UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

Reports 2010
Number 18

GENERATING CAPACITY AND SUSTAINABLE USE OF GEOTHERMAL RESOURCES IN NEVIS

Anelda Maynard-Date
Nevis Electricity Company Limited
P.O. Box 852; Pinney's Commercial Site, Charlestown
NEVIS W.I.
adate@nevlec.com

ABSTRACT

Verification of the generating capacity and the sustainability of the geothermal resource on Nevis is important for the development of the country. The existence of numerous surface manifestations on the western side of the island led to studies and later exploratory work in 2007 by the West Indies Power Holding. The success of the exploratory work resulted in the proposed installation of an initial 10 MWe power plant and future expansion, first to 35 MWe to include the sister island of St. Kitts. Available field and downhole data indicate that a 210-260ºC high-temperature reservoir exists below a depth of approximately 600 m on the western side of the island. A volumetric resource assessment, incorporating parameter uncertainties by using a Monte Carlo approach, was applied and the results support the installation of the first phase of a 10 MWe plant. Under a very conservative analysis, the proven reservoir can supply 18-83 MWe for a period of 30 years. The results also imply that the expected 25 MWe addition of St. Kitts to the grid would not pose problems for the geothermal reservoir. Adopting the concept that a sustainable production level E_0 can be defined for every geothermal reservoir, the sustainability of the geothermal development based on a 100 year analysis supports a steady generation of 10 MWe. However, it is best to keep in mind that since no production has taken place to date, the value of E_0 given in the report is not fixed and is likely to be higher, considering that recharge was not factored into the volumetric assessment. The analysis is, therefore, purely speculative and serves only as a guideline of the methods necessary to monitor the resource. It is clear that for the geothermal energy to become sustainable, this renewable source of energy must find a balance with the environment, and with economic and socio-political factors. Thus, if power plant extraction of heat and mass exceeds the rate of replenishment after years of development, then the production rate may need to be lowered to facilitate sustainability. This scenario is best avoided with proper monitoring and modelling of the reservoir.

1. INTRODUCTION

Nevis, which is part of the twin island federation of Saint Christopher & Nevis, more commonly known as St. Kitts and Nevis, is located in the Caribbean Lesser Antilles at approximately 17°09'North and 62°35'West. It forms a part of the inner arc of volcanic islands with Saba in the north and Grenada in the south on the subduction zone of the Caribbean and North American plates, as

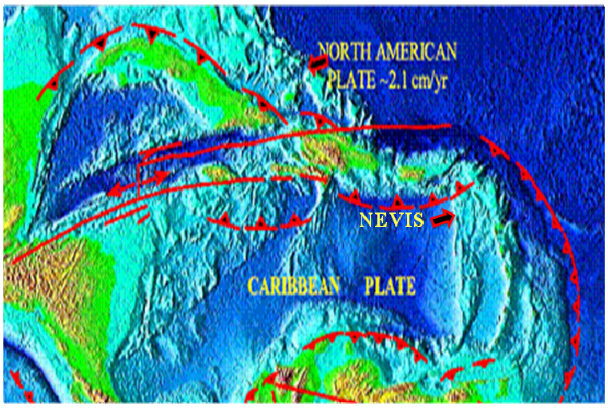

FIGURE 1: Subduction zone of the Caribbean and North American plates (Geoalba, 2001)

shown in Figure 1 (Geoalba, 2001). Nevis is the smaller of the two islands and is about 93 km^2 with a population of around twelve thousand inhabitants (Includipedia, 2007). Provided for by the constitution of St. Kitts and Nevis, the operations on Nevis are governed principally by the Nevis Island Administration (NIA). The island's main industries are service-based, being tourism and offshore banking. Nestled in the Caribbean, the tourism industry is frequently interrupted by the annual hurricane season which is known to impact at one point or the other quite negatively. With this as the motivating force, NIA diligently explores other avenues to sustain and advance the economy of the island.

Prior to the studies done by the West Indies Power Holdings, Ltd. (WIPH), four major studies exploring the geothermal potential of the island were conducted, by P.H.A. Martin-Kaye (1959); Hutton and Nockholds (1978); Geotermica Italiana (1992) and Morgan & Vichabian (2004). From the literature that was reviewed for this study, the reoccurring theme that emerged was that the surface manifestations along with the preliminary geothermal surveys indicated that the apparent areas suitable for geothermal exploitation were on the western side of the island. The quantification of this reserve, however, varied tremendously from study to study.

The objectives of this work will be to estimate the Nevis reservoir size and generating capacity in terms of 'proven' (based on the work done by WIPH) and 'possible' (total area inclusive of the proven) reservoir area, thickness and temperature. It will also try to authenticate, via the volumetric assessment (using the Monte Carlo style approach) that it is possible for WIPH to provide up to 35 MWe to the federation of St. Kitts and Nevis. Like any renewable form of energy, the study will assess the sustainability of the resource so that it can benefit Nevisians in the distant future. This will be somewhat of a qualitative analysis since sustainability is an ever changing concept and can only be valued when the response of the reservoir as it relates to power generation can be determined. Analogies can be made to other high-temperature fields worldwide but the reality can only be determined with time and constant modelling of the system.

2. REVIEW MATERIAL

2.1 Literature review

2.1.1 Geology of Nevis

The geology of Nevis is consistent in all literature. Nevis was formed on an inner arc along with Saba, St. Eustatius, St.Kitts, Montserrat, Guadeloupe, Martinique, Dominica, St. Lucia, St. Vincent and Grenada. It is believed to be formed in the Pliocene age as part of the younger inner arc, as opposed to the older outer arc, of the Miocene age (LaFleur and Hoag, 2010). Radiometric age dating has shown Nevis to have rocks between the ages of 3.4 to 0.1 million years (Hutton and Nockolds, 1978). The report by Hutton and Nockolds (1978) evaluated the age of the various volcanic centres on the island and found them to be as follows (Figure 2):

- Windy Hill volcanic centre: – 3.4 ± 0.5 Ma.
- Cades Bay volcanic centre: – 3.22 ± 0.16 Ma.
- Hurricane Hill volcanic centre: – 2.7 ± 0.5 Ma.

- Saddle Hill volcanic centre: – 1.80 ± 0.3 Ma.
- Butlers volcanic centre: – 1.10 ± 0.16 Ma.

A small dacite dome grew from one of the Nevis craters and was dated at 0.10 ± 0.06 Ma (Hutton and Nockolds, 1978). From the statistics gathered, it appears that after Nevis peak was formed and prior to the growth of the small dacite dome in the crater, an eruption took place with large pyroclastic deposits which formed the inhabited areas of the island. These areas were dated at 0.23 ± 0.16 Ma (Hutton and Nockolds, 1978).

The predominant rock type was found to be andesites and dacites. According to the description made, the andesites are typically porphyritic, with phenocrysts of plagioclase, and lesser pyroxene and minor oxide minerals (Geotermica Italiana, 1992). The report went on to describe the dacites to be texturally similar but with amphibole as the predominant mafic phenocrysts; biotite and quartz are also present. The drill cutting from WIPH Nevis 1 slim hole showed volcano-clastic deposits of hornblende bearing dacite with lesser amounts of andesite (LaFleur and Hoag, 2010).

In Nevis the general fault trend was found to be west-northwest with patterns of moderate deformation created typically by regional tectonic stresses and localized stresses related to the growth of Nevis Peak volcano or related crates (Figure 3). In most of these faults (regardless of the direction), it was observed that they appear to form a right-stepping series of en echelon faults (GeothermEx, Inc., 2005). The faults were also described to have left-lateral with normal down-dip slip characteristics, in general. Additional work done by WIPH confirmed the patterns as shown in Figure 2 with dip ranging between 70 and 83° from horizontal. Little work was done on the east side of the island regarding the fault trending. This was because the presence of young and active fault scarps is more prevalent on the western side of the island. These surface manifestations show the island is still structurally active (GeothermEx Inc., 2005). Areas of surface manifestation include (Figure 3):

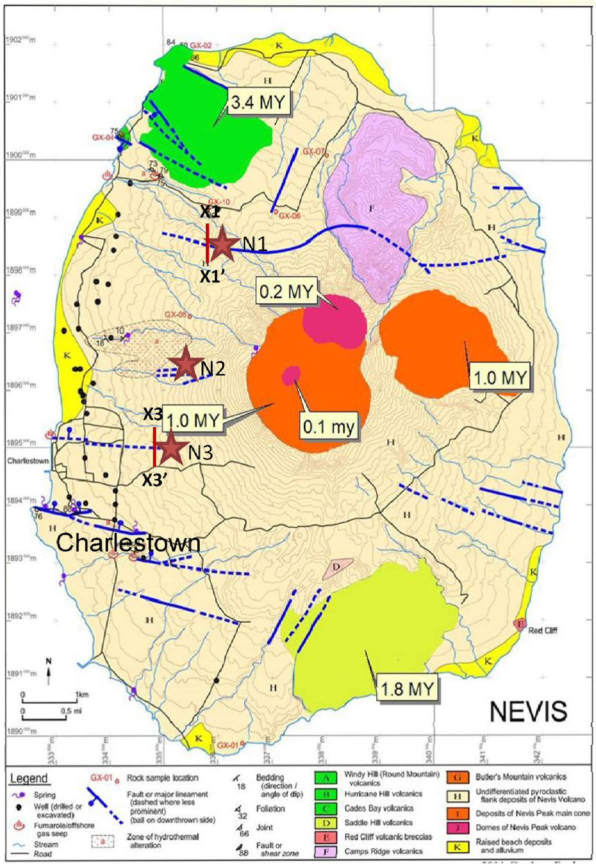

FIGURE 2: Age of eruptions and location of slim hole wells and resistivity cross-sections (X1-X1' and X3-X3') defined in Figures 4 and 5 (modified from LaFleur and Hoag, 2010; GeothermEx Inc., 2005)

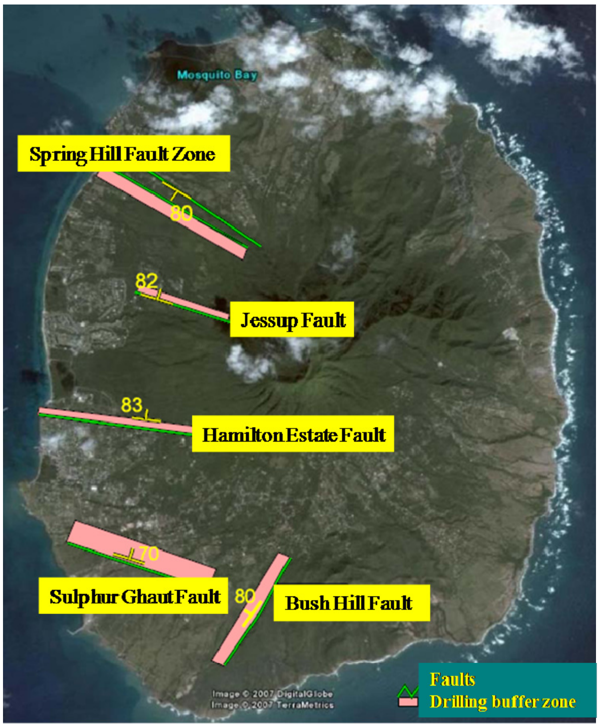

FIGURE 3: Fault zones and corresponding dip values on Nevis (modified from LaFleur and Hoag, 2010)

- Farms Estate/Sulphur ghaut fault – fumarole area where water vapour and gas discharges can both be smelled and seen. The area is along an axis trending slightly northeast with alteration of acid-sulphates dominated by kaolinite (GeothermEx Inc., 2005) and temperatures above 100ºC. Mineral deposits of iron oxide, pyrite, sulphate minerals, native sulphur and silica (as opal) are also present.
- Cades Bay/Spring Hill fault zone – Over the years the surface manifestations have decreased. A small boiling pool and steam vents were observed in 1955 (Robson and Willmore, 1955). In 1978, a hot spring was recorded in the report of Hutton and Nockolds whereas the work done by Geotermica Italiana (1992) reported a very weak vapour emission. At present there are little to no such visual manifestations at the site where the small boiling pool and the steam vent were identified. Temperature measured in the general vicinity of Cades Bay (Figure 2) reached 97ºC with alterations similar to Farms Estate with clay minerals being most ubiquitous and iron oxide and sulphate minerals in smaller quantities (GeothermEx Inc., 2005).
- Belmont/Jessup fault zone – This is the largest hydrothermal alteration mapped in Nevis (Martin-Kaye, 1959). Records from the local water department record a water well temperature of 75ºC at a depth of only 60 m.
- Bath/Sulphur ghaut fault – Hot spring with temperatures up to 48ºC along this fault which is truncated by an east-northeast trending fault. This fault is said to intersect with the Farms Estate fault, which is connected hydraulically (LaFleur and Hoag, 2010).
- Low ground/Bush Hill fault – This fault is not very visible and has an east-southeast trending orientation. The manifestation is seen in the form of low scraps, hills and a mud pit at 68ºC. An account from the local water department reported an incident of a worker getting severely burned by the well water in this area. This implies that the temperature must be near boiling (GeothermEx. Inc., 2005).

2.1.2 Geochemistry of Nevis

According to all the literature reviewed, the fluid chemistry of the geothermal resource was found to be thermally altered seawater with retrograde minerals. Extensive work done by GeothermEx Inc. (2005) identified the fluids to be predominantly acid sulphate and sodium chloride based. The general high levels of bicarbonate water suggest that the fluid being discharge in hot springs and fumaroles may be local groundwater heated from a steam source and not from the reservoir directly. This prevents accurate analysis using geothermometers, but gives an indication of a very wide reservoir since the data was collected mostly from water wells located throughout the island.

Helium isotopes were measured in gas samples and mixed water thermal outflow by GeothermEx Inc. (2005) and LaFleur and Hoag (2010), respectively, throughout the western side of the island. The results of their findings suggest that there is a definite magmatic origin existing there. This is based on the fact that the He^3/He^4 ratio found in a sample was much higher than that in the atmosphere, indicating a magmatic component present in the sample. The higher the ratio value, the more prominent is its presence. The results from both companies concur to give He^3/He^4 ratio values between 1.5 and 7.8 times that of the atmospheric ratio (LaFleur and Hoag, 2010). The lower values obtained (1.5) were concluded to be the consequence of the samples being mixed with shallow groundwater.

2.1.3 Geophysics of Nevis

Extensive geophysical analyses have been carried out on Nevis over the last fifty years. Major works were done by OAS (GeothermEx Inc., 2005) in the form of self- potential (SP) and gravity testing, and by WIPH (LaFleur and Hoag, 2010) with controlled source audio frequency using the magneto-telluric method (CSAMT), the magneto-telluric method (MT) and the transient electromagnetic method (TEM).

The findings of the OAS research indicated that the faults or fractures were the conduits (Figure 2) for the hydrothermal fluid. Where surface manifestations existed, they were found to be due to permeable fractures or faults from deeper heat sources. The gravity maps revealed noticeable gravity anomalies covering most of Charlestown, the focus of that study. The higher gravity value found in the research was explained as possibly being due to denser rock or regions where solidified magma intrusions were closer to the surface. The report went on to show a probable depth to the top of the body to lie between 200 and 1250 m. The gravity body which was found to exist under most of Charlestown is believed to be the heat source of the geothermal system. The wells dug by the local water department were all found to be hot in this area. However, based on calculations done under the Morgan and Vichabian study in 2004, the impervious layer spoken about by the water department is most likely not the cap rock to the reservoir. The authors of the report believed that the true reservoir exists at about a 1 km depth. This assumption was proven true by the results of the slim hole wells done later by WIPH (see next section).

The results of the geophysical work done by WIPH, seen in Figure 4, show a N-S resistivity cross-section together with the faults and the slim holes. Refer to Figure 2 to see the location of cross-section X3-X3'. The results of the geophysical data enabled WIPH to successfully identify three locations on the western side of the island for slim hole drilling (Figure 4).

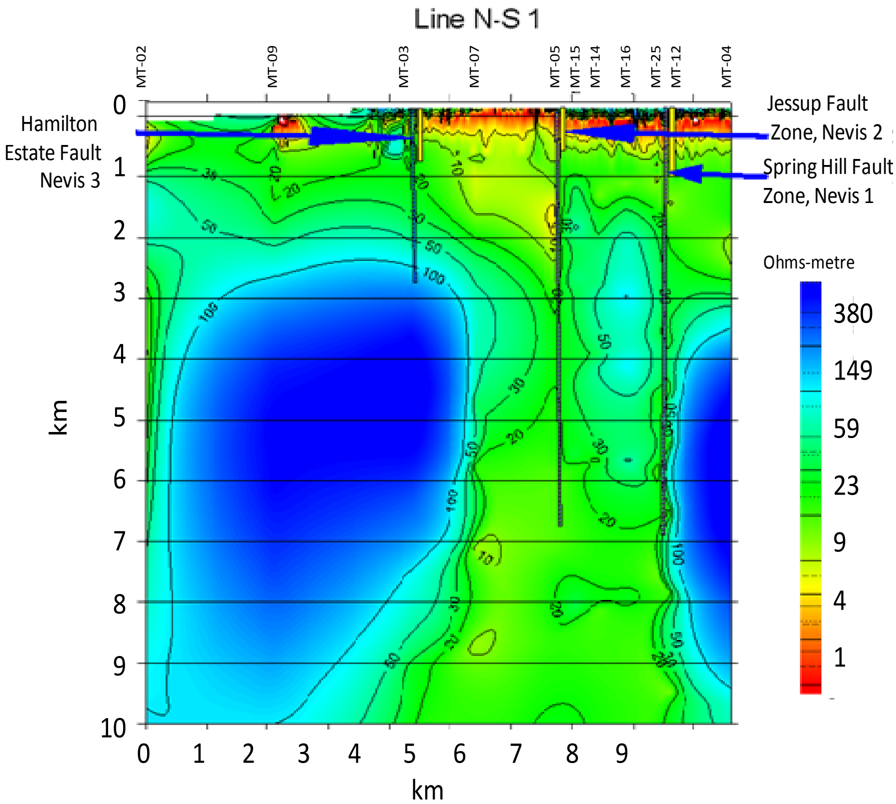

FIGURE 4: N-S resistivity cross-section (X3-X3') together with faults and slim holes in Nevis (LaFleur and Hoag, 2010)

2.2 Current reservoir development by WIPH

Many studies have been done in Nevis concerning the geothermal potential of the island but until recently all were based on surface exploration only. In 2007, a contract was signed between NIA and WIPH giving WIPH the right to explore for this resource with the ultimate objective of harnessing the geothermal fluid for electricity generation. The contract also ensured that when power was sold to countries outside of the federation, royalty payments would be levied on WIPH in accordance with the quantity sold. The success rate of WIPH through the drilling of 3 slim holes has provided renewed hope to the people of Nevis that the cost for electricity can be reduced once the mode of electricity generation is changed from diesel to geothermal. This reduction will be seen with the removal of the fuel surcharge that accounts for about 40% of the overall electricity bill. Furthermore, the federation's dependency on the world market oil price will be at a minimum, as 80% of the total oil purchase will be removed (CIA, 2009).

Since the development of geothermal energy is undoubtedly a positive move for the island, verification of the promises made by WIPH is paramount for proper developmental planning. Table 1 gives a summary of the information published in WIPH website press releases. It gives the basic information concerning the reservoir's condition. Nevis wells 1 and 3 were found to be self-flowing, with Nevis 3 being the more impressive of the two. Nevis 2 did not flow since, upon reaching a depth of 732 m, the drill bit got stuck. A temperature of 260ºC had been reached at this point, but drilling was abandoned and the operation was moved to the subsequent well now known as Nevis 3.

TABLE 1: Slim hole well information (WIPH, 2008a and b)

Well	**Fault location**	**Year**	**Depth (m)**	**Pressure (bars)**	**Temperature (ºC)**
Nevis 1	Spring Hill	June 2008	1065	82	250
Nevis 2	Jessups	July 2008	732	-	260
Nevis 3	Hamilton Estate	October 2008	899	16	201

Figure 5 shows the resistivity cross-section X1-X1' through Nevis 1, seen in Figure 2, along with the downhole temperature measured at two separate times, in January and in June 2008, depicted by red and blue graphs, respectively. The resistivity cross-section shows the typical structure of high-temperature field alterations seen in volcanic rocks (Hersir and Árnason, 2009). Rocks change from one formation to another as conditions such as temperature, pressure and or chemical conditions change. This phenomenon is termed thermal alteration. If alteration occurs as a result of hydrothermal fluids altering the mineralogy of the rock, then the process is referred to as hydrothermal alteration. It is believed (Hersir and Árnason, 2009), based on extensive work done in Iceland, that there is a definite correlation between mineral alteration and the temperature of the reservoir if no cooling has occurred. If there has been no cooling, then the temperature of the reservoir can be estimated by studying the alteration of the minerals present.

Figure 5 shows an uppermost high-resistivity layer where the unaltered rocks are found. The local water department recorded temperatures of 56 and 76ºC (GeothermEx Inc., 2005) in wells in the

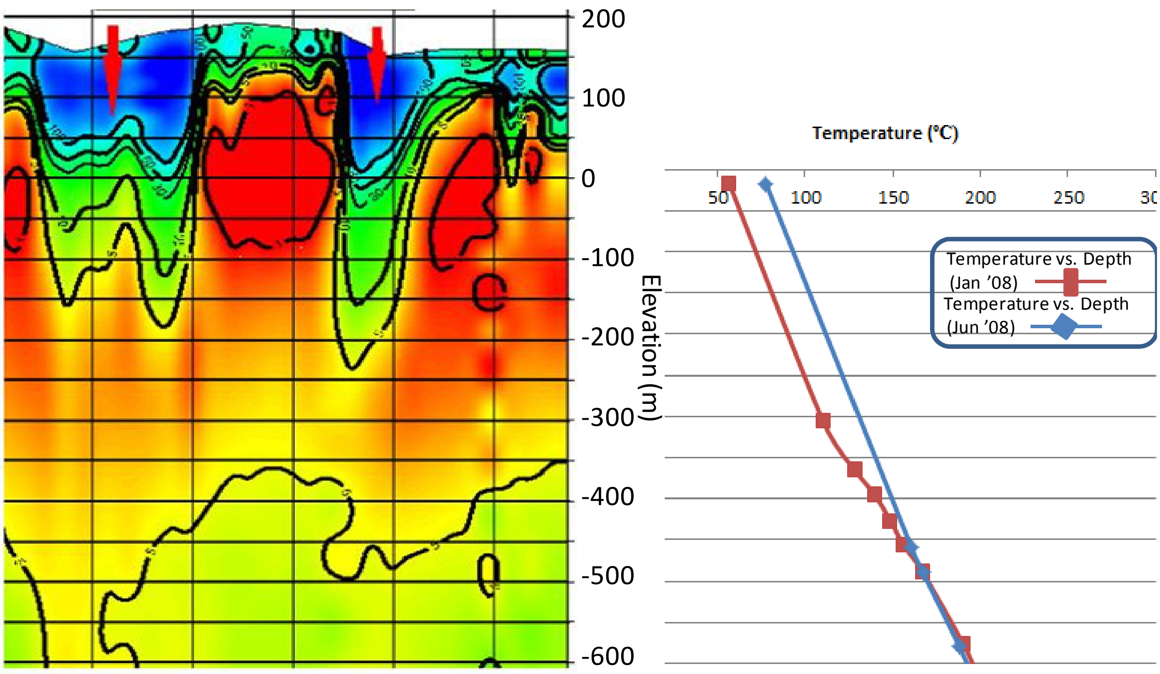

FIGURE 5: Downhole temperature and resistivity cross-section X1-X1' of Nevis 1 (modified from LaFleur and Hoag, 2010)

general vicinity of this fault. This zone of unaltered rocks is in keeping with the temperature range 50-100ºC (Árnason et al., 2000) for high-temperature fields. Conduction mostly occurs by pore fluid in this highly resistive upper layer. The next layer represents the smectite-zeolite zone with temperatures below 220ºC and it has low resistivity since the ions are more loosely connected and facilitate movement and, hence, conduction (Figure 5). Below this layer is the mixed-layer clay zone where temperature ranges from 220 to 250ºC. Transition to this layer starts as early as 220ºC. Below this, resistivity increases again as the chlorite zone becomes more dominant with the ions being held more tightly in the matrix. For Nevis 1, the mixed-layer clay zone is shallow, at approximately 1 km depth. As this profile of Nevis 1 depicts the structure of a typical high-temperature field so closely, it is very possible that, if no cooling has occurred over the years, then as the depth increases, the temperature will increase, in keeping with the geothermal wells investigated in Iceland (Árnason and Karlsdóttir, 1996). It therefore, can be concluded here that when coupling the temperature of Nevis 1 with the resistivity model (Figure 5), that a reservoir hotter than 230ºC may coincide with the depth where the subsurface resistivity changes from being very conductive to a higher resistivity under the conductive layer.

Findings from WIPH regarding prolonged speculation that the geothermal fluid is basically altered seawater was proven to be true when Paul Hirtz of Thermochem Inc. of Santa Rosa, California tested the sample to find it to be predominantly hydrothermally altered seawater, slightly diluted with meteoric water (LaFleur and Hoag, 2010).

3. DETERMINING THE GENERATING CAPACITY USING VOLUMETRIC MODELLING

In order to estimate a green field generating capacity without wells and a production history, basically three methods become available to the reservoir engineer. These methods are the volumetric method, lumped parameter modelling and distributed parameter modelling (numerical simulation). In this paper, the volumetric method will be used to estimate the generating capacity on Nevis.

From data obtained from the WIPH press release (WIPH, 2008a), Nevis 1 reservoir temperature and bottom hole pressure were found to be 250ºC and 82 bars, respectively, at 1065 m depth (Table 1). This indicates that the reservoir is a single-phase liquid-dominated field where the enthalpy is 1086 kJ/kg and the density is 804 kg/m^3 at a depth of 1065 m. Likewise, the data for Nevis 3, according to the WIPH press release (WIPH, 2008b), had a temperature of 201ºC which will give a minimum pressure of 16 bars at a depth of 889 m (Table 1) when the steam table is applied for a liquid-dominated system. The information went on to indicate that the two wells, separated by a distance of 4 km, penetrated a continuous geothermal reservoir.

By determining that the reservoir is liquid-dominated with the use of Tafla (Arason et al., 2004), an electronic steam table, the governing equation can be selected and its basic input parameters estimated for the volumetric method's governing equation. For such a reservoir, the heat to be extracted, denoted by 'Q', is calculated using the following equations (Halldórsdóttir et al., 2010):

$$Q = Q_r + Q_w \tag{1}$$

$$Q = A\,h\,(1-\phi)c_r\rho_r\,(T-T_o) + A\,h\,\phi\,c_w\rho_w(T-T_o) \tag{2}$$

$$P = \frac{n\,R\,Q}{t} \tag{3}$$

where Q_r = Heat of the rock (kJ);
Q_w = Heat of the water (kJ);
A = Surface area of the reservoir (m^2);
h = Thickness of the system (m);

c_r = Specific heat of the rock (J/kgºC);
ρ_r = Density of the rock (kg/m^3);
T = Temperature of reservoir (ºC);
T_0 = Cut-off temperature (ºC);
ϕ = Porosity;
c_w = specific heat capacity of water (J/kgºC);
ρ_w = density of water (kg/m^3);
P = Power (MWe);
n = Electrical utilization constant;
R = Recovery factor;
t = Utilization time example 30, 50 and 90 years (s).

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 needed to estimate the electrical power potential in this programme were found to be: the reservoir surface area, thickness of the system, temperature distribution in the reservoir, porosity of the rock, the physical characteristics of the rock and water in the system, the recovery factor, the cut-off temperature, the conversion efficiency factor of heat to electricity, and the production time or plant life. The basis for the assumption made for each of the underlying parameters is explained such that the rationality for the figures used becomes apparent.

Based on thermal activity on the western side of Nevis, it is clear that a usable geothermal resource exists. Studies done from 1959 to the present indicate the existence of this system, through resistivity measurements and later, with the drilling of three slim holes by WIPH. The surface area of the reservoir, shown in Figure 6, was estimated to include the accessible area where development of this resource can occur. The locations of all three slim-hole drill sites were included in the estimate. A triangular distribution for the surface area of the reservoir was used here with minimum and maximum values of 7 and 20 km^2, respectively. A most likely value of 12 km^2 was selected for the reservoir surface area. The total area that can be developed was limited by two main factors, namely the existence of geothermal potential and local regulations that restrict development beyond the 333 m elevation contour in order to conserve the rain forest found there.

Another parameter is the thickness of the system which was estimated to be 1, 1.5 and 2 km representing the minimum, best fit and maximum values for the Monte Carlo statistical analysis. These are typical values for high temperature fields as can be seen in Svartsengi in Iceland (Björnsson and Steingrímsson, 1992). Additionally, Nevis 1 was drilled to approximately 1 km without any temperature inversion occurring (see Figure 7). This indicates that the thickness will be in excess of 1 km so a most likely value of 1.5 km is quite appropriate.

From the various studies done on Nevis regarding the geology of the island, it is known that the lava is basaltic. And, in keeping with Sigurdsson and Stefánsson (1994), the porosity of basaltic lava lies in the range of 5-15%. Bearing this in mind, a most likely fixed value of 10% was used in the simulations.

The characteristics of the specific heat of rock and water, along with the density of the rock and water, were defined in the simulation. In Monte Carlo, the heat capacity is calculated from the following equation (Halldórsdóttir et al., 2010):

$$C = s_w \rho_r \phi + s_w \rho_r (1 - \phi) \tag{4}$$

where C = Heat capacity (J/m^3 °C);
s_w & s_r = Specific heat of water and rock, respectively (J/kgºC);
ρ_w & ρ_r = Density of water and rock, respectively (kg/m^3);
ϕ = Porosity.

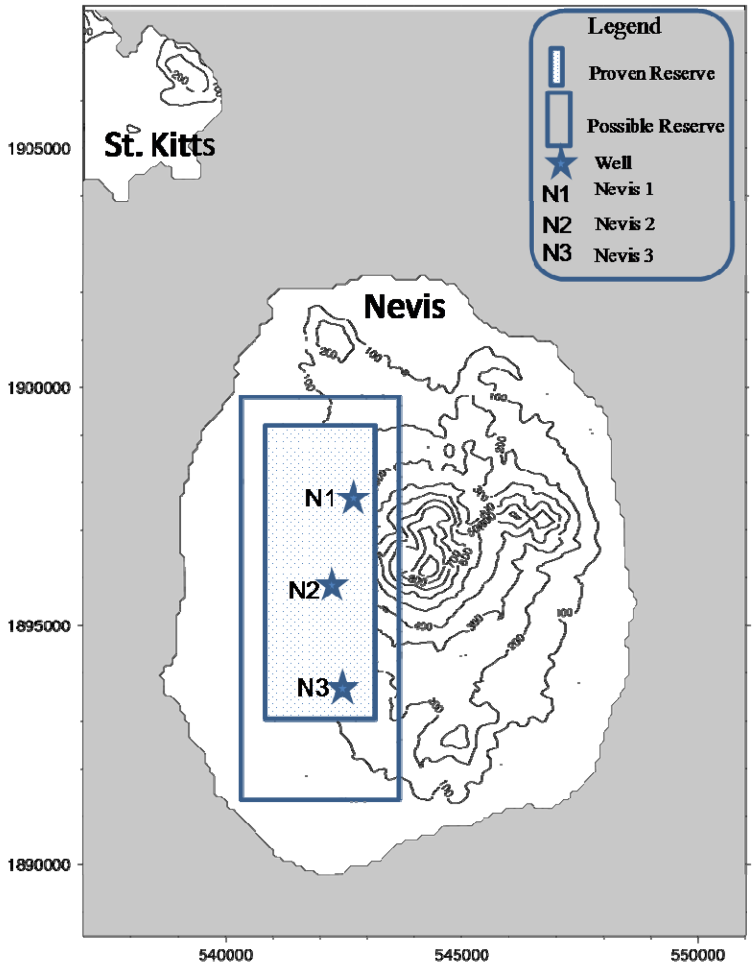

FIGURE 6: Possible and proven reservoir area

The condition of the reservoir at Nevis 1 was used to determine the density of the water at a given temperature and bottom hole pressure values obtained from WIPH (see Table 1). The specific heat and density of the rock was set at the default value as this value seldom varies significantly and is, therefore, not expected to affect the results dramatically.

The downhole temperature for Nevis 1 shows high temperature, about 250ºC, at relatively shallow depths (Figure 7). From data from slim holes (see Table 1), the temperature distribution ranges from 201 to 260ºC. Seeing that this field has similar characteristics as that of Svartsengi, Icelandic high-temperature field (Björnsson and Steingrímsson, 1992), it can be assumed that the temperature for the field, after deep hole drilling is completed, will be in the range of 220-280ºC. Also, the closest geothermal operation in the Caribbean is the Bouillante field in Guadeloupe, which also has temperatures similar to those discovered so far in Nevis, i.e. 250-260ºC (Bouchot et al., 2010). For the volumetric calculation, it was assumed that the boiling curve ratio should lie between 0.7 and 0.9, with 0.8 being the optimum value for the triangular distribution.

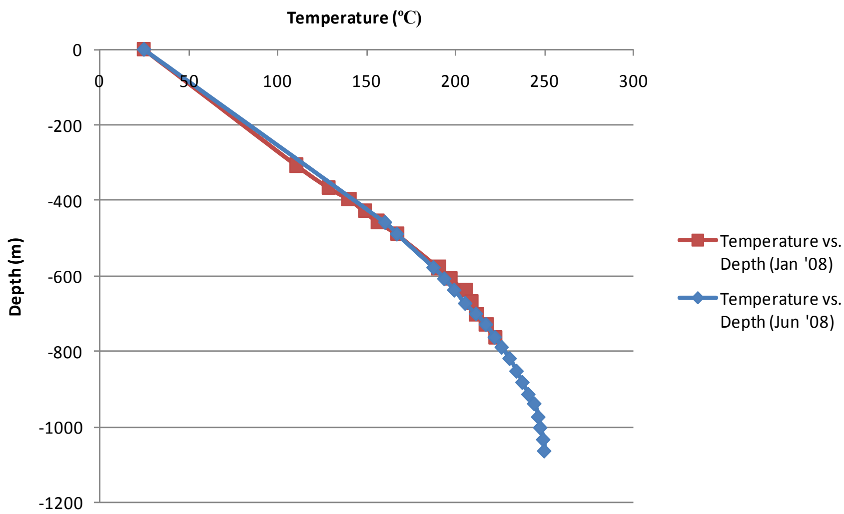

FIGURE 7: Downhole temperature for Nevis 1 (Spring Hill)

The recovery factor is the amount of heat that is expected to be extracted from the reservoir. This value is affected by the porosity and the permeability values. A linear correlation was developed between the recovery factor and porosity (Muffler, 1977; 1979); the porosity of 10%, stated above, gives a recovery factor of 25%. Since the porosity factor was assumed fixed and not proven, a conservative range of values was used for the recovery factor. This ran from a minimum of 10% to a maximum of 25%, 15% being set as the most likely for the triangular distribution.

The cut-off temperature used in the volumetric calculation was set at 180ºC since, at this temperature, the corresponding pressure (10 bars) would be the minimum value set for a flowing well head pressure and because below this value the reservoir would be considered dead due to its inability to flow. The conversion efficiency factor, which is the mean electric conversion coefficient, is estimated from the cut-off temperature (Wilcox, 2006). He says that with a cut-off temperature of 180ºC, the value for the conversion efficiency factor becomes 13%.

The Monte Carlo simulation was done for three (3) separate periods namely 30, 50 and 90 years. The variation in the number of years was done to assess the output potential if the resource was active for a varied number of years.

4. MONTE CARLO VOLUMETRIC ASSESSMENT APPROACH

4.1 Input data for volumetric assessment

Table 2 shows the input data for the volumetric assessment under conservative conditions for 30, 50 and 90 years. The preceding text explained the various functions used in Table 2.

TABLE 2: Input data for a Monte Carlo simulation for 30, 50 and 90 years

Function	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)		600		FIXED
Lower depth of reserve (m)	1000	1500	2000	TRIANGULAR
Area (km^2)	7	12	20	TRIANGULAR
Temperat. of upper depth (ºC)	220	250	280	TRIANGULAR
Cut-off temperature (ºC)		180		FIXED
Porosity (%)		10		FIXED
Spec. heat of rock (J/kg ºC)	900	950	980	TRIANGULAR
Density of rock (kg/m^3)	2600	2750	2900	TRIANGULAR
Spec. heat of water (J/kg ºC)		4185		FIXED
Density of water (kg/m^3)		800		FIXED
Boil curve ratio (%)	70	80	90	TRIANGULAR
Linear water heat grad. (ºC/km)		0		FIXED
Latent heat of lava (J/kg)		0		FIXED
Recovery factor (%)	10	15	25	TRIANGULAR
Conversion efficiency (%)		13		FIXED
Accessibility (%)		100		FIXED

4.2 Initial results of Monte Carlo

With the volumetric parameters shown in Table 2, the assessment continues with the Monte Carlo approach. The same input data were used for all three generation periods of 30, 50 and 90 years; Figures 8-10 show the results accordingly. The results in Figure 8 shows that the volumetric assessment predicts that there is a 90% chance that the reservoir will produce between 18 to 83 MWe for 30 years. For a development period of 50 years the graph in Figure 9 shows that electrical power

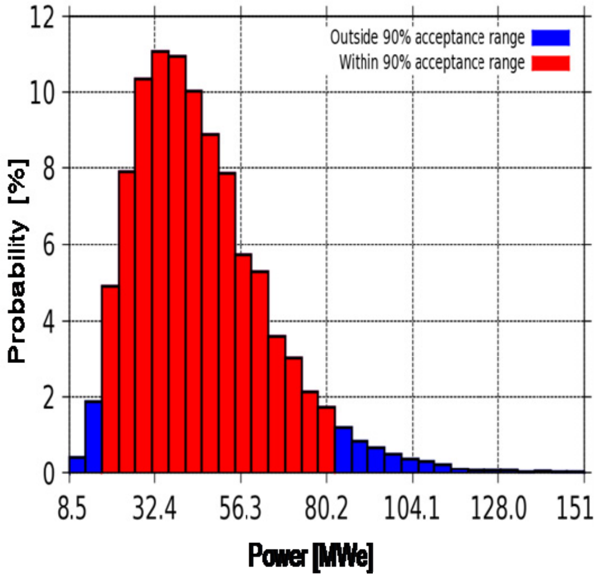

FIGURE 8: Probability distribution of power for 30 years

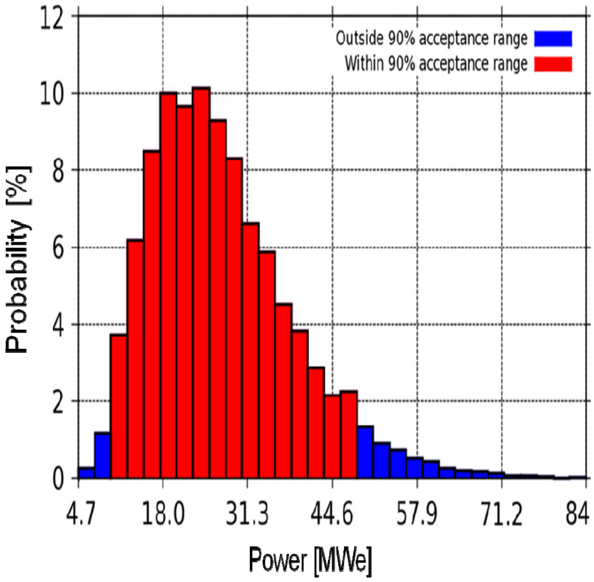

FIGURE 9: Probability distribution of power for 50 years

from 5-45 MWe can be collected with 90% accuracy. In the case of 90 years (Figure 10), the predicted electrical power to be generated is estimated to be 7-27 MWe. As the number of years increases, the amount of power to be obtained decreases since the total power has to be redistributed over a longer time frame. The distributed power reduced by about half by increasing the years from 50 to 90.

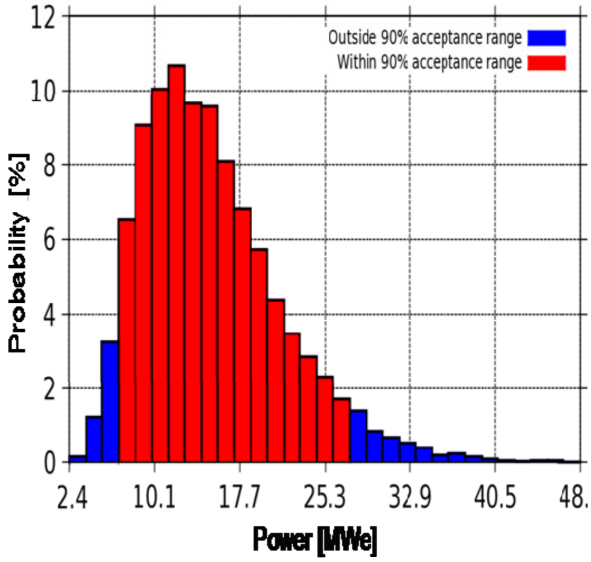

FIGURE 10: Probability distribution of power for 90 years

Another important deduction from the results obtained, regardless of the scenario adopted, is that there is a 90% chance that the reservoir will always sustain a minimum of 10 MWe. This value is what WIPH is contracted to provide to the island of Nevis in the initial stage. Thereafter, an additional amount of 20-25MWe would be required to meet the demand brought about with the addition of St. Kitts to the grid. This combined grid of St. Kitts and Nevis would bring the total demand to 35 MWe. Therefore, if the exploitation lasted for 30 years, it seems likely that the reservoir could comfortably meet the needs of the people of St. Kitts and Nevis with latitude for growth in power consumption (see Table 3 for details).

TABLE 3: Volumetric generating capacity for 30, 50 and 90 years of production

Parameters	Power (MWe)		
	30 years	**50 years**	**90 years**
Most probable value (at least 10% probability)	34	24	12
90% probability interval	18-83	5-45	7-27
Mean	45	27	15
Median	42	25	14
Standard deviation	19	11	6
90% limit	9-152	10-49	2-48

4.3 Monte Carlo results for the possible area in Nevis

As the three wells drilled by WIPH all identify commercial temperature, it is likely that the resource area is substantially larger than the most likely 12 km^2 estimated from Figure 6. Therefore, Monte Carlo was run again with changes made to some fundamental parameters to give more optimistic values for the reservoir generating capacity (Table 4). The other parameters kept the same values listed in Table 2. The results of the simulation (Figures 11 and 12) ensure that for a period of 100 years, there is a 90% chance that the reservoir will generate 32 MWe (Table 5). However, this value may reach as high as 64 MWe and even higher since the Monte Carlo simulation does not factor in the effects of reinjection or the natural recharge of the geothermal system. Also, as technology increases with time and a more efficient method for tapping the resource becomes available, this value may be altered.

TABLE 4: Modified input data in Monte Carlo simulation for 100 years

Function	Minimum	Best Fit	Maximum	Distribution
Number of runs		100000		Fixed
Lower depth (m)	1000	1500	2000	Triangular
Area (km^2)		20		Fixed
Recovery factor (%)		25		Fixed

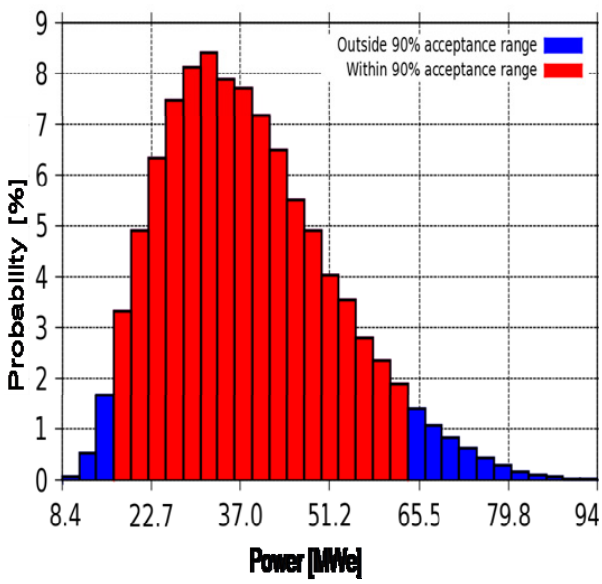

FIGURE 11: Probability distribution of power for 100 years production, assuming a 20 km^2 reservoir area

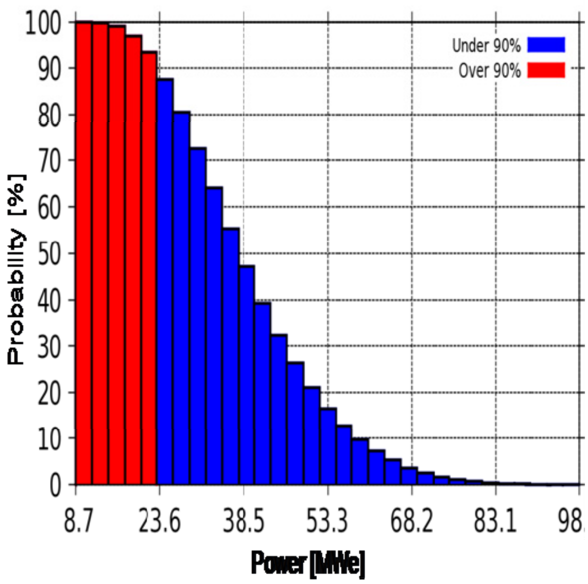

FIGURE 12: Probability distribution of cumulative power for 100 years production, assuming a 20 km^2 reservoir area

TABLE 5: Normal and cumulative probability distribution for power generation

Parameters	Power (MWe)	
	Normal distribution for 100 years	Cumulative distribution for 100 years
Most probable value (at least 8% probability)	32	10
90% probability interval	17-64	0-23
Mean	38	38
Median	36	36
Standard deviation	14	14
90% limit	8-94	9-98

The volumetric assessment for the 100 years speaks to the sustainability of the project. This will be discussed in more depth in the next chapter.

5. DISCUSSION

5.1 Sustainability of the geothermal resource in Nevis

In 1987 the United Nations released the Brundtland report which coined the definition for sustainable development as development which meets the needs of the present without compromising the ability of future generations to meet their own needs (The Brundtland Commission, 1987). The report went on to explain that the holistic approach to sustainable development involves the balancing of three main factors namely, the environment, the economic value and the socio-political impact. These parameters must be balanced such that the outcome of the development, whatever it may be, cannot be negative for the predetermined timeframe.

Another term of concern that must be explained before we can proceed is 'renewable energy'. Renewable energy is a term used to imply that the energy is derived from a natural process that is replenished constantly. Therefore, even though renewable and sustainable are sometimes used interchangeably, they are not the same. The sustainability of a renewable source is the rate at which it is replenished for the predetermined time of consideration such that no or little negative environmental, economic and socio-political impact is felt over the time in question. From the inception, it should be made clear that the analysis that is about to be drawn is based solely on logical speculation, since no production or injection well has been drilled to date. The analysis will serve as a guide for what to look for as data is collected and modelling done.

The graph in Figure 13 shows the essence of the definition of sustainable production presented by Axelsson et al. (2001). 'E_0' represents the sustainable level of production and 'E' denotes production. Therefore, when $E > E_0$ the production is considered excessive and not sustainable. On the other hand, when $E < E_0$ then the development is under-utilised and can be increased to maximise the output. It will be sustainable since it is below the E_0 line. For example, if the sustainable time frame is considered 30 years (it is normally considered to be 100-300 years or 50-100 years), and if we refer to Table 3, then E_0 = 34 MWe. This implies that the size of the power plant will be curtailed to about 30-35 MWe. This ensures that sustainability is observed. Likewise, if the sustainable timeframe is for 50-100 years, then E_0 will be reduced to12 MWe under initial conditions as shown in Table 3 but, if we refer to Table 5 using the total possible estimated area, it goes up to 32 MWe.

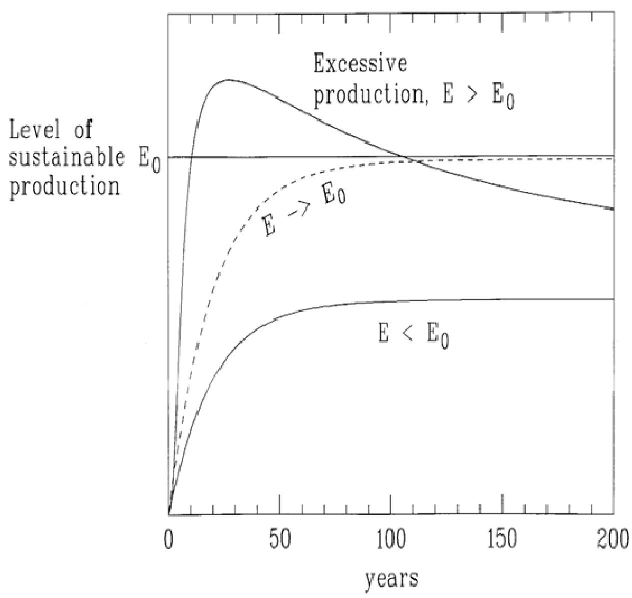

FIGURE 13: Schematic graph showing the essence of sustainable production (Axelsson et al., 2001)

Given that the present base load for the Nevis Electricity Company Ltd. (NEVLEC) is 6 MWe, at a growth rate of 3% annually, the predicted value of the Monte Carlo simulation will support the growth in Nevis for over 50 years, considering the base load value only and about 35 years for the total load. With the addition of St Kitts to the grid, the sustainable development of the proven geothermal resource is not possible since the total power demand [E = 30MWe] will just about equal E_0 which is 32 MWe (Table 5).

Sustainable research and modelling (Axelsson, 2010; Rybach and Mongillo, 2006) indicate that the long-term behaviour and capacity of the geothermal reservoir is based on boundary conditions, natural recharge, the reinjection rate, production conditions such as pressure draw-down, the effect of cooling due to reinjection, and the mode of production (whether it is continuous, step or periodic etc. and will change from time to time). Each reservoir is different and with production records the validity of the above analysis will be proven. The analysis made, however, brings awareness of limitations but does not infer that the conditions may not change as the environment changes. However, even though St. Kitts can be added to the grid and the amount of power sold managed, the addition of neighbouring countries should be carefully analysed and, until the behaviour of the geothermal system becomes more apparent, further negotiation for external sale of power should be reconsidered unless the value of E_0 can somehow be raised with added information. And even looking at the results for the 30 year (Table 3) simulation, there is a 90% likelihood that the power generated from the field lies between 18-83MWe. Factoring the same annual growth rate of 3% as before, this only allow 35 years of growth for the federation of St. Kitts and Nevis. In order to justify the price of the submarine cables that would have to be installed to feed the neighbouring countries, the total power demand would have to be sufficiently high. And with the cap of approximately 83 MWe, and the knowledge that from day one the federation requires 30 MWe, this only allows 50 MWe to be sold from the start. From start time to operation time, this value would be reduced significantly and to rationalize the sale of power with this reduced amount to other countries may not be cost effective for the developer or the buyer if cost is being transferred.

The issues of sustainability are not straightforward and to develop a policy to ensure sustainability (Axelsson 2010), two steps must be included in the policy.

- *Sustainability goals* – these are the objectives which sets the policies or guidelines. They should address the resource, economics, environmental and social aspects of the sustainable development.
- *Sustainability indicators* – these will be based on the goals and must be measureable (quantitative or qualitative) parameters geared to monitor the sustainability of the development. Axelsson (2010) went on to explain that the resource related indicators should address the following:
    1. *Reservoir evolution* – drawdown pressure, production temperature or enthalpy and major chemical constituents.
    2. *Remaining life of reservoir* – through reservoir modelling (simple, numerical or detailed) assess the remaining life of the reservoir to its capacity. It should also evaluate the need for re-injection wells or makeup wells.
    3. *Primary energy efficiency* – refers to the utilization and utilization factor of the energy harnessed.
    4. *Reservoir integrity* – estimates whether permanent damage to the reservoir is calculable due to scaling or cooling.

The establishment of the sustainability assessment protocol, which is the sustainability goals plus the indictors, will arm the regulators with valuable information with which to make educated decisions towards the continued development of the geothermal resource on the island.

5.2 Implication of geothermal development in Nevis

The fact that WIPH has proven a geothermal existence with their three slim hole wells equates to a multitude of benefits for Nevis and the federation on a whole. Below is a list of benefits this project can bring to the shores of St. Kitts and Nevis. In no way has the list been exhausted but it represents some of the more obvious benefits:

- *Economic* – The economic benefits to be gained in the federation are primarily those gained in the reduction of foreign exchange expended in the purchase of oil. The Central Intelligence Agency (CIA, 2009) World Factbook 2009 estimated the oil consumption for St. Kitts and Nevis to be 1,000 bbl/day. Approximately 80% of this value is used in the generation of electricity for the islands. With the use of geothermal energy, the quantity of oil purchased by the federation will drastically drop. This translates to savings in the purchase of foreign exchange for the country and serves to reduce our economy's dependency on the world market price for oil.
- *Carbon credits* – these represent a reduction in greenhouse gases in the atmosphere. They are measured in tons of carbon dioxide equivalent (tons CO_2e). All diesel operated power plants emit carbon into the atmosphere but renewable methods of electricity generation do not affect the environment in this manner. Carbon offset, therefore, calculates the amount of carbon emissions that, for example, a power plant would emit if it was still using diesel to produce the same amount of energy being generated by a geothermal plant. Being a tourist destination, it is very important for the islands to go completely green and reduce all carbon emissions. Secondly, the sale of the carbon credits would provide added revenue for the country. In 2006 alone, about $5.5 billion of carbon offset were purchased, reflecting about 1.6 billion metric tons of CO_2e reduced (Bang, 2009).
- *Consumer reduction in the price of electricity* – Over the years, the price of electricity has increased not because of an increase in the base tariff but due to the increase in the fuel cost on the world market. Caribbean countries were forced to add a fuel surcharge to the electricity bill to offset the rapid rise in the price of oil. With the use of geothermal energy, this part of the bill, which in Nevis can reflect up to 40% of the overall cost, can be removed. This will provide the customers with a tremendous reduction in the price of electricity.
- *Increase in development* – It is believed, based on evidence in other geothermal based countries, that the price for electricity will be stabilized with the elimination of the country's dependency on the price of oil. The simulation that was done in Monte Carlo indicates that the entire energy requirement of the island can be met by this resource. It is felt that this will encourage investors with power dependent developments to be confident that the capacity is available and environmentally friendly.
- *Increase in agricultural products* – The increase in agricultural products can be in various forms. One of the by products of electricity generation via the use of geothermal energy is heat. This excess heat can be channelled to heat up other things such as greenhouses or to dry products such as fish and vegetables. This reduces the electricity cost for the entrepreneur and allows him/her to produce products of high quality.
- *Water heating* – As in the above case, this too is a spin-off effect of power generation from geothermal means. Here the heat is used to heat up water that is taken to the homes or businesses and can easily be an extension of the Nevis Water Department. This makes hot water more affordable to more people since the start-up cost for the water heater and the continued cost for electricity, or the replacement of the battery in the case of a solar water heater, is removed. For businesses such as hotels, dry cleaners etc., the cost benefit becomes great since a large part of the electricity is used for heating water.
- *Improved social benefits and tourist attraction* – This project will make Nevis one of the few places in the world to be 100% green. In this changing world where this fact is very important to all, it becomes one of the selling points as a tourist destination in the Caribbean. Additionally, as seen in Iceland, Japan, China etc. water from geothermal sites can be used to make public bathing parks and saunas.

As said before, the benefits of this project are not limited to what is listed or solely restricted to the generation of electricity. The benefits are far reaching and will affect all of the people on the island and, if developed properly, can only affect the nation positively for an indefinite time.

6. CONCLUSIONS AND RECOMMENDATIONS

The objectives set out in the introduction dealt with three main factors, namely, the size of the Nevis geothermal reservoir, total power to be exploited from the field, and sustainability of the resource. From the literature review, it was acknowledged through various works that the western side of the island is the most likely area where geothermal activity exists. Additional work done by WIPH verified that the geothermal reservoir exists and the temperature and pressure data allow one to confidently ascertain that the resource does not merely exist but is commercially viable. Tests done on the working fluid showed that it is basically sea water mixed with fresh groundwater.

From work done by WIPH, a proven resource area of 8 km^2 was estimated and a most likely value of 12 km^2 was used in a volumetric generating capacity estimate, incorporating Monte Carlo style random distribution of several primary reservoir parameters into the simulations. For the possible area, a value of 20 km^2 was estimated based on all of the studies done on the western side of the island. This reflects what the report considers to be the total reservoir size. The size of the reservoir was, however, restricted by two main factors: the proven existence of the geothermal potential and the height regulation that does not permit development beyond this point to preserve the rain forest.

When the field in Nevis was compared to that in Svartsengi Iceland, in terms of the surface resistivity survey, similar observations were made. It allowed us to conclude that this high-temperature geothermal system in Nevis, being of the same basaltic rock and sea water regeneration, should operate in a similar fashion to the Svartsengi field in Iceland. The findings of the Monte Carlo simulation, which were purposely set at a conservative scale due to the high level of uncertainty, gave encouraging values for the power output. The values obtained support the WIPH assertion that the field could provide the island with 10 MWe. They also support the connection of the grid to St. Kitts via a submarine cable. The addition of St. Kitts would require WIPH to install a power plant with a capacity of at least 35 MWe with plans to increase it as time goes by to further the growth of the federation.

The issue of sustainability of geothermal development on Nevis comes with hard decisions to be made by Nevis Island Administration. A most likely generating capacity value obtained for a 100 years of continuous production is 32 MWe. Therefore, considering this as the upper limit, and applying a 3% growth rate to the initial load of 10MWe, it will take approximately 40 years for Nevis to reach this limit. Adopting a 100 year criterion in defining a level of sustainable geothermal development, then the resource may be considered sustainable. If a greater extraction of mass and heat takes place to supply both St. Kitts and Nevis, it will reduce the above estimate to a much lower time frame to attain the 32 MWe. As the estimated volumetric generating capacity neglects natural recharge of hot water to the productive reservoir, 32 MWe can be regarded as a conservative value and it is likely to rise with time as more information is attained from the reservoir. As a safety precaution, Nevis Island Administration may consider limiting the initial development license to approximately 35 MWe and then revise its decision when more data and production history become available.

The project started by WIPH to provide power to Nevis and by extension, to St. Kitts is therefore, a brilliant one and holds a lot of advantages for the country. These include a reduction in the spending of foreign exchange due to an 80% decrease in the purchase of oil, the removal of fuel surcharges from the electricity bill which currently accounts for about 40% of the present cost, and added revenue from the sale of carbon credits. Other benefits incorporate social advancement with the creation of public bathing areas or saunas supplied by the hot water of the geothermal system, as seen in Iceland, Japan, and China. The advantages are far reaching and will affect every person in the federation in a positive manner.

This project attempted to determine the generating capacity and explore the possibility of developing a sustainable resource on Nevis. It examined WIPH's proposal to provide 10 MWe to Nevis and evaluated the possibility to sell energy outside the federation. It is the belief of the author that WIPH can provide sufficient power to supply the federation. However, it is recommended that a period of 5-10 years should pass to allow sufficient time in which to collect data to determine how the reservoir functions. Based on monitoring, revised models can be done on the field and a more informed decision can be made toward the sale of power to other countries.

ACKNOWLEDGEMENTS

I would like to extend heartfelt thanks to all those that were instrumental in whatever capacity in assisting me to write my report. Special mention is to be given to the UNU-GTP staff; the government of Iceland; Nevis Island Administration and the related departments; Nevis Electricity Company Limited; West Indies Power Holding Limited and my invaluable supervisors, namely Mr. Grímur Björnsson and Mr. Gestur Gíslason, and finally my family.

REFERENCES

Arason, Th., Björnsson, G., Axelsson, G., Bjarnason, J.Ö., and Helgason, P., 2004: *ICEBOX – geothermal reservoir engineering software for Windows. A user's manual.* ISOR, Reykjavík, report 2004/014, 80 pp.

Árnason, K. and Karlsdóttir, R., 1996: *A TEM resistivity survey of the Krafla high-temperature field.* Orkustofnun, Reykjavík, report OS-96005/JHD-02 (in Icelandic), 96 pp.

Árnason, K., Karlsdóttir, R., Eysteinsson, H., Flóvenz, Ó.G., and Gudlaugsson, S.Th., 2000: The resistivity structure of high-temperature geothermal systems in Iceland. *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan,* 923-928.

Axelsson, G., 2010: Sustainable geothermal energy utilization. *Proceedings of the 16th Building Industry Days, Debrecen, Hungary,* 18 pp.

Axelsson, G., Gudmundsson, Á., Steingrímsson, B., Pálmason, G., Ármannsson, H., Tulinius, H., Flóvenz, Ó.G., Björnsson, S., and Stefánsson, V., 2001: Sustainable production of geothermal energy: suggested definition. *IGA-News, Quarterly No. 43,* 1-2.

Bang, N., 2009: *Carbon credits are an important way of mitigating the growth of greenhouse gases.* Stock Markets Review, website:*www.stockmarketsreview.com/extras/carbon_credits_20091117_1654*

Björnsson, G., and Steingrímsson, B., 1992: Fifteen years of temperature and pressure monitoring in the Svartsengi high-temperature geothermal field in SW-Iceland. *Geoth. Res. Council, Trans., 16,* 627- 633.

Bouchot, V., Sanjuan, B., Traineau, H., Guillou-Frottier, L., Thinon, I., Baltassat, J.M., Fabriol, H., Bourgeois, B., and Lasne, E., 2010: Assessment of the Bouillante geothermal field (Guadeloupe, French West Indies): Towards a conceptual model of the high temperature geothermal system. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia,* 10 pp.

CIA, 2009: *World factbook*. Central Intelligence Agency, webpage:
www.cia.gov/library/publications/the-world-factbook/geos/sc.html

Geoalba, 2001: *Tectonic-structural interpretation*. Geoalba, webpage:
www.geoalba.com/Article.mvc/Detail/111/1

GeothermEx, Inc., 2005: *Geological and geochemical studies in Nevis, West Indies.* Organization of American States, Washington, D.C., DTCD & CARICOM.

Geotermica Italiana, 1992: *Exploration for geothermal resources in the Eastern Caribbean, final report*. Geotermica Italiana, Pisa, Italy.

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.

Hersir, G.P. and Árnason, K., 2009: Resistivity of rocks. *Papers presented at "Short Course on Surface Exploration for Geothermal Resources", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador, October 2009,* 8 pp.

Hutton, C.O., and Nockholds, S.R. 1978: The petrology of Nevis, Leeward Islands, West Indies. *Overseas Geology & Mineral Resources, 52*, 1-31.

Includipedia, 2007: *Nevis*. Includipedia, webpage: *www.includipedia.com/wiki/Nevis*

LaFleur, J., and Hoag, R., 2010: *Geothermal exploration on Nevis: A Caribbean success story.* West Indies Power Holding, Ltd., in print.

Martin-Kaye, P.H.A., 1959: *The geology of the Leeward and British Virgin Islands: Castries, St. Lucia.* Voice Publishing Co., St. Lucia, 117 pp

Morgan, D., and Vichabian, Y., 2004: *Final report for self potential and gravity studies of Nevis for geothermal exploration*. MIT and SP International, performed for the OAS Geo-Caraibes project.

Muffler, L.P.J., 1977: USGS geothermal resource assessment. *Proceedings of the 3rd Stanford Geothermal Workshop, Stanford University, Stanford, CA*, 3-8.

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

Robson, G.R., and Willmore, P.L., 1955: Some heat measurements in West Indian soufrières. *Bull. Volcanologique., 17*, 13-39.

Rybach, L. and Mongillo, M., 2006: Geothermal sustainability – A review with identified research needs. *Geoth. Res. Council, Trans., 30,* 1083-1090.

Sigurdsson, Ó., and Stefánsson, V., 1994: *Resource parameters – Measurements from rock core.* Orkustofnun report OS-94049/JHD-28 (in Icelandic), 35 pp.

The Brundtland Commission, 1987: *Report of the World Commission on Environment and Development*. United Nations.

Thorgilsson, G., 2008: *Monte Carlo program.* ISOR & Orkustofnun, Reykjavík.

Wilcox, G. (editor), 2006: *The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st century.* Massachusetts Institute of Technology.

WIPH, 2008a: *Nevis geothermal reservoir comes to life*. West Indies Power, Ltd., Nevis, webpage: *www.westindiespower.com/news.asp?pag=detail&idNews=11&from=1.*

WIPH, 2008b: *Third geothermal well on Nevis roars alive*. West Indies Power Ltd., Nevis, webpage: *www.westindiespower.com/news.asp?pag=detail&idNews=21&from=1*