Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

# Binary Cycle Plant Design for Water-Dominated, Low Enthalpy Geothermal System

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**Keywords:** geothermal, low enthalpy, Binary Cycle power plant, Organic Rankine Cycle

## ABSTRACT

Binary cycle technology allows the exploitation and development of low to medium temperature geothermal resources (i.e. 80 - 180°C) at economically viable scales. The Bath geothermal reservoir in eastern Jamaica is located in the Blue Mountain Inlier (BMI) which undergoes tectonic uplift. Na-Cl-$SO_4$-type waters discharge from an aerially-exposed and fissured suite of basalts, gabbros, and deep marine sedimentary deposits at temperatures of 51.3°C to 52°C. Reservoir temperatures estimated from a recent hydrogeochemical investigation and geothermometric analyses range from 82°C and 223°C. The minimal depth of circulation for the Bath hot springs-south (BTHS) water sample is 2.80 km based on the Truesdell (1977) silica geothermometer. The power potential estimated for the Bath geothermal reservoir ranges from of ≈28– 170 $MW_t$ assuming an average geothermal gradient of 30°C/km for the Caribbean region and reservoir temperatures estimated at 82-120°C. Cl/$SO_4$ vs. Li/B ion ratios suggest the existence of a shallow, more accessible low enthalpy geothermal reservoir that warrants exploration drilling and resource development. Suggestions for the design and optimization of a 5 MWe geothermal binary power plant utilizing Organic Rankine Cycle (ORC) technology are proposed for future geothermal energy production from the reservoir.

## 1. INTRODUCTION

### 1.1 Background

The demand for renewable energy resources, sustainable approaches to energy development, and resource management are expected to increase in the near future (Rosen and Dincer, 2001; Jalilinasrabady and Itoi, 2012). Environmental concerns for atmospheric and water pollution have led the way to the exploitation of renewable energy resources (Parada, 2012). Lower temperature/low enthalpy geothermal resources located far away from tectonic plate boundaries may hold resources for potential geothermal energy development. Binary cycle power plants are becoming an increasing option for the exploitation of geothermal energy from lower to moderate enthalpy resources (Hochstein, 1990; Barbier, 2002). In contrast to dry-steam or flash-steam geothermal plants, the separation of steam is not necessary for the generation of power at binary power plants. An increase in the number of suppliers in response to the demand and flexibility in the configuration of energy conversions systems for geothermal binary power plants makes them attractive for optimum design strategies and the reduction of production costs. Several islands in the eastern Caribbean have geothermal resources for potential energy development and are being increasingly viewed as optimal locations for testing their capability of transitioning to clean energy. Jamaica has devised a long-term policy with specific incentives for alternative energy resources. However, one logical step Jamaica should take towards increasing its energy portfolio and adding capacity to its power generation mix is to include the exploration and development of its geothermal resources for energy independence and economic sustainability. According to Jamaica's National Energy Policy 2009-2030, it seeks to significantly increase investments in renewable energy technologies and has targeted at least a 20% contribution towards the energy mix from renewable energy sources by 2030. Borehole fluid temperatures, fluid enthalpies, vapor pressure, and well-head pressure data are not currently available for the Bath field site. Preliminary results of a 2011 hydrogeochemical investigation, exposed hot rocks, and the tectonic settings of the BMI and Plantain Garden Fault (PGRF)/Enriquillo-Plantain Garden Fault Zone (EPGFZ) warrant geothermal well exploration to acquire accurate reservoir temperatures and harness geothermal potential at Bath. The typical range for turbine-generator unit capacities is 20-80 MWe, but turbine-generator unit capacities of 5–110 MWe are available with more systematic approaches to the optimization of geothermal plant design (Dipippio, 2008). In this paper, optimization strategies are suggested for the design of a 5 MWe geothermal binary plant with geothermal fluid inlet temperatures 110-140°C, Organic Rankine Cycle (ORC) technology with water as the condensing medium, and multicomponent working fluid media near Bath hot springs for the purposes of supplementing electricity production from renewable resources.

### 1.2 Low Enthalpy Geothermal Resources

Low enthalpy geothermal resources are characterized based on a deep liquid temperature range at 80-180°C whereas high enthalpy resource temperatures are > 250°C. Appropriate technology for geothermal production is critically dependent on the temperature and enthalpy of the geothermal fluid. A specialized cycle required to achieve efficiency of power conversion is integral to the viability of a geothermal energy development project.

### 1.3 Binary Cycle Operation

Geothermal binary power plants are used to generate electricity (Franco and Villiani, 2009; Jalilinasrabady and Itoi, 2012; Moon and Zarrouk, 2012; Parada, 2012) and could become the most widely used type of geothermal plant in the future. Therefore, binary power cycles may be modified to increase the power output from low-enthalpy resources. The main components of a geothermal binary power plant are the heat exchangers (i.e. evaporator, pre-heater, and condenser), turbine-generator unit, and pumps used during the heat recovery cycle (HRC). Recovery heat exchangers (RHE) and the cooling system (CS) are closely related subsystems of the thermal and fluid dynamic performance (Franco and Villiani, 2009). A critical step in the design optimization of a geothermal binary power plant is the selection of an appropriate working fluid for the thermodynamic cycle, power plant components such as the recovery heat exchangers (RHE) and the cooling systems (CS). Geothermal production wells used for the extraction of the geothermal fluid ($T_{geo}$) from an underground reservoir allow flow through pipelines to heat exchangers. Some of the energy from the heated fluid

$T_{geo}$) during a primary cycle is transferred to an organic working fluid ($F_{work}$) that has a low boiling point and vaporizes during a secondary cycle. Operational temperatures for geothermal binary power plants are 80-180°C, but with the selection of the most efficient working fluid ($F_{work}$) for operation, the temperature range may be extended from 75°C to 180°C. Heat is exchanged between the cooling fluid cycle and the working fluid vapor via a condenser. The vapor thermodynamic energy of the working fluid is converted to mechanical energy on a rotating turbine shaft coupled to a generator to produce electricity rather than from geothermal steam. Geothermal binary power plants are closed cycles and a system cycle is completed as the condensed fluid is recycled back into the heat exchangers by a pump and the cooled geothermal fluid is re-injected into the reservoir (Dipippio 2008; Bliem and Mines, 1991; Saleh et al., 2007). Essentially, if water extracted from the geothermal wells to the surface is not sufficiently hot to produce steam, it may be directed to a binary cycle power plant to produce steam.

#### 1.3.1 Rankine and Organic Rankine Cycles used in Binary Power Plants

The Rankine Cycle is predominantly used in geothermal power generation (Franco and Villiani, 2009; Jalilinasrabady and Itoi, 2012). Variations of heat recovery cycles used in geothermal binary power plants include a basic Rankine Cycle; Organic Rankine Cycle (ORC); more complex power cycles such as the Kalina Cycle® (Prananto et al, 2018); a supercritical secondary cycle (Gu and Sato, 2001) or a dual pressure level Rankine cycle for higher electricity output (Kaplan, 2007); and bottoming plants that use binary cycle power to generate electricity after the utilization in a flash power plant. A conventional Rankine Cycle employs the conversion of thermal energy to mechanical energy through repeated cycles of the vaporization of a liquid medium (e. g. water) with heating, expansion of the vapor to produce mechanical energy, and the condensation of the medium through compression by a pump. A modification of the Rankine Cycle is the Organic Rankine Cycle (ORC) used in geothermal binary power plants employs an organic fluid (e.g. isobutane, isopentane, n-pentane) with a lower boiling point and higher vapor pressure than water used at all points related to the thermodynamic cycle. Organic Rankine Cycles have demonstrated record of success for decades (Colonna et al., 2015). Italy-based Exergy renowned for its design, engineering, and manufacture of ORC systems and its radial outflow turbine (ROT) technology introduced a binary plant equipped with a dual pressure-level cycle on a single turbine at its low-enthalpy Akca geothermal plant located in the Denizli region of Turkey. The Akça plant designed by Ormat Technologies (Reno, Nevada, USA) uses a fluid temperature of 105°C (220°F) and generates a power output 4 MWe, allowing efficient operation with resource temperatures down below 100°C. Based on the preliminary data, a 5MWe binary power plant developed at Bath would be highly beneficial the region of south-eastern Jamaica for purposes other than space heating not needed in Jamaica.

#### 1.3.2 Advantages of Binary Cycle Technology

Multiple high enthalpy binary power plants are in service worldwide. However, binary cycle technology can be utilized on a wide range of resources from low enthalpy to high enthalpy and are the most widely used type of geothermal power plant (Parada, 2012). Geothermal power stations are typically used for base load (constant power) with high capacity and availability factors because the power generation is characterized by initial high fixed costs and low variable operational costs. Comparative advantages of geothermal power are its renewability, reliability, small environmental footprint, total base load, and lower costs compared to other power sources (i.e. fossil fuels, biofuels, nuclear power, photovoltaic cells, solar, wind, and costs projected for adaptation to clean coal). Of a particular note, binary heat recovery systems allow the separation of the geothermal fluid and working fluid(s) during the power generation process. An added advantage of binary power plants is they bypass the possible impact of pollution from fluids as cooled geothermal fluids are reinjected back into the underground reservoir. Greenhouse ($CO_2$) emissions from binary cycle plants are generally small at 79 $CO_2$eq/kWh compared to substantial emissions from fossil fuels (Geothermal Energy Association, 2013) at around 930 $CO_2$eq/kWh from natural gas; 1042 $CO_2$eq/kWh; 1170 $CO_2$eq/kWh from oil, and 689 $CO_2$eq/kWh from coal (Moomaw et al., 2011). Therefore, there is very minimal or no impact from atmospheric emissions from the geothermal binary power plant operational process. Energy sustainability and return on investment from this type of project may be maximized by the reinjection of the total volume of geothermal fluid to maintain reservoir pressures and the ability to change reservoir conditions maintaining long term high efficiency at lower operating costs for a prospective binary power plant at Bath. Overall, geothermal binary power plants are ideal choices for the exploitation a low enthalpy resource such as the Bath geothermal reservoir.

## 2. GEOLOGICAL SETTING

### 2.1 Study Site

Bath geothermal reservoir is situated in the eastern section of the Cretaceous age Blue Mountain Inlier (BMI) of Jamaica (Figure 1a-b). Boiling hot springs emerge from aerially-exposed, fissured hot rocks of the Bath Dunrobin Formation (Figure 1e-f). The Bath Dunrobin Formation consists of Late Cretaceous suites of massive tholeiitic basalts intercalated with tuffs and overlain by a thick sedimentary succession of deep marine sedimentary strata: the Bath Limestone and Cross Pass Shales (Hastie et al. 2008; Hastie et al. 2010). Igneous-sedimentary sequences are duplicated and extremely deformed by a series of stacked overlapping thrust faults (duplexes). Both the tectonic and geologic settings of the BMI are extremely complex. A recent Thermochronometry study of the rugged terrain by Cochran and Spotila (2017) revealed the areas within the region underwent neotectonic exhumation (Figure 1b-c). The BMI is situated on the Blue Mountain Tectonic Block, the smallest of three terranes separated by faults and troughs and contains the largest zone of Cretaceous rocks on the island. Two other terranes are the central Clarendon and western Hanover Tectonic Blocks in Figure 1a (Lewis et al. 1990). A trace of the Enriquillo–Plantain Garden Fault Zone (EPGFZ) is the Plantain Garden Fault (Figure1a-b) that divides eastern St. Thomas parish into the basaltic pillow lavas of the Bath-Dunrobin Formation and the Cross Pass Shales (Wadge et al., 1982) to the north and to the south, a succession of clastics (the Richmond Formation) and shallow marine carbonates (the Yellow and White Limestone Groups). Trace element signatures of the basalts indicate they erupted from mantle plumes and are representative of oceanic plateau basalts that formed large igneous provinces (LIPs) (Hastie et al. 2008; Hastie et al. 2010; Hastie et al. 2010; Hastie et al. 2011; Jackson et al., 1980). Biostratigraphic correlation between Late Cretaceous age fossils ≈ 88-92 Ma (Montgomery and Pessagno, 1999) and lithostratigraphic sequences of sedimentary rocks intercalated with the basalts are linked to major extrusion of basalts of the Caribbean Large Igneous Province (CLIP) (Kerr et al., 2003). Evidence of the uplift of oceanic lithosphere are the ultramafic rocks forming part of a dismembered Late Cretaceous ophiolite suite spanning approximately 2 $km^2$ and adjoining other strata in the Blue Mountain Inlier are (Wadge et al. 1982, Hastie et al. 2008). These ultramafic rocks consists of primarily dunite with unaltered olivine, orthopyroxene, clinopyroxene and chromite.

### 2.2 Tectonic Setting

Jamaica sits at the emergent tip of a drowned carbonate platform on the Nicaraguan Rise and straddles the northern boundary between the Caribbean and North American Plates. The Caribbean Plate moves eastward relative to the North American Plate (Figure 1d). The Gônave Microplate north of Jamaica moves west relative to the Caribbean Plate (Benford et al., 2012b; Mann et al., 2007). Sinistral E-W striking faults (e.g. Plantain Garden Fault) are currently reactivated as transfer zones within a contractual restraining bend along the Blue Mountain Fault and their presence along with NNW striking fault sets (Figure 1a-b) are evidence of neotectonic deformation in Jamaica (Benford et al. 2015). The EPGFZ transects Lake Enriquillo (Dominican Republic), oceanic lithosphere, the Caribbean Plate along southern Hispaniola and along the Plantain Garden River in east St. Thomas Parish, Jamaica (Figure 1a-d). Geochemical and paleomagnetic evidence suggest the Caribbean Plate is the remnant of two separate Cretaceous oceanic plateaus (terranes) that migrated northeastward on the Farallon Plate along major strike-slip faults into Caribbean basin between North and South America (Kerr and Tarney, 2005).

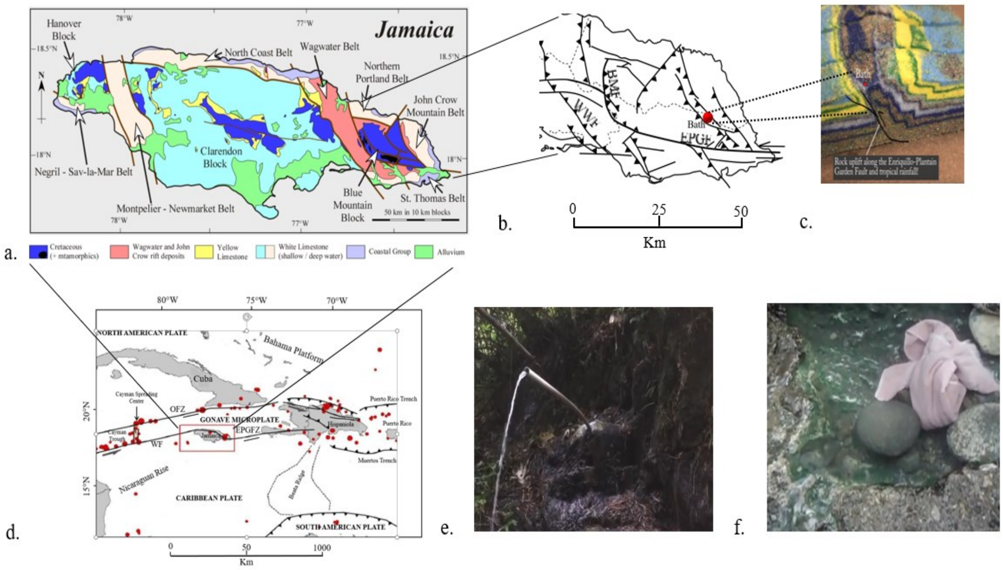


**Figure 1: a. Simplified geological map of Jamaica, b. Map of major faults in eastern Jamaica (Benford et al., 2012a), c. Demonstration model of the pattern of rock uplift (exhumation) along a restraining bend step over in eastern Jamaica where deep exhumation along a main fault such as the Plantain Garden Fault results in the erosion of buried rock during uplift (blogs.agu.org), d. Tectonic setting of Jamaica in a restraining bend on the E-trending, left-lateral plate boundary between the Gônave Microplate and Caribbean Plate during the Miocene epoch over 23 million years ago (Benford et al., 2012a), e. Rock outcrop of the Bath volcanics along the Sulfur River gorge with hot water flow from a PVC pipe, f. Photo of a boiling spring that emerges from one of numerous fissures at Bath.**

## 3.0 HYDROCHEMISTRY

### 3.1 Hydrochemical Facies

Table 1 lists the preliminary physiochemical data and ion concentrations acquired for the BTHN and BTHS thermal water samples in 2011. The data were used to assess Jamaica's geothermal potential prior to any future exploratory well drilling, reservoir modeling, and resource development. The Schoeller semilogarithmic diagram (Schoeller, 1962) in Figure 2a represents major ion analyses in milliequivalents per liter (Meq/L) for the BTHS and BTHN samples and classifies their hydrochemical water type as Na-Cl-$SO_4$ (Hylton et al., 1987). Concentration ratios and any influence by mixing between ions are shown as slopes of the lines between the chemical ions. The relative contents of Cl, $SO_4$, and $HCO_3$ in the BTHN and BTHS waters plot in the "volcanic waters" field (Figure 2b). BTHN and BTHS plot in the low B/Cl region of the Cl-Li-B ternary plot and suggest these thermal waters emerge from aging hydrothermal systems (Figure 2c). The enrichment of Cl and $SO_4$ in groundwater is generally due to mixing of seawater or dissolution of evaporite minerals deposited in a marine environment. Based on the low concentrations of $Na^+$, $Cl^-$, and $SO_4$, (Table 1) the Bath show very little influence from seawater miximg. Boron, chloride and lithium are tracers of fluids from geothermal sources. The Cl /$SO_4$ vs. Li/B relationships in Figure 2d imply the occurrence of shallow mixing of the Bath geothermal fluids with other geothermal waters in Jamaica. The thermal character of the BTHN and BTHS samples are indicative of shallow mixing between meteoritic recharge and somewhat deeper circulating waters ≥ 50 years (Wishart, 2013).

TABLE 1: Physical parameters and concentrations of major and minor ions of the Bath hot spring samples BTHS and BTHN.

| Sample | T (°C) | pH | TDS (ppm) | EC (µS/cm) | ORP (mV) | Na (mg/L) | Ca (mg/L) | Mg (mg/L) | K (mg/L) | B (mg/L) | Li (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| BTHS | 51.3 | 8.76 | 588 | 840 | -99 | 121 | 22.1 | 0.32 | 1.26 | 3/03 | 0.0005 |
| BTHN | 48.0 | 8.82 | 524 | 754 | -90 | 140 | 29.0 | 0.34 | 2.20 | 3.70 | 0.0005 |
| Sample | Fe (mg/L) | $SO_4^{2-}$ (mg/L) | F (mg/L) | Zn (mg/L) | Cl (mg/L) | $SO_4$ (mg/L) | $HCO_3^-$ (mg/L) | $SiO_2$ (mg/L) | $HS^-$ (mg/L) | $PO_4^{3-}$ (mg/L) | DO (%) |
| BTHS | 5.82 | 59.8 | 3.40 | 0.02 | 121 | 59.8 | 46.4 | 29.7 | 0.094 | 6.73 | 45.3 |
| BTHN | 5.80 | 92.6 | 4.05 | 0.02 | 160 | 92.6 | 45.4 | 31.0 | 0.094 | 6.73 | 45.3 |

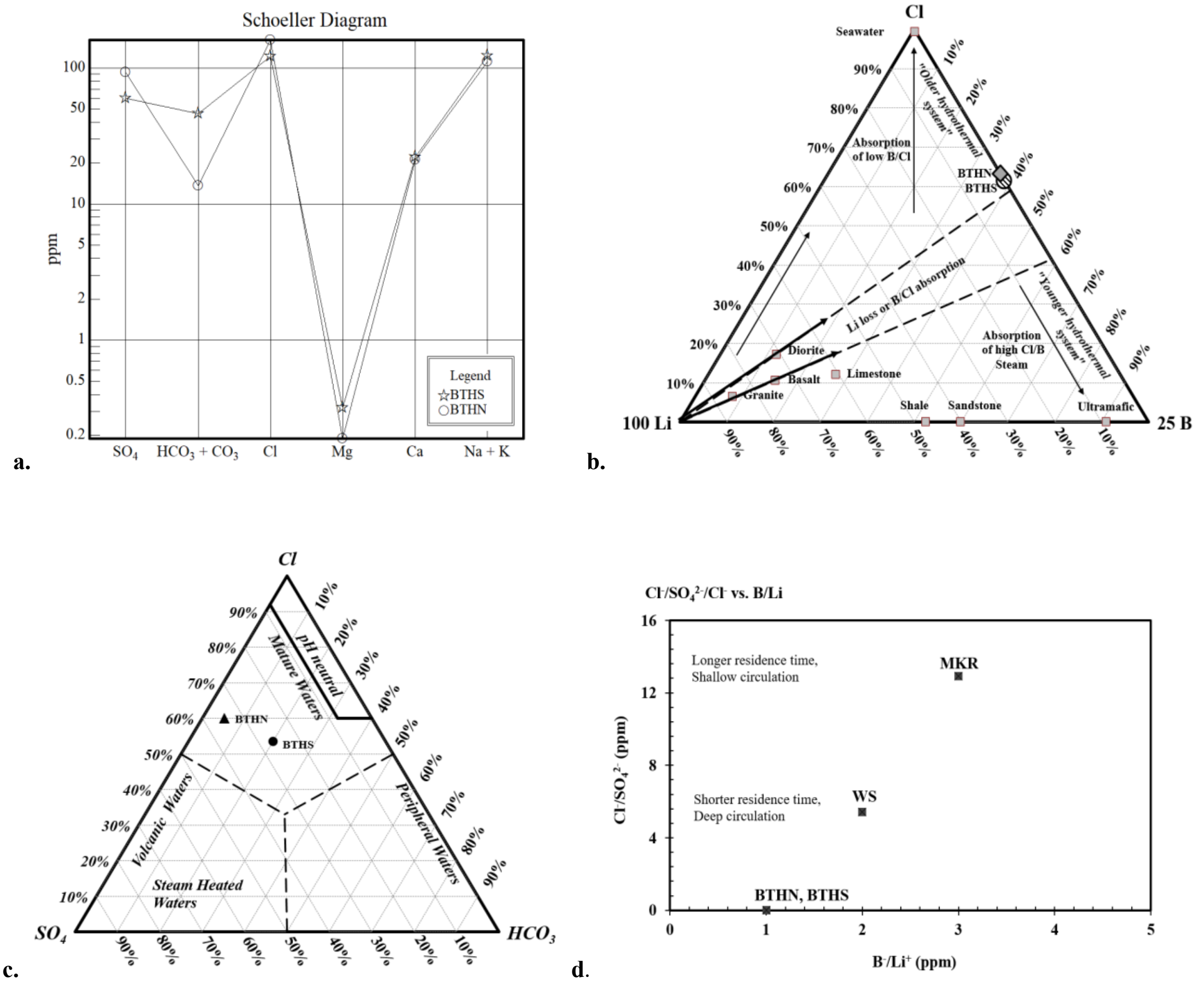


**Figure 2: Characterization of the chemical signature of the Bath thermal water samples (BTHN and BTHS) a. Schoeller semilogarithmic diagram. b. Cl-B-Li ternary diagram. c.   d. Cl/SO4 vs. B/Li relationships used to indicate the depth of mixing in geothermal waters of Jamaica: BTHN, BTHS – Bath springs; MKR – Milk River spring; WS – Windsor spring.**

## 4.0 METHODOLOGY

### 4.1 Geothermometry

Table 2 lists estimates of reservoir temperatures (82°C – 223°C) for the BTHN and BTHS water modelled discharge temperatures of 51.3–52°C using a silica ($SiO_2$) and cation (Na/K, Na-K-Ca, Na-K-Mg) geothermometric equations in AquaChem and SOLGEO (Verma et al., 2008). Fluids may undergo 'partial' or 'full equilibration' during interaction with the mineral-rock surface of fractures and yield lower temperature estimates as a result of mixing with other fluids during ascent to the surface. Therefore, the application of various geothermometers to the same field frequently yields different values for reservoir temperature. It is worth mentioning the results of various silica-phase geothermometers (e.g. amorphous silica and chalcedony) yielded erroneous geotemperatures even lower than actual discharge fluid temperatures. The quartz geothermometers estimated geotemperatures at 84 - 86°C whereas Na-K geothermometers estimated a range of geotemperatures at 82 - 118°C. Lower geotemperatures estimated from other silica phase geothermometers may have resulted from dilution by waters of lower silica content or the precipitation of silica (loss) during ascent to the surface. Figure 3 is the Na-K-Mg ternary geoindicator (Giggenbach, 1988) used to distinguish the equilibrium status in geothermal systems and the level of mixing by the inter-relations among Na, K, and Mg in geothermal fluids. BTHS and BTHN waters plot away from 'seawater' field of the ternary diagram and are 'partially equilibrated' with respect to water and minerals in solution. The reservoir temperature for both samples was estimated at 120°C. Differences of ±9 to 19°C in geotemperature estimates for BTHN and BTHS water samples derived from Na-K geothermometer are no doubt due to two different sampling points where they were collected. The BTHN water was sampled from the outflow of a 4-ft PVC pipe extending from hot rocks whereas the BTHS was sampled directly from a boiling spring discharging from a rock fissure. Na-K and Na-K-Ca solute geothermometers assume the attainment of chemical equilibrium between fluid-rock reactions in geothermal systems. Estimated geotemperatures may be lowered as re-equilibration occurs along the flow path and dilution occurs due to near surface mixing, possibly resulting in a minimum estimate of the highest temperature reached in the system (Grasby and Hutcheon, 2001). Therefore, geotemperatures estimated from other silica phase geothermometers were considered unreliable for Bath thermal waters due to probable re-equilibration during ascent or silica loss from precipitation (Fournier and Truesdell, 1977; Fournier, 1977). $Na^+$ and $K^+$ take longer to re-equilibrate in thermal waters based on feldspar content and could indicate a deeper, hotter geothermal system (Verma et al., 2008). $Ca^{2+}$ and $HCO_3^-$ concentrations are lower than chloride in the BTHS and BTHN waters. Na-K geothermometers are reliable for temperatures >100°C. Therefore, geotemperatures estimated from the Na-K geothermometer were deemed more reasonable for the Bath reservoir. The Na-K-Ca (Fournier and Truesdell, 1973) geothermometer was used to eliminate the possible effect of $Ca^{2+}$ on the Na-K geothermometer and for comparison with other geothermometers and results for non-equilibrated waters. However, the Na-K-Ca geothermometer yielded a reservoir of temperature of 223°C considered anomalous compared to geotemperature estimates the Na-K and one quartz geothermometer. Dilution, possible boiling, and loss of $Ca^{2+}$ may have affected the Na-K-Ca temperature leading to changes in ion concentration and overestimation of reservoir temperature. Furthermore, the level of error may also be proportional to $CO_2$ loss. Verma et al. 2008 discourages the use of K-Mg, Na-Li, Na-K-Ca, Na-K-Mg, and Na-K-Ca-Mg geothermometers that have led to errors, but deem the Na-K geothermometers more appropriate for providing more reliable results.

TABLE 2: Temperatures estimated from solute and silica geothermometers

| Geothermo-meter | Equation | Range (°C) | Estimate BTHS (°C) | Estimate BTHN (°C) | Source |
|---|---|---|---|---|---|
| $SiO_2$ | $T_{Na/K} = \left[\frac{1535}{0.989 - log\, S}\right] - 273.15$ | 100-275 | 84 | 86 | Truesdell (1977) |
| Na-K | $T_{Na/K} = \left[\frac{1217(\pm 93.9)}{log\left(\frac{Na}{K}\right) + 1.483}\right] - 273.15$ | 0-250 | 102 | 84 | Fournier (1979) |
| Na-K | $T_{Na/K} = \left[\frac{1319}{log\left(\frac{Na}{K}\right) + 1.699}\right] - 273.15$ | 25-350 | 107 | 89 | Arnórsson et al. (1983b) |
| Na-K | $T_{Na/K} = \left[\frac{1390}{log\left(\frac{Na_m}{K_m}\right) + 1.75}\right] - 273.15$ | NR | 118 | 99 | Giggenbach (1988) |
| Na-K | $T_{Na/K} = 733.6 - 770.551[\log\left(\frac{Na_m}{K_m}\right) + 378.189[log\left(\frac{Na_m}{K_m}\right)^2 - 95.753[log\left(\frac{Na_m}{K_m}\right)^3\ 9.5444[log\left(\frac{Na_m}{K_m}\right)^2$ | 0-350 | 88 | 72 | Arnórsson et al. (2000) |
| Na-K | $T_{Na/K} = \left[\frac{1289(\pm 76}{log\left(\frac{Na}{K}\right) + 0.615}\right] - 273.15$ | NR | 104 | 85 | Verma & Santoyo (1997) |
| Na-K | $T_{Na/K} = \left[\frac{1052}{1 + e\left(1.714\, log\left(\frac{Na}{K}\right) + 0.252\right) + 76}\right]$ | 100-350 | 112 | 103 | Can (2002) |
| Na-K-Mg* | Na-K-Mg Ternary Diagram | 60-340 | 120 | 120 | Giggenbach (1988) |
| Na-K-Mg | $T_{Na/K} = \left[\frac{1178}{log\left(\frac{Na}{K}\right) + 1.239}\right] - 273.15$ | NR | 86 | 97 | Nieva & Nieva (1987) |
| Na-K-Ca | $T_{Na-K-Ca} = \left[\frac{1647}{log\left(\frac{Na_m}{K_m}\right) + \beta\left(Log\left(\frac{Ca^{0.5}{}_m}{Na_m}\right) + 2.06\right) + 2.47}\right] - 273.15$ | 0-250 | 223 | 136 | Fournier & Truesdell (1973) |
| K-Mg | $T_{K/Mg} = \left[\frac{4410}{14.00 - log\left(\frac{K^2}{KMg}\right)}\right] - 273.15$ | NR | 59 | 64 | Giggenbach (1988) |
| Na-K/Mg-Ca* | 10cMg/(10cMg + *c*Ca) vs. 10cK/(10*c*K + *c*Na) | 40-340 | 130 | 130 | Giggenbach (1988) |

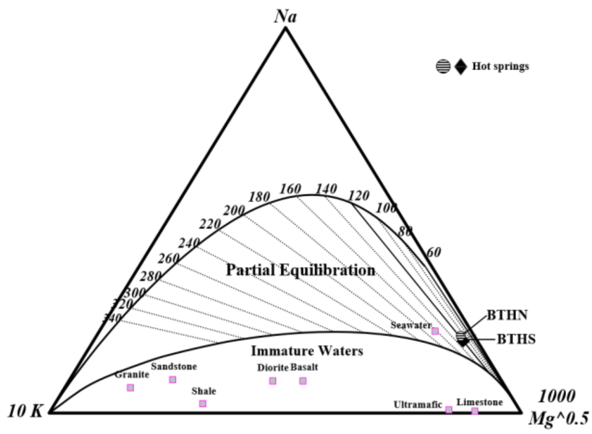


**Figure 3: a. Na-K/Mg-Ca diagram for the Bath hot spring samples (BTHS and BTHN) based on Giggenbach, 1988, b. Graphical evaluation of water-rock equilibration temperatures for the Bath thermal springs (BTHN and BTHS) using Na-K-Mg concentration (Giggenbach, 1988).**

Giggenbach (1988) proposed the 10cMg/(10*c*Mg + *c*Ca) vs. 10cK/(10*c*K + *c*Na) geoindicator (Figure 4) based on chemical equilibria (Giggenbach 1981; 1984) to show the relationship between the cation concentrations in geochemical solutions and their sources e. g. mixing with seawater and the dissolution of crustal rocks (Figure 4). The relative abundance of $Mg^{2+}$to $Ca^{2+}$ (carbonates) and $Na^{+}$ to $K^{+}$ (alkali-silicates) in thermal waters (Besser, et al., 2018) may also be compared on the diagram. Full equilibrium attained between these ionic ratios during water-rock interaction is represented by the bold line. Both BTHS and BTHN samples plot below the 'Full Equilibrium' line and closer to the rock-water and ion exchange region. It may be implied the chemical composition of the waters are controlled by rock-water interaction rather than equilibrium between water and minerals in solution. The reservoir temperature estimated by this geoindicator is 130°C with no influence from mixing with seawater as previously indicated in Figures 2a-d and 3.

### 4.2 Boron-Chloride-Fluid Enthalpy

Chloride ($Cl^{-}$) and boron ($B^{+}$) are regarded as a chemically-conservative, soluble elements in geothermal fluids (or a common reservoir source) as their solubility is neither temperature nor pressure-dependent on chemical equilibria. The Cl, B, vs. fluid enthalpy graph (Figure 5) delineates the geothermal water samples BTHN and BTHS and a geothermal brine from Milk River thermal spring (MKR) in south central Jamaica as low enthalpy resources (with geotemperatures >80°C and less than 180°C), but two distinctive and separate geothermal reservoirs on the island based on their chloride ($Cl^-$) and boron ($B^+$) concentrations versus fluid enthalpy..

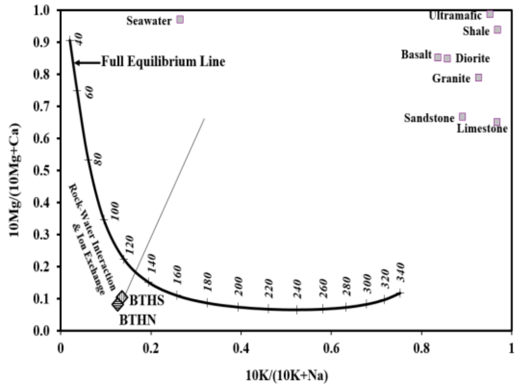


**Figure 4: Diagram of Giggenbach (1988) geoindicator 10cMg/(10*c*Mg + *c*Ca) vs. 10cK/(10*c*K + *c*Na) based on chemical equilibria (Giggenbach 1981, 1984) showing the relationship between the cation concentrations of geochemical solutions and the sources of ions e. g. mixing with seawater and the dissolution of crustal rocks.**

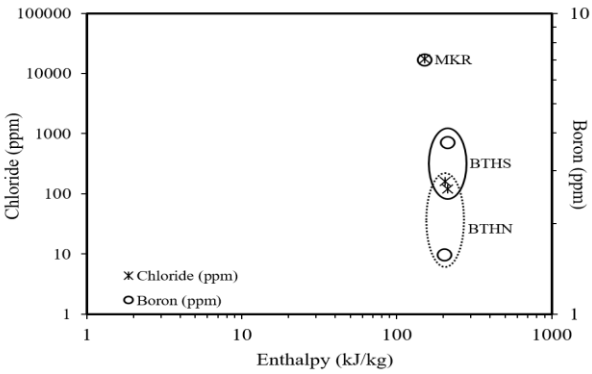


**Figure 5: Boron-Chloride vs. Fluid Enthalpy for geothermal waters in Jamaica. [BTHN and BTHS - Bath thermal springs and Milk River thermal spring (MKR) in south central Jamaica.**

### 4.3 Estimation of Depth to Geothermal Reservoir

Figure 6 is a hypothetical model of the Bath geothermal reservoir: however, estimated depths do not preclude the possibility that the system is much shallower than indicated by ionic ratios in Figure 5. Another argument that may lend support to a shallower geothermal reservoir at Bath is the Blue Mountain Inlier in eastern Jamaica lies in close proximity to a major E-W striking tectonic feature, the Plantain Garden River Fault (PGRF). The PGRF is a trace of a large strike-slip fault, the Enriquillo–Plantain Garden Fault Zone (EPGFZ) that terminates in the Dominican Republic. The mantle is at a higher elevation in eastern Jamaica compared the thick limestone sediments that overlie the volcanic basement of central Jamaica. Based on the BTHS sample, the minimum depth to fluid circulation in the Bath reservoir was estimated to be 2.80 km under the assumption of a 30°C/km geothermal gradient for the Caribbean region; however.as no borehole data are available. It must be cautioned, the temperature of a geothermal fluid sampled at the surface may not be a geotemperature of indicator of the subsurface reservoir. The volumetric assessment of geothermal energy contained in a volume of rock and water may be calculated under the assumption that it is homogenous with no recharge occurring (Hochstein, 1975; Pasvanoğlu, 2012). A rough estimate of the thermal energy in the subsurface of the Bath geothermal reservoir was calculated using Equation (1):

$$E = E_t + E_w = \quad VC_r\rho_r(1-\emptyset)(T_i - T_0) + VC_w\rho_w(1-\emptyset) + (T_i - T_0) \tag{1}$$

where,

$E$ = total energy (stored heat in the system), rock and fluid (kJ); $V$ = reservoir volume ($m^3$); $T_I$ = temperature of the aquifer (°C); $T_o$ = reference temperature (°C); $C_r$ = rock specific heat capacity of (kJ/kg°C); $C_w$ = specific heat of water (kJ/kg°C); $\rho_{r,f}$ = density of reservoir rock (kg/$m^3$); $\rho_w$ = density of water (kg/$m^3$); $\emptyset$ = porosity of rock; $hf$ = enthalpy (kJ/kg).
The following assumptions were made for to determine a rough estimate of potential thermal energy of the Bath geothermal reservoir:

Area (A) = 1 $km^2$; V = 5 x $10^5$ $m^3$; $T_1$ = 82°C; $T_o$ = 15°C (discharge temperature at ground surface); $\rho_r$ = 3000 kg/$km^3$; $\rho_{w51.3°C}$ = 970.33 kg/$m^3$; $hf_{82°C}$ = 343.35 (kJ/kg); $hf_{51.3°C}$ = 213.51 (kJ/kg) (Zarrouk and Watson, 2001); Ø = 0.06; $C_r$ = 0.840 kJ/kg°C; $C_w$ = 4.198 kJ/kg°C (at 80°C all the water is liquid); ΔT/ΔZ = 30°C/km; assumed reservoir thickness = 1000 m; therefore the assumed

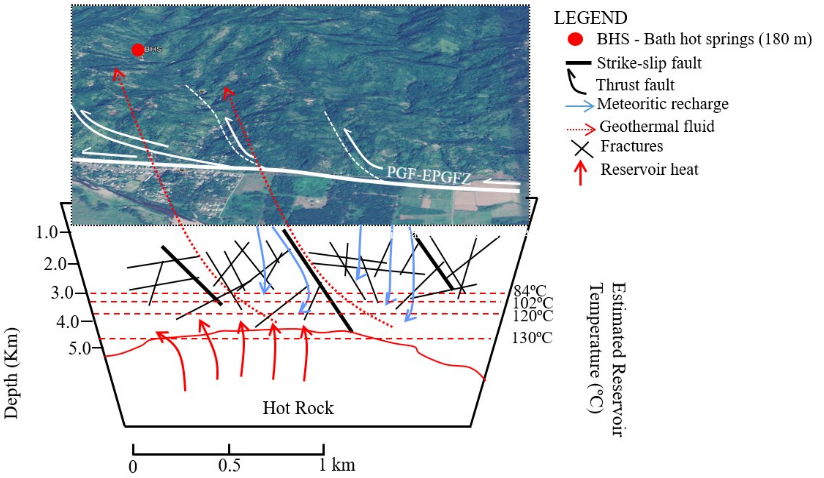


**Figure 6: Conceptual model of the hydrodynamics of the Bath geothermal reservoir.**

temperature gradient is 30°C x (300/1000) = 15°C. The temperature difference ΔT = (82 - 51.3°C) = 52°C. The estimated stored heat (total energy volume) of fractured reservoir using the parameters listed above in Equation 1 is 6.794 x $10^{16}$ J. From Equation 1, the estimated input power potential ($MW_t$) calculated using the Hochstein (1975) stored heat recovery method, an arbitrary recovery factor (*r*) as 25 % of the stored heat (0.25), and lifetime for exploration of 25 years minimum with the assumption of a functional geothermal system operating 365 days per year is (Equation 2):

$$Reserve\ (MW_t) = \frac{Stored\ heat\ X\ Recovery\ Factor}{Life\ Time} = 27.98\ MW_t \tag{2}$$

## 5.0 GEOTHERMAL RESOURCE EXPLORATION AND DEVELOPMENT

### 5.1 Exploratory Geothermal Well Drilling

Jamaica currently derives its electricity mostly from fossil-fueled and hydroelectric power plants provided to the commercial, residential, agricultural, and industrial sectors. Despite that alternative forms of energy (including renewable energy) cannot completely replace fossil fuels, they provide flexibility to available energy resources; reduce the island's dependence on limited (non-renewable) fossil fuel reserves; and reduce greenhouse emissions to the environment in light of a changing climate. Preliminary estimates of the Bath reservoir temperatures are 82 -130°C (Table 2; Figure 3 and 4). The next phase of geothermal investigation should involve the implementation of a geothermal exploratory well drilling program at Bath to test the temperature and evaluate the potential of extraction of sufficient geothermal fluids for Binary cycle power generation from the low enthalpy resource. Well drilling is needed to provide critical fluid data (e.g. fluid enthalpy, fluid inlet temperatures, well head pressures and vapor pressures. Thermal gradient holes (TGH) are required to determine the local geothermal gradient and the detection of anomalous geothermal gradients necessary for reservoir modeling and characterization (Parada, 2012) and provide data for reservoir modeling. The design strategies suggested here could prove very helpful streamlining a guideline of options for the optimization of a geothermal binary power plant for potential developers to review. Therefore, suggestions for the optimal design of a 5MWe geothermal binary power plant based on preliminary geotemperature estimates prior well exploration could assist in the fine-tuning the appropriate scale of development of a future geothermal binary power plant at Bath to avoid operational challenges or failure of the plant.

### 5.2 Silica Scaling Potential or Corrosion

In a liquid-dominated system such as Bath, the liquid phase controls the pressure in the reservoir and some steam may be present (Parada, 2012). For the scenario regarding a geothermal binary power plant, heat from water (primary working fluid) would be transferred to a working fluid. Therefore the potential for silica scaling (scaling) or corrosion from steam and brine is expected to be minimal. The Bath geothermal waters is an overall alkaline, Na-Cl-$SO_4$ type water with moderate concentrations of chloride Cl ≈121-160 mg/L, but depleted in sulfate and not considered a true a brine (Cl ≈121-160 mg/L). Brine concentration varies from 50,000 to 75, 000 mg/L with a higher density than seawater. A trace concentration (0.094 mg/L) of hydrogen sulfide (HS) in the water would act as a natural inhibitor of corrosion or scaling (Jalilinasrabady and Itoi, 2012; Papic, 1991) caused by geothermal brines through reaction with oxygen in the water. Geothermal brines are used to directly turbines in dry-steam and flash-steam geothermal plants. Based on the relatively low concentration of dissolved $SiO_2$ (Table 1) in the BTHN and BTHS water samples, the geothermal reservoir should chemistry is not expected to pose the problem of potential silica scaling in the primary or secondary (working) cycle components.

### 5.3 Critical Factors to Binary Cycle Plant Design Optimization

Based on a review of the literature, there is no particular procedure for design optimization of a binary geothermal power plant. However it is clear, a multivariate research approach and tedious analytical evaluation of numerous input variables: fluid properties throughout the system used assess the thermodynamic efficiency; the type of power cycle employed; objective functions; assessment of thermodynamic performance during the primary and secondary cycles; constraints; plant components; and sensitivity to modification or flexibility incorporate to achieve the optimal plant design (Franco and Villiani, 2009). A schematic of a proposed geothermal binary power plant with a wet cooling system for condensation that could be implemented at the Bath geothermal site is illustrated in Figure 7. Technical specifications including thermodynamic cycle, saturation pressure, maximum temperature depth of the production wells to the reservoir, selection of the working fluid, (i.e. temperature, enthalpy, pressure) will be specific to the geology of the Bath site. The sustainability of the geothermal fluid is critical to the operational conditions of the geothermal system; and economic feasibility of operational costs. Fluid enthalpy, geothermal fluid (brine) chemistry, well head pressure ($P_{In}$), vapor pressure, and capital cost are key to the design and potential scale appropriate geothermal binary power plant based on an estimated 28–170 $MW_t$ a geothermal resources prior to exploratory well drilling. In this section, design optimization strategies for enhancing the efficiency are suggested for the design of a 5 MWe geothermal binary plant with Organic Rankine Cycle (ORC) technology; geothermal fluid inlet temperatures 80-130°C; multicomponent medium of working fluids; and a wet cooling system near Bath hot springs for the purposes of supplementing electrical power production from renewable resources. Optimization will be achieved when the most efficient use of the maximum available energy is matched with the appropriate size power plant and minimum cost of power. The suggestions for optimization of the binary plant design briefly outlined in this section could prove very helpful to provide a guideline of options for the optimization of a geothermal binary power plant for potential consideration by developers. A binary cycle power plant operating with fluid inlet temperatures at or below 140°C in Jamaica could become the Caribbean's first low enthalpy geothermal resource used to supplement power production to an electrical grid.

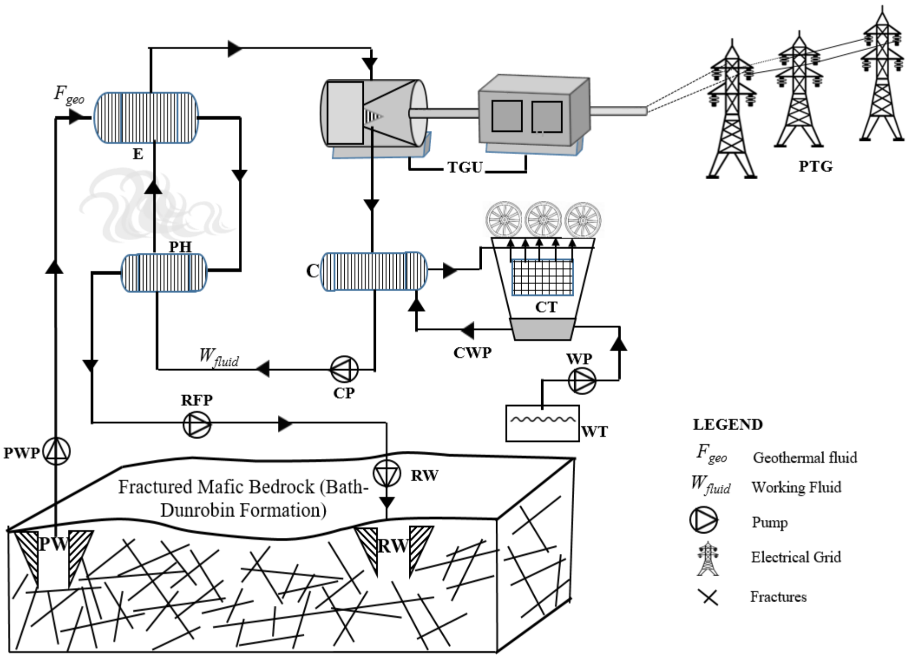


**Figure 7: Schematic of a prospective geothermal binary power plant powered by an Organic Rankine Cycle (ORC) on a liquid-dominated reservoir at Bath St. Thomas, Jamaica. [PW-Production Well; PWP-Production Well Pump; E-Evaporator; PH-Pre-heater; WT- Water Pump; C-Condenser; $F_{work}$ -Working Fluid CP-Condenser Pump; TGU-Turbine-Generator Unit; CT-Cooling Tower; CWP- Cooling Water Pump; RFP-Reinjection Fluid Pump; RW-Reinjection Well; WT-Water Tank; and PTG-Power Transmission Grid.**

### 5.4 Thermodynamic Efficiency

5.4.1 Mass Fluid Inflow

The First Law efficiencies of geothermal plants are restricted by low-temperature/low enthalpy systems. The amount of geothermal energy that can be converted to electricity while limited by the Second Law of efficiencies is also a function of the plant design and the efficiency of various components. The potential power output is dependent on the amount of heat that can be extracted from ($F_{geo}$) before reinjection and the temperature at which heat from the power cycle is rejected. A constant geothermal fluid inlet temperature ($T_{geo}$) will have to be maintained during the lifecycle of the binary plant. Inlet fluid temperature is very critical to the performance of the system. Franco and Villiani (2009) suggest a higher fluid inlet temperature (140-160°C) be used rather than a lower inlet temperature (80-130°C) for viability of thermodynamic efficiency. In consideration of the thermodynamic system level where the amount of heat transfer to the working fluid ($F_{work}$) is equal to heat losses from the geothermal fluid ($F_{geo}$), the energy balance is given by Equation 3:

$$\dot{m}_{gf}(h_{s1} - h_{s3}) = \dot{m}_{wf}(h_3 - h_1) \quad (3)$$

where $\dot{m}_{gf}$ is the mass of the geothermal fluid; $\dot{m}_{wf}$ is the mass of the working fluid; and h refers to the values of enthalpies at each specific point. It is important to find a match between the temperature geothermal fluid ($T_{geo}$) and working fluid ($F_{work}$) to balance the required system temperature. The enthalpy in the energy balance may be replaced by the difference in temperature if the heat capacity of $T_{geo}$ is known as follows in Equation 4 (Franco and Villiani, 2009):

$$\dot{m}_{gf}Cp_{gf}(T_{s1} - hT_{s3}) = \dot{m}_{wf}(h_3 - h_1) \quad (4)$$

where $Cp_{gf}$ is the specific heat of the geothermal fluid and $T$ refers to the temperature at each specific point.

5.4.2 Simulation of Thermodynamic Cycles

The geothermal fluid data collected during exploration drilling represents the initial point of the thermodynamic process. Simulations of thermodynamic calculations for the binary and other cycles using Engineering Equation Solver (EES). EES (Klein and Alvarado, 1994) distributed by F-Chart Software (2012) is general equation solver software equipped with high accuracy thermodynamic property database for fluids (Parada, 2012). Cycle models with assumed wellhead pressures may be simulated to determine the optimized output of the geothermal resource and thermal performance of water heating in relation to the working fluid, exergy analysis, and calculation of the turbine inlet and outlet enthalpies. Results may be used to aid conceptual design in the selection of working fluids, specifications for heat exchangers (i.e. tube diameter and pitch), pressure that results in the maximum power production, and sensitivity analysis for the optimization of operating conditions.

5.4.3 Heat Exchangers

The heat exchangers of a geothermal binary power plant are the evaporator, pre-heater, and condenser (Figure 7). The size and cost of heat exchangers are related to minimal temperature difference in the heat exchanger between the geothermal fluid and the working fluid-pinch-point ($\Delta T_{pinch}$) which impacts the pre-heating effect. A lowered preheating-effect reduces power plant efficiency and power output as a result of higher a higher pinch point (Van Erdeweghe et al., 2017). A recuperator is an additional heat exchanger used to increase the temperature of the working fluid at the pre-heater entry point (Prananto et al., 2018) but increases the operational cost of the plant (Parada, 2012) . The condenser condenses the working fluid while dissipating heat to the environment. Condenser temperature is critical, may not be beneficial when reduced and is not necessarily optimized when lowest. The options for cooling in a binary cycle power plant are either a wet or dry cooling system. A wet cooling involves the condensation of a working fluid ($F_{work}$) by water located in an area with easy access of the plant. Geothermal binary cycle power plants with dry cooling systems are a highly sustainable way to exploit a liquid water-dominated geothermal reservoir because no additional water is required. A dry cooling system would require short sleeves installed inside the end of each of their tubes to allow expansion for tight contact. However, in the example of a dry cooling system, caution needs to be exercised to ensure it is designed to adequately cool the working fluid to allow the plant to operate at full capacity prevent and avoid system failure. Changes in weather and climate may affect the condensation temperature. The power consumption (parasitic load) is increased when there is very little difference between the condensation temperature and ambient temperature. The range of temperature for the wet cooling tower should be set between is between 10 and 25°Cand not lower, as a higher thermodynamic performance of the recovery cycle would increase fan requirements and costs (Franco and Villiani, 2009). The Bath geothermal reservoir would have access to water as there are numerous cold water springs located in areas above the hot springs around the site.

5.4.3 Selection of the Working Fluid

The selection of a working fluid that acts as a medium of energy conversion is critical to thermodynamic efficiency. Transfer of geothermal fluid enthalpy ($h$) or thermal energy to the working fluid ($F_{work}$ ) through heat exchangers. The $F_{work}$ is vaporized by a condenser and used to run the turbine coupled to a generator to produce electrical energy (Dipippio, 2008; Bliem and Mines, 1991; Saleh et al., 2007). Vaporization of the working fluid occurs at constant temperature, but its temperature rises during preheating. Fluids with low efficiency in conversion of thermal energy into mechanical energy and drastic changes in their thermodynamic properties due to reduced efficiency during heating at a higher temperature range should be avoided. Low temperature geothermal fluid (e.g. water) may be used to heat an organic working fluid (expands and raises the pressure) drives the turbine coupled to a generator to produce electricity in a binary cycle power plant. Multicomponent media are composed of two or more working fluids evaporating and condensing at variable temperatures in order to increase the thermodynamic efficiency. They may be selected for the purposes of (1) achieving a better match between the geothermal fluids and working fluids and (2) the working fluid and the cooling medium to reduce the exergy loss due to heat transfer. The option to select a zeotropic mixture (e.g. isobutane-isopentane or isobutane and R152a [refrigerant]) over a pure working fluid that limits the energy efficiency would enhance thermodynamic performance of the cycle through optimal matching between the temperature profiles of the primary fluid and working fluid (secondary fluid). Smaller temperature differences were observed using hydrocarbons as working fluids (Franco and Villiani, 2009). Considerations for the selection of the appropriate organic working fluid used for lower temperature heat sources in geothermal binary power plants include health safety, environmental impact, critical temperature, low boiling point, saturation vapor state, the heat recovery process, economy, and its thermodynamic properties.

5.4.4 Exergy

The power potential is dependent on the fluid temperature; fluid mass flow rate; the amount of extractable heat from the fluid; and temperature at which heat from the power cycle is rejected. The exergy (kW per kg/s) potential of a geothermal resource is the theoretical maximum power that can be generated a cycle, (e.g. binary cycle) is dependent on site-specific conditions of a geothermal reservoir and the prevailing ambient temperature for heat rejection temperature. The specific exergy of ($T_{geo}$) may be calculated by Equation 5 (Franco and Villiani, 2009):

$$E_x = h_1 - h_2 - T_0(S_1 - S_2) \quad (5)$$

where $h$ is the specific enthalpy of $T_{geo}$ at each inlet or outlet and $s$ is the specific entropy of $T_{geo}$ at each inlet or outlet. The exergy may be reduced by any temperature reduction that does not produce energy e. g. (1) a drop in pressure that lowers the temperature or (2) disparity between the temperature profiles of geothermal source fluid $T_{geo}$ during heat extraction and working fluid ($F_{work}$) leading to high differences in temperature. Two ratios may be defined to determine the exergetic availability of a geothermal resource by upper limit of the Second Law efficiency (Equation 6) and lower limit of the Second Law efficiency (Equation 7) as follows:

$$\frac{E_x}{Ex_0} = \frac{(T_{geo} - T_{rej}) - T_0 ln(T_{geo}/T_{rej})}{(T_{geo} - T_0) - T_0 ln(T_{geo}/T_0)} \quad (6)$$

$$\frac{E_x}{Q_0} = \frac{(T_{geo} - T_{rej}) - T_0 ln(T_{geo}/T_{rej})}{(T_{geo}/T_0)} \quad (7)$$

5.4.5 Thermal Efficiency

Low thermal efficiencies occur as a result of the low temperature range of the fluid available to the cycle: therefore, low thermal efficiencies are possible. Efficiency of conversion may be a very important factor to make energy production more viable by the incorporation of multicomponent media (e.g. isobutane and isopentane) rather than a pure fluid as the working fluid for the heat recovery cycle. The efficiency is defined by Equation 8:

$$\eta < 1 - \frac{T_c}{T_h} \quad (8)$$

where, $\eta$ is the efficiency, $T_c$ is the absolute temperature of the cold reservoir, and $T_h$ is the absolute temperature of the hot reservoir. The thermal efficiency of a geothermal reservoir is compared to a theoretical 'Carnot cycle' model of the ideal closed power for which there is no temperature difference between $F_{geo}$ and $F_{work}$ occurring along the process. Dipippio (2007) in his review of Carnot and Triangular cycle thermal efficiencies, highlighted that it Carnot cycle sets an unrealistically high upper limit on the thermal efficiency of binary cycle power plants. Dipippio (2007) assessed the Triangular Cycle as a more appropriate and relevant cycle against which to measure the thermal efficiency of geothermal binary power plants and revealed actual binary plants can achieve relative efficiencies as high as 85%. The First and Second Law efficiencies are typically used for the analyses of binary power plants; however the more appropriate Second Law of efficiency reflects the thermodynamic quality of the thermal efficiency conversion process as a decrease in geothermal fluid inlet temperature ($T_{geo}$) may occur. The standard expression for the Second Law of efficiency may be defined using a conventional reference temperature $T_0$ as Equation 9:

$$A = \frac{W_{net}}{m_{geo}e_{geo}} = \frac{W_{net}}{m_{geo}|(h_{geo-}h_0) - T_o(S_{geo}s_0)|} \quad (9)$$

where $h_0$ and $s_0$ are the reference values for enthalpy and entropy calculated for Eq. 4 ($T = T_0$)

**CONCLUSION**

The hydrochemical water type of the Bath hot spring samples (BTHS and BTHN) is a Na-Cl-$SO_4$. $Cl^-/SO_4^-$ vs. $Li^+/B^+$ ion ratios infer the Bath geothermal reservoir is a shallow, more accessible low enthalpy geothermal resource that warrants the implementation of geothermal exploratory well drilling to assess binary cycle power generation from the low enthalpy resource. The power potential estimated for the Bath geothermal reservoir ranges from of ≈28– 170 $MW_t$ assuming an average geothermal gradient of 30°C/km for the Caribbean region and reservoir temperatures estimated at 82-120°C. Based on the BTHS sample, the minimum depth to fluid circulation in the Bath reservoir was estimated to be 2.80 km under the assumption of a 30°C/km geothermal gradient for the Caribbean region; however.as no borehole data are available. Thermal gradient holes (TGH) are required to determine the local geothermal gradient and the detection of anomalous geothermal gradients necessary for reservoir modeling and characterization and provide data for geothermal reservoir modeling. The geothermal fluid data collected during exploration drilling represents the initial point of the thermodynamic process. The next phase of geothermal investigation should involve the implementation of a geothermal exploratory well drilling program at Bath to test the temperature and evaluate the potential of extraction of sufficient geothermal fluids for Binary cycle power generation from the low enthalpy resource.

A multivariate research approach and tedious analytical evaluation of numerous input variables: fluid properties throughout the system used assess the thermodynamic efficiency; the type of power cycle employed; objective functions; assessment of thermodynamic performance during the primary and secondary cycles; constraints; plant components; and sensitivity to modification or flexibility incorporate to achieve the optimal plant design. Factors that are key to the design process for optimizing a geothermal binary power plant requires tedious analytical evaluation of input variables used assess the thermodynamic efficiency, variables, power cycles, functions, constraints, and comparing with the incorporation of flexibility of modifying plant components. A critical step in the design optimization of a geothermal binary power plant is the selection of an appropriate working fluid for the thermodynamic cycle, power plant components such as the recovery heat exchangers (RHE) and the cooling systems (CS). Multicomponent working media composed of two or more fluids evaporating and condensing at variable temperatures should be selected for the purposes of (1) achieving a better match between the geothermal fluids and working fluids and (2) the working fluid and the cooling medium to reduce the exergy loss due to heat transfer. The sustainability of the geothermal fluid is critical to the operational conditions of the geothermal system; and economic feasibility of operational costs. Optimization will be achieved when the most efficient use of the maximum available energy is matched with the appropriate size power plant and minimum cost of power. Suggestions for the optimal design of a 5MWe geothermal binary power plant based on preliminary geotemperature estimates prior well exploration could assist in the fine-tuning the appropriate scale of development of a future geothermal binary power plant at Bath to avoid operational challenges or failure of the plant. The design strategies suggested here could prove very helpful streamlining a guideline of options for the optimization of a geothermal binary power plant for potential developers to review. A binary cycle power plant operating with fluid inlet temperatures at or below 140°C in Jamaica could become the Caribbean's first low enthalpy geothermal resource used to supplement supplementing electricity production from renewable resources.

## ACKNOWLEDGEMENT

The author wishes to acknowledge the partial funding provided for this project from National Science Foundation (NSF) ADVANCE Grants awarded from Wright State University and Central State University, in southwest Ohio.

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