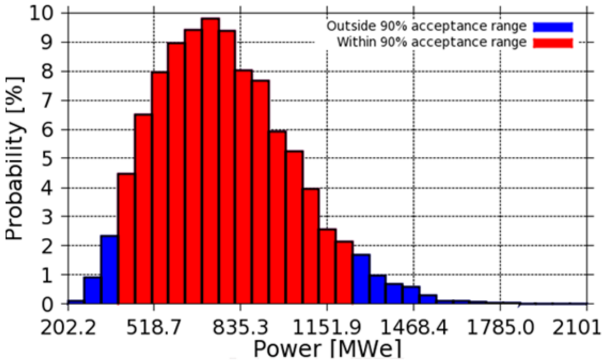

FIGURE 13: Probability distribution of power for 100 years production, assuming a 1000 km^2 reservoir area

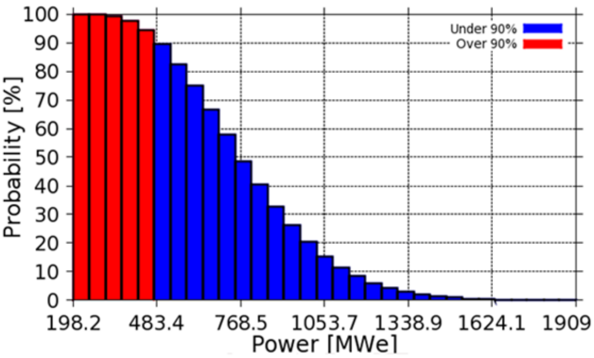

FIGURE 14: Probability distribution of cumulative power for 100 years production, assuming a 1000 km^2 reservoir area

8. SELECTING SITES FOR FUTURE GEOTHERMAL DEVELOPMENT

8.1 Exploration and reconnaissance study for many sites

The purpose of this phase is to select the commercially exploitable geothermal resource for additional work. The first task is to perform a study based on all the available existing data regarding the geothermal field and environment in order to define the resource and the scope of subsequent exploration activities:

- Geological mapping of important geological features in order to understand the geological structure of the geothermal system.
- Geochemical analysis of surface manifestations or existing shallow wells, if available, to get indications on the reservoir temperatures.
- Geophysical explorations such as resistivity measurements, gravity and ground based magnetics where needed to better understand the subsurface temperatures of the resource.
- Drilling of shallow exploration wells (50-300 m) to measure the temperature gradients in order to locate the up flow zone of hot fluids in the geothermal reservoir.

8.2 Pre-feasibility study for developing 1-2 sites

If the results received from the exploration phase are favourable, choosing and developing exploitable sites comprises the next phase. This study may include the following activities:

- Analysis of market in the area;
- Land access;
- More focussed geophysical exploration, for example ground magnetics;
- Drilling of slim wells (> 300 m);
- Environmental baseline study;
- Fluid chemical analysis;
- Production potential assessment;
- Pre-feasibility data analysing and reporting.

8.3 Feasibility study

In this phase the commercial level of the geothermal resource is determined by the following activities where deep drilling is the focus:

- Environmental impact assessment;
- Drilling of production/injection wells;
- Fluid sampling and chemical analysis;
- Well testing and well logging;
- Conceptual modelling;
- Production potential assessment (reservoir modelling);
- Preliminary design of power plant and surface equipment;
- Feasibility data analysing and reporting.

8.4 Detailed design and power plant construction

If the project is still feasible and other requirements are satisfied (i.e. a hot water reservoir is proven, signing of power purchase agreement and availability of finances), detailed design and construction can be started with the following activities:

- Infrastructure facilities design and civil works;
- Detailed design of power plant and fluid gathering system;
- Detailed design of power transmission lines and point of access determined;
- Contracting of service providers for detailed design, engineering, procurement, construction and project management;
- Construction of the power plant and facilities;
- Training of operators and commissioning.

9. POSSIBLE APPLICATIONS

The reservoir temperature of Sri Lanka is estimated here to be in the 100-140°C range. Thus, probably 5% of the raw heat could be utilised to generate electricity. The rest of the raw heat could be utilised for other suitable applications. The Lindal diagram (Figure 15) indicates the temperature range of geothermal fluids suitable for various applications. Possible applications for geothermal energy in Sri Lanka based on the Lindal diagram are the following:

Power generation: At present in Sri Lanka, 42% of electricity is generated by hydro, 51% by thermal and the rest by renewable sources. The country needs to reduce the expenditure for fossil fuels. Hence, geothermal resources with reasonable subsurface temperatures could be used for electricity generation through binary cycle power plants. This would reduce fuel costs as well as emissions of CO_2 to the environment.

Air conditioning: In Sri Lanka, the total installed capacity of electricity generation is nearly 2860 MW and the maximum demand per day is approximately 2000 MW. Electricity consumption on a normal day is 30 GWh. This value can increase up to 35 GWh on hot days and decrease on rainy days. The difference, 10 GWh, between the upper margin and the lower margin would probably be used for air conditioning and water supply. These geothermal resources could be used for air conditioning in villages and towns within 10-20 km distance from the geothermal site. The technology is based on well-known absorption chillers and requires the building of a district cooling pipe system.

Hot water supply: Another electricity consuming activity is the heating of water. At present, a main hot water supply network is not available in Sri Lanka. If geothermal hot water from the reservoirs could be supplied to nearby consumers, it would reduce the cost of fossil fuels and would be another income source for the National Water Supply and Drainage Board of Sri Lanka.

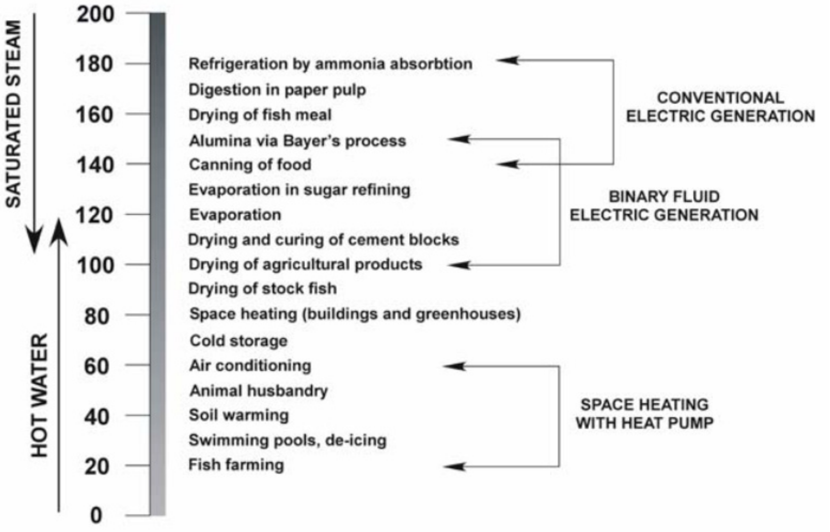

FIGURE 15: Lindal diagram (Gudmundsson et al., 1985)

Drying of stock fish: Sri Lanka is a tropical country in South Asia. Drying of stock fish is carried out normally by sunshine on the shore. During drying, yields can be infected by insects. Here, geothermal heat could be utilized in a controlled and continuous manner to protect hygiene and prevent the wastage of food. It would also supply continuous production independent of weather conditions.

Development as tourist attraction places: At present, most hot spring areas are already being used as bathing and tourist attraction places. Hot springs with lower subsurface temperatures could be developed as public bathing places and saunas. Since all the hot springs are located in the eastern part of the country, and some of them are close to the sea, there is a greater possibility for developing some hot spring locations into tourist attractions.

10. CONCLUSIONS

The main objective of the study was to determine the potential of Sri Lanka's geothermal energy resources. The major conclusions of the study are as follows:

- According to the study, geothermometers indicate that the subsurface temperature of the geothermal reservoirs could be between 100 and 140°C.
- A subsurface temperature of 140°C is indicative of possible development of low-temperature geothermal resources.
- A potential geothermal energy source was estimated in a geothermal belt with a length of 350 km (length of the hot spring belt), a thickness of 2 km and a width of 2 km.
- A potential of 1335 MWe generating capacity for 50 years and 723 MWe generating capacity for 100 years were estimated by a Monte Carlo simulation.
- A USD 10 million investment might be enough to develop a 2 MWe power plant.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to the United Nations University Geothermal Training Programme and to my employer, Sri Lanka Sustainable Energy Authority, for giving me the opportunity to participate in the six months training in Iceland. My sincere gratitude to the UNU-GTP staff: Dr. Ingvar B. Fridleifsson, Mr. Lúdvík S. Georgsson, Ms. Thórhildur Ísberg, Mr. Markús A.G. Wilde and Mr. Ingimar G. Haraldsson. Special gratitude goes to Mr. Grímur Björnsson and Mr. Gestur Gíslason for their dedicated guidance and technical support during the preparation of my project. I also thank the UNU-GTP 2011 colleagues for their memorable co-operation.

Finally, I express my deepest gratitude to my workmates, friends, relatives and my family. To my dear wife, and daughter (born during my training) and my mother - thanks for your encouragement, sacrifice, and unconditional love during my six months of study.

REFERENCES

Abayakoon, S.B.S., 1995: Seismic risk analysis of Sri Lanka. *J. Geolog. Soc. Sri Lanka, 6*, 65-72.

ANSS, 2006: *Advanced national seismic system*. Webpage: *www.usgs.gov*

Buchel, G., 1994: Gravity, magnetic and structural patterns at the deep-crustal plate boundary zone between West and East Gondwana in Sri Lanka. *Precamb. Res., 66*, 77-91.

D'Amore, F., and Arnórsson, S., 2000: Geothermometry. In: Arnórsson, S. (ed.), *Isotopic and chemical techniques in geothermal exploration, development and use. Sampling methods, data handling, interpretation*. International Atomic Energy Agency, Vienna, 152-199.

Dharmasiri, J.K., and Basnayake, S.B., 1986: Origin of thermal springs of Sri Lanka. *Sri Lanka Association for the Advancement of Science, 42,* 156-157.

Dissanayake, C.B., 1985: Application of plate tectonics to mineral exploration – discovery of a mineralised belt in Sri Lanka. In: Dissanayake, C.B., and Cooray, P.G. (eds.), *Recent Advances in the Geology of Sri Lanka,* CIFEG, Paris, 41-47.

Dissanayake, C.B., and Jayasena, H.A.H., 1988: Origin of geothermal systems of Sri Lanka. *Geothermics, 17-4,* 657-669.

Dissanayake, C.B., and Munasinghe, T., 1984: Reconstruction of the Precambrian sedimentary basin in the granulite belt of Sri Lanka. *Chem. Geol., 47,* 221-247.

Dissanayake, C.B., and Rupasinghe, M.S., 1986: Possibilities for diamond occurrences in Sri Lanka. *J. Gemmologists Assoc. of Sri* Lanka, 3, 2-6.

Dissanayake, C.B., and Weerasooriya, S.V.R., 1986: Fluoride as an indicator or mineralization – hydrogeochemistry of a Precambrian mineralised belt in Sri Lanka. *Chem. Geol., 56*, 257-270.

Fernando, M.J., 1983: Microseismic activity in Sri Lanka. *Abstr. Symp. Geol. Sri Lanka, Peradeniya, Sri Lanka*, 2-3

Fernando, M.J., and Kulasinghe, A.N.S., 1986: Seismicity of Sri Lanka. *Physics of Earth and Planetary Interiors, 44,* 99-106.

Fonseka, G.M., 1994: Geothermal systems in Sri Lanka and exploitation of geothermal energy. *J. Geo. Soc. Sri Lanka, 5.*

Fonseka, G.M., 1995: Sources of geothermal heat and hydrogen: In: Dhanayake, K. (ed.), *Handbook on geology and mineral resources of Sri Lanka,* GEOSAS-II, Colombo, Sri Lanka*,* 29-31.

Fonseka, J.P.R., Silva, N.R.De., Balendran, V.S., and Seneviratne, L.K., 1963: Minerals and thermal waters of Ceylon. *Internat. Geological Congress, 19,* 9-19.

Fournier, R.O., 1985: The behaviour of silica in hydrothermal solutions. *Rev. Econ. Geol, 2*, 45-61.

Fournier, R.O., 1991: Water geothermometers applied to geothermal energy. In: D'Amore, F., (coordinator), *Applications of geochemistry in geothermal reservoir development.* UNITAR/UNDP, publication, Rome, 37-69.

Fournier, R.O., and Marshall, W.L., 1983: Calculation of amorphous silica solubilities at 25°C to 300°C and apparent cation hydration numbers in aqueous salt solutions using the concept of effective density of water. *Geochim. Cosmochm. Acta, 47*, 587-596.

Fournier, R.O., and Potter, R.W. II, 1982: An equation correlating the solubility of quartz in water from 25 to 900°C at pressures up to 10,000 bars. *Geochem. Cosmochim. Acta, 46*, 1969-1974.

Fournier, R.O., and Truesdell, A.H., 1973: An empirical Na-K-Ca geothermometer for natural waters. *Geochim. Cosmochim. Acta*, *37*, 1255-1275.

Giggenbach, W.F., 1988: Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators. *Geochim. Cosmochim. Acta*, *52*, 2749-2765.

Giggenbach, W.F., 1991: Chemical techniques in geothermal exploration. In: D'Amore, F. (coordinator), *Applications of geochemistry in geothermal reservoir development.* UNITAR/UNDP, Rome, Italy, 119-142.

Gudmundsson, J.S., Freeston, D.H., and Lienau, P.J., 1985: The Lindal diagram. *Geothermal Resources Council, Transactions, 9*, 15-19.

Gunarathne, P.M.S.S., 2004: *Hydrological and geochemical aspects of Gal Wewa thermal spring and its development potential.* University of Peradeniya, Faculty of Science, 25 pp.

Halldórsdóttir, S., Björnsson, H., Mortensen, A.K., Axelsson, G., and Gudmundsson, Á., 2010: Temperature model and volumetric assessment of the Krafla geothermal field in N-Iceland. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia,* 10 pp.

Hatherton, T., Pattiarachchi, D.B., and Ranasinghe, V.V.C., 1975: *Gravity map of Sri Lanka, 1:1,000,000.* Geol. Survey Dept., Sri Lanka, Prof. Paper 3, 39 pp.

Holzl, S., and Kohler, H., 1989: *U-Pb Geochronologie an Unterkrustengesteinen Sri Lankas* (in German). Eur. J. Min., 1, Beiheft., 1, 75 pp.

Jayawardena, D.E. de S., 1982: The geology and tectonic setting of the copper-iron prospect at Seruwila, Northeast of Sri Lanka. *J. Nat. Sci. Counc. Sri Lanka, 10,* 129-143.

Kleinschrodt, R., 1994: Large scale thrusting in the lower crustal basement of Sri Lanka. *Precamb. Res., 66,* 39-57.

Kroner, A., Cooray, P.G., and Vitanage, P.W. 1991: Lithotectonic subdivision of the Precambrian basement in Sri Lanka. In: Kroner, A. (ed.), *The crystalline crust of Sri Lanka. Part I: Summary of research of the German – Sri Lanka consortium*. Geol. Surv. Dept., Sri Lanka, prof. paper. 5, 5-21.

Kroner, A., Williams, I.S., Compston, W.Baur, N., Vitanage, P.W., and Perera, L.R.K., 1987: Zircon ion microprobe dating of high grade rocks in Sri Lanka. *J. Geol., 95,* 775-791.

Milisenda, C., Liew, T. C., Hoffmann, A.W., and Kroner, A., 1988: Isotopic mapping of age provinces in Precambrian high grade terrains: Sri Lanka. *J. Geol., 96,* 608-615.

Muffler, L.P.J. (editor), 1979: *Assessment of geothermal resources of the United States – 1978.* USGS, circular 790, Arlington, VA.

Munasinghe, T., and Dissanayake, C.B., 1980: Are charnokites metamorphosed Archaean volcanic rocks? A case study from Sri Lanka. *Precamb. Res., 12,* 459-470.

Peiris, N., 2007: Seismic hazard assessment of Sri Lanka and seismic risk in Colombo. *Presented at the 8th Pacific Conference on Earthquake Engineering, Singapore.*

Perry, L.D., Costain, J.K., and Geiser, P.A., 1979: Heat flow in Western Virginia and a model for the origin of thermal physics in folded applications. *J. of Geophys. Res, 84, B12,* 6875-6883.

Reed, M.H., and Spycher, N.F., 1984: Calculation of pH and mineral equilibria in hydrothermal water with application to geothermometry and studies of boiling and dilution. *Geochim. Cosmochim. Acta, 48*, 1479-1490.

Stacey, F.D., and Davis, P.M., 2008: *Physics of the earth.* Cambridge University Press, Cambridge, UK, 546 pp.

Susewhewa, D.L., Wanaguru, D.C., Thotawatta, R.T., and Wickramasinghe., 2004: *Investigation of technical and financial viability of wind power in Sri Lanka.* University of Moratuwa, unpublished paper.

Sykes, L.R., 1970: Seismicity of the Indian Ocean and a possible nascent island arc between Ceylon and Australia. *J. Geophys. Res., 75*, 5041-5055.

Taylor, S., 1997: *A magnetic survey of the Mahapelessa hot springs in southern Sri Lanka*. University of Edinburgh, Departm. of Gelogy and Geophysics, 24 pp + apps.

Thorgilsson, G., 2008: *Monte Carlo program*. UNU-GTP, Iceland, unpublished lecture notes.

U.S. Library of Congress, 2011: *Geology of Sri Lanka*. U.S. Library of Congress, webpage: *country studies.us/sri-lanka/31.htm.*

Vitanage, P.W., 1985: The geology, structure and tectonics of Sri Lanka and South India. In: Dissanayake, C.B., and Cooray, P.G. (eds.), *Recent advances in the Geology of Sri Lanka*. CIFEG Occasional Publ., 5-15.

Wickramaratne, W.S., 1985: The discovery of native sulphur in the Highland – Vijayan mineralized belt (abstr.). *Assoc. Adv. Sci. Sri Lanka, 40.*