Preliminary Assessment of Offshore Geothermal Resource Potential of Portugal - The Case of Azorean Deep-Sea Hydrothermal Vents

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Keywords

Offshore geothermal energy, hydrothermal vents, resource assessment, volumetric method, Azores archipelago, Portugal, supercritical

ABSTRACT

Hydrothermal vents are submarine hot springs and geysers that originate in volcanically active areas often at mid-ocean ridges, where the planet tectonic plates are spreading apart and magma wells up to or close to the surface of the seafloor. Hydrothermal circulation at the deep ocean ridges is an essential complex process regulating mass and energy transfer from the interior of the Earth through the oceanic lithosphere, to the hydrosphere and the atmosphere. Hydrothermal venting has long been recognised to provide significant fluxes of both heat and chemicals to the deep ocean. Hydrothermal fluids are generally with high heat flows and dissolved minerals, making them an excellent target for exploitation of hydrothermal energy and mineral resources. The energy extraction from the hydrothermal vents could provide a carbon-free and sustainable source of energy for the future generations.

A substantial number of hydrothermal fields are located in the vicinity of the Azorean archipelago (Portugal) comprising high-temperature fluids under supercritical conditions. The hydrothermal vents of the Azores are a chain of vents that are fragments of the Mid-Atlantic Ridge. These geological structures, developed from masses of basalt, are of a geomorphological interest, in addition to being a rich ecosystem of diverse subaquatic plant and animal life.

Although challenges and barriers exist in exploring mid-ocean ridge hydrothermal vents, these resources remain to be one of the most potential and stable sources of renewable energy. The study at hand presents a preliminary assessment of geothermal resource potential of the Azorean hydrothermal vents using a modified version of the volumetric stored-heat assessment method developed by the United States Geological Society (USGS) (1979) and the energy balance method presented by G.Hiriart (2010). The further part of the study aims at using the obtained data to assess the technological and economic potential of energy extraction from the hydrothermal vents.

1. Introduction

The recent and estimated trends indicate that renewable resources will provide a rising contribution to the global power systems in the coming decades. Though renewable energy is one of the fastest growing markets in the world, much of geothermal energy resources has remained unexplored. Geothermal power generation is low carbon, a cost-competitive source that offers a stable base-load power output, that must overcome several challenges and perceived barriers to capture a more significant share of renewables (Deloitte, 2008).

Offshore geothermal energy has remained highly an underdeveloped energy resource with massive potential. In the contexts of climate change and energy security, offshore geothermal acts as an excellent resource as it bridges both the conventional feedstock and renewable energy options for electric power generation. It is because geothermal power provides base-load generation allowing it to compete with other baseload feedstocks such as coal and natural gas. At the same time, it is clean and renewable that competes with other renewable energy options such as wind and solar.

The ocean has immense resources that could support the humanity energy needs. Mid-ocean ridges are one such kind of sources with significant potential of geothermal energy. The hydrothermal fluids in these settings are observed with extreme heat flows making them highly attractive for energy extraction (Hiriart et al, 2010a). As described in (Pedamallu et al, 2017) the Azorean archipelago is one such setting with an extensive number of hydrothermal fields containing high-temperature fluids under supercritical conditions.

The geothermal resource evaluation is made to confirm the existence of a geothermal resource that can be exploited at a reliable capacity for a specified period with distinct fluid characteristics and resource management. The study at hand presents a preliminary assessment of theoretical geothermal resource potential of the Azorean hydrothermal vents using a modified version of the volumetric stored-heat assessment method developed by the United States Geological Society (USGS) and the energy balance method (Hiriart et al, 2010b).

2. Site Description/ Study Area

2.1 The Azorean Archipelago & the Mid Atlantic Ridge

The archipelago of the Azores is a cluster of nine volcanic islands situated in the North Atlantic Ocean with an Exclusive Economic Zone (EEZ) of one million square kilometres and a mean depth of about 3000 m (Peran et al, 2016). The Islands of the Azores are located between 37° and 40° N latitude and 25° and 31° W longitude, placed along a narrow area that extends for about 600 km. It includes the Western Group (the Flores and Corvo Islands), the Central Group (the Terceira, Graciosa, São Jorge, Pico and Faial Islands) and the Eastern Group (the São Miguel and Santa Maria Islands and the Formigas Islets) (Oliveira et al, 2004). The islands are dispersed along a general WNW–ESE trend crossing the Mid-Atlantic Ridge in the area where the Eurasian, African and North American lithospheric plates meet. Seamounts are the most common features in the Azores and occupy 37% of the total area of the exclusive economic zone of Azores (Morato et al, 2008).

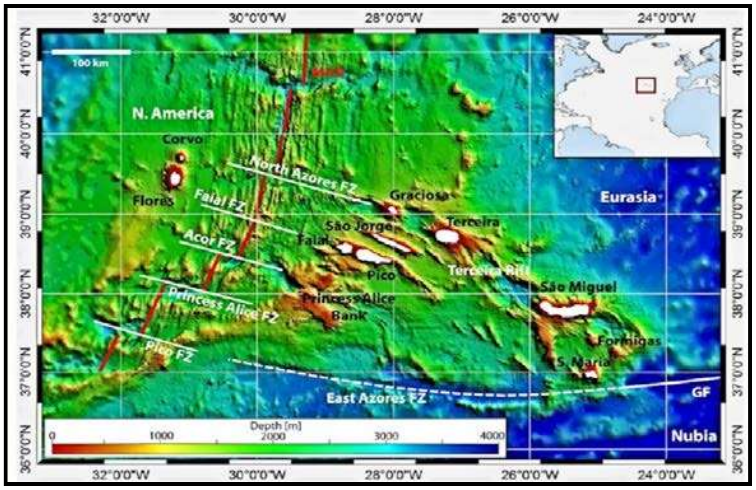

Figure 1: General Tectonic Framework of the Azorean Archipelago (adopted from - Weiß et al, 2014)

The Mid-Atlantic Ridge (MAR) is about 3 km in height above the ocean floor and 1000 to 1500 km wide, has several transform faults and an axial rift valley along its length (Centre, 2018). The MAR detaches the North American Plate from the Eurasian Plate in the North Atlantic, and the South American Plate from the African Plate in the South Atlantic as shown in figure 1.

The MAR near the Azores has four known major hydrothermal vent fields (figure 2) namely, Menez Gwen located at (37°51′N, 31°31′W, 800m depth) (Cerqueira et al, 2015), Lucky Strike located at (37º18'N, 32º16'W, 1738m) (Langmuir et al, 1997), Saldanha located at (36º34'N, 32º26'W, 2200 m) (Biscoito et al, 2006), and Rainbow (36º14'N, 33º54'W, 2250m depth) (Khripounoff et al, 2001). Each site presents specific geological, chemical, hydrothermal, and biological characteristics.

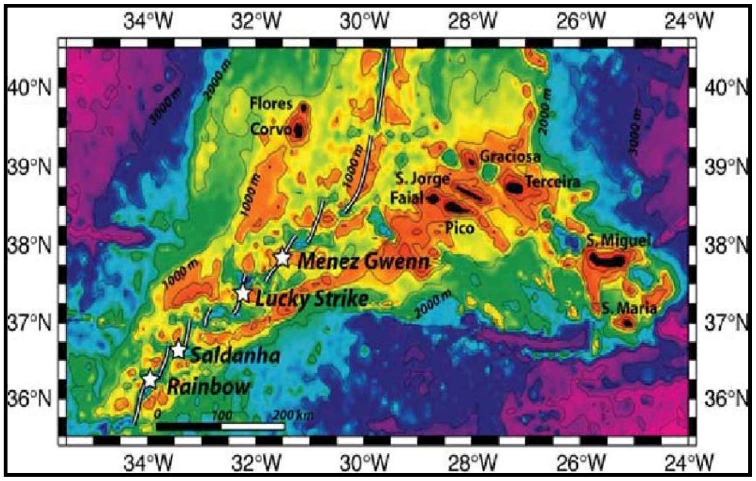

Figure 2: Location of the hydrothermal vent fields (white stars) near the Azores Triple Junction (Colaço et al, 2010)

2.1.1 The Lucky Strike hydrothermal vent field

The Lucky Strike hydrothermal vent field was the first Atlantic site found on crust that is dominated by a hot spot signature which was discovered in 1992 during the US mission Fazar. It is the largest known hydrothermal field within the Azorean archipelago with an area of 50 sq.km along with 21 active vents that extend over approximately one square kilometre along the sea floor (Ventsdata.interridge.org, accessed. May 2017). The Lucky Strike Hydrothermal Field is located in a depression formed by the lower slopes of three extinct volcanoes surrounding a lava lake at ca. 1700 m depth. These volcanoes are at the summit of the Lucky Strike Seamount (37°17.5’N) emerging from the MAR rift valley. Many individual sites as shown in figure 3 are found in the vent field that exhibit diverse manifestations of hydrothermal activity, ranging from black smokers to flanges (Saldanha et al, 1996). Vent morphologies range from flanges and chimneys with pool temperatures of 200-212°C to black smoker chimneys with temperatures up to 333°C (Charlou et al, 2000) and chimneys discharging lower temperature diffuse fluids.

The vents at Lucky Strike surround a flat expanse of ropy lava and spectacular pillar structures, interpreted as a fossil lava lake (Fouquet et al, 1995). Hydrothermal vents to the south and the west of the lava lake are built on a unique formation of layered basaltic breccia; sometimes silica-cemented, that forms a slab-like material up to a meter-thick (Langmuir et al, 1997), (Ondréas et al, 1997), (Humphris et al, 2002).

2.1.2 Saldanha Hydrothermal Field

The Saldanha hydrothermal field (36^{o}34’ N; 33^{o}26’ W) (NTO5), is located at the MAR, south of Azores Archipelago between the Pico Fracture Zone (PFZ), and the Oceanographer Fracture Zone (OFZ) (Dias et al, 2006).

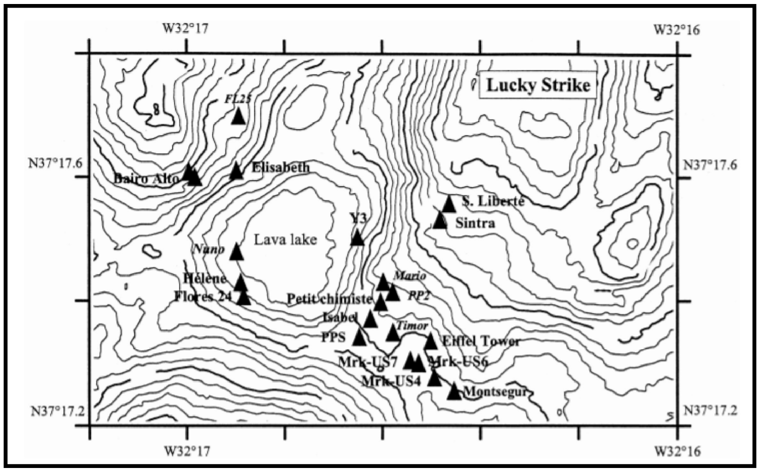

Figure 3: Lucky Strike Hydrothermal Field (Charlou et al, 2000)

Saldanha is a diffuse hydrothermal system where transparent and low-temperature fluids (6-9 ^{o}C) emanate from discrete orifices on the seafloor, triggered by ultramafic and mafic heat sources. The lower temperatures measured at the diffuse vents are probably a consequence of cooling effects during conductive circulation and seawater interactions. The mineralogy of the sediments, in particular, the occurrence of sulphide, suggests higher temperatures for this system than the ones measured at the vents. Petrographic and geochemical studies of sediments from this vent area, collected by a gravity core during CD167 in 2004, revealed that hydrothermal fluids have reacted with these sediments at temperatures higher than 250 °C (Dias et al, 2010).

The Mount Saldanha is a submarine hill of about 700 m with an area of 400 sq.m located at a depth of 2200m (Barriga et al, 1998; Biscoito et al, 2006). The top of the mount contains rock types like gabbros, basalts, etc. depicting varying degree of hydrothermal alterations. The observed hydrothermal alterations suggest higher temperatures of 300-400 ^{0}C immediately under the sediment. The Mt. Saldanha may represent the earliest phase of the hydrothermal field (Barriga et al, 1998).

2.1.3 Menez Gwen Hydrothermal Field

The Menez Gwen hydrothermal vent field is located at (37°51′N, 31°31′W) is a ridge centred, basalt-hosted hydrothermal complex, at 850 m depth in the Mid-Atlantic Ridge, inside the Portuguese exclusive economic zone within the Azores Marine Park (Cerqueira et al, 2015). The Menez Gwen hydrothermal field was discovered in 1994 during the DIVA expedition (Saldanha et al, 1996). It is the shallowest known vent system on the Mid-Atlantic Ridge that host chemosynthetic communities. The Menez Gwen seamount has a diameter of 17 sq.km, and the active vent field is located at the topographic high of the ridge segment as represented in figure 4. The central part of the volcano consists of an axial graben with an area of 12 sq.km and 300m depth filled with fresh lava (Saldanha et al, 1996). The lava has no sediment cover, and it has been suggested that the entire small volcano built up during the latest eruptive episode (Ondréas et al, 1997). The hydrothermal activity at Menez hydrothermal activity is mainly concentrated over small areas, primarily on a small volcano located at the top central area of the field and whose highest point reaches 800 m below the sea surface (Marcon et al, 2013). The diffuse fluid temperature extends between 10 and 56 °C while the hottest spotted fluid escapes from chimneys at an approximate temperature of 284 °C (Cerqueira et al, 2015).

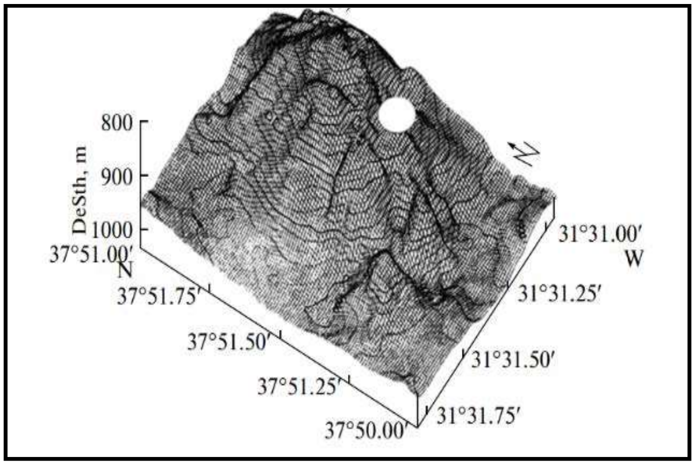

Figure 4: Block Diagram of Menez Gwen Volcano (Lein et al, 2010)

2.1.4 Rainbow Hydrothermal Field

The Rainbow field is situated at 36º14’N, 33º54’W, southwest of the Azores on the Azorean fragment of the MAR at a depth of 2270 m (Christiansen et al, 2003; Charlou et al, 2002). Rainbow was discovered during the FLORES diving cruise in 1997 (Fouquet et al, 1997). Rainbow is based on ultramafic rocks, causing the fluid to be more acidic with higher metal and methane concentrations (Douville et al, 2002). The active vent field is spread over an area of 15 sq.km, that is located on the western flank of the Rainbow ridge (Fouquet et al, 1997). Rainbow was found to have ten groups of active black smokers (see figure 5) owing to the high temperatures 364°C, which have some of the strongest plumes, whereby diffusion could be 10-15 km from the vent (German et al, 1996). The Rainbow consists of active vents that vigorously emit fluids with uniform chemical composition of major, minor, trace elements (Douville et al, 2002).

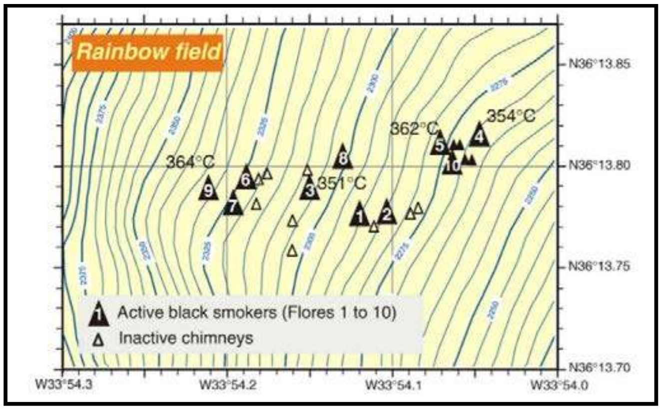

Figure 5: The Rainbow Hydrothermal Field (Konn et al, 2009)

3. Methods of Assessment

The geothermal resource assessment is required to confirm the existence of a geothermal resource that could be exploited at a guaranteed capacity for a specified period with well-defined fluid characteristics and resource management (Sarmiento et al, 2011).

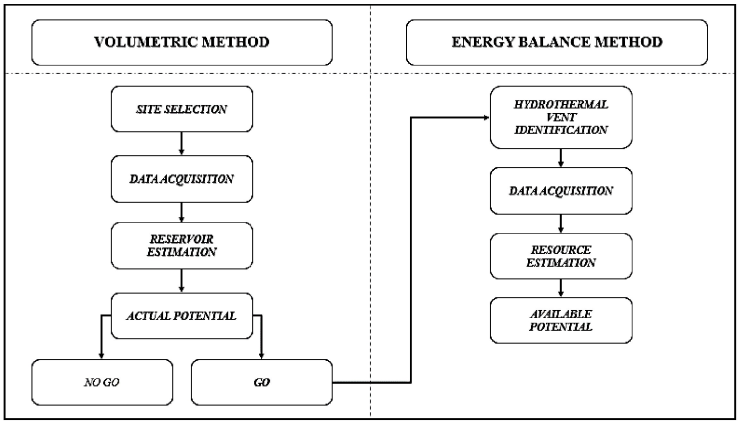

Figure 6: Framework of Assessment

The study considers two important methods of resource assessment (see figure 6) to estimate the available resource potential.

A modified version of the volumetric stored-heat assessment method is used (Equations 1,2 and 3) to assess the geothermal reservoir potential. The volumetric stored-heat method was developed by the USGS in the 1970s to assess the production potential of geothermal systems (Muffler, 1979). The volumetric method refers to the review of thermal energy in the rock and the fluid which could be mined based on specified reservoir volume, reservoir temperature, and reference or final temperature. The actual available power is assessed using Equation 4. The analysis is made for two scenarios with a heat recovery factors of 0.1 and 0.05 and conversion factors of 0.15 and 0.06.

$$E_t = E_f + E_r \tag{1}$$

$$E_r = A \times h\,[\rho_r . C_r . (1-\emptyset).(T_i - T_f)] \tag{2}$$

$$E_f = A \times h\,[\rho_f . C_f . (\emptyset).(T_i - T_f)] \tag{3}$$

$$P = \frac{E_t \times R_f \times C_e}{P_f \times t} \tag{4}$$

Where, E_t, E_r, E_f are total energy (kJ/kg), energy in rock, and energy in fluid respectively; A, h, t are area (m^2), height (m) and time in years; ρr, ρf are rock density and fluid density (kg/m^3); Ø is rock porosity; C_r, C_f is specific heat of rock and specific heat of fluid (kJ/kg.^{o}C); R_f, C_e, P_f are recovery factor, conversion efficiency and plant factor; T_i, T_f is initial temperature of fluid, rejection temperature of fluid, measured in ^{o}C.

Further, the energy escaping from the individual vent is assessed using the energy balance method as shown in Equation 5. The energy balance considers the submarine technology with one heat exchanger in the bow and one in the stern. The heat exchangers are located on top of the vent, and the other is exposed to the cold water of the deep sea. Inside the submarine, a binary cycle plant is operated between those two, hot and cold, spots.

The obtained results were used to identify the available potential of the hydrothermal vents using Equation 6. For the power plant sizing, the heat exchanger efficiency and cycle efficiency of the chosen technology Table1 is considered.

$$E_{HV} = \frac{\pi}{4} D^2 \times \upsilon \times \rho_{avg} \times C_f \times (T_h - T_c) \tag{5}$$

$$P_{HV} = E_{HV} \times \eta_{HEX} \times \eta_{CF} \tag{6}$$

Where D is the diameter of vent in meters; υ is the velocity of exiting fluid (m/s); $T_h and\ T_c$ are temperature of vent fluid and temperature of surrounding water measured in ^{o}C; P_{HV} is the power potential of hydrothermal vent; E_{HV} is the total thermal energy; η_{HEX} is the efficiency of heat exchanger; η_{CF} is the conversion efficiency.

3.1 Parameters, Assumptions & Limitations

An extensive review of the literature has been made on the mid-ocean ridge hydrothermal vent fields of the Azores. A wide range of parameters were considered for the estimation of the resource potential of the hydrothermal fluids. Previously published geological, geochemical, and geophysical data on the hydrothermal fields and the hydrothermal fluids of the Azores were included in the study. The theoretical available thermal power in the discrete hydrothermal vent fluids are assessed using the parameters of fluid flow, vent diameter, fluid temperature, and depth.

Table 1: Input Variables

Input Variables	*Units*	*Hydrothermal Vent Fields*			
		Menez Gwen	*Saldanha*	*Lucky Strike*	*Rainbow*
Number of Active Vents	-	10	1	22	10
Vents Considered (this study)	-	1	1	16	10
Fluid temperature	^{0}C	284	6	333	360
Depth	m	850	2200	1700	2200
Pressure	bar	86	221	171	221
Rock Density	kg/m^3	2000			
Fluid Density	kg/m^3	746.35	-	649.66	576.74
Heat capacity of the rock	*kJ/kg.K*	2			
Heat capacity of the fluid	*kJ/kg.K*	5			
Porosity of Rock	-	10 %			
Fluid Velocity	m/s	3			
Rejection Temperature	^{0}C	90 (Binary Plant)			
Vent Diameter	m	0.3			
Recovery Factor	-	0.1 (case1) & 0.05 (case2)			
Conversion efficiency	-	0.15 (case1) & 0.06 (case2)			
Heat Exchanger efficiency	-	13 %			
Cycle efficiency		31 %			

In arrears to the early stage of the research on offshore geothermal utilisation and due to the limited availability of data, few assumptions have been made in order move further with the analysis. The rock density has been considered the same for all the vent fields since all of them are volcanic rocks. Though the temperature of the fluid and the depth of each vent in the vent field may be different, this study considers the same temperature and depth for all individual vents located in the vent field. The rock porosity is assumed as 10% as stated in (Suarez, 1998) however the effective porosity must be considered to obtain more accurate results. The fluid velocity and the diameter of the typical vents are considered as shown in Table 1 and could be different from the actual scenario since it is site-specific in nature.

The limitations of the study include the avoided drilling scenario as described in Parada et al, (2012) and Hiriart et al (2010a). The energy estimates include only the use of thermal fluids that are fuming out of the hydrothermal vents. Higher energy output can be achieved if conventional methods are used. These calculations are restricted to the submarine areas of the Azores.

4. Results & Discussion

As a preliminary assessment, the reservoir estimation has been made using the equations 1, 2, 3 and 4. The analysis is presented for the complete study area, and the hydrothermal field Saldanha has been excluded from the study due to its lower temperature fluids and low reservoir potential. The obtained results as presented in figure 6, suggest that the vent fields Lucky Strike, Menez Gwen and the Rainbow have a huge reservoir potential and can be a reliable source for geothermal energy production.

Since the hydrothermal vent fields are environmentally sensitive areas with diverse species, drilling must be avoided to obtain environmental sustainability. To make sustainable use of the available resource, the energy content of the fluids escaping from the vent orifice has been assessed using Equation (5&6) The energy of the escaping fluids from the discrete hydrothermal vents can be readily captured and used for power production.

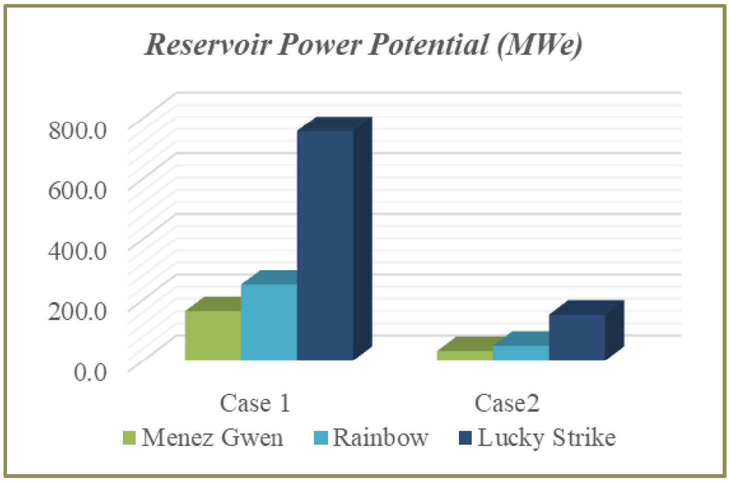

Figure 6: Reservoir Power Potential

The results as presented in figure 7 suggest that the hydrothermal vents in the Lucky Strike hydrothermal field have greater power potential of 9.1 MWe for single vent followed by Menez Gwen with 8.8 MWe and Rainbow with 8.7 MWe. However, considering the total number of vents in the hydrothermal vent field, Lucky Strike hydrothermal vent field constitutes greater power potential of 145 MWe followed by Rainbow with 87 MWe and Menez Gwen with 8.8 MWe. The observed differences are explicitly due to the variations in fluid temperatures, depth, and number of vents in the hydrothermal vent fields.

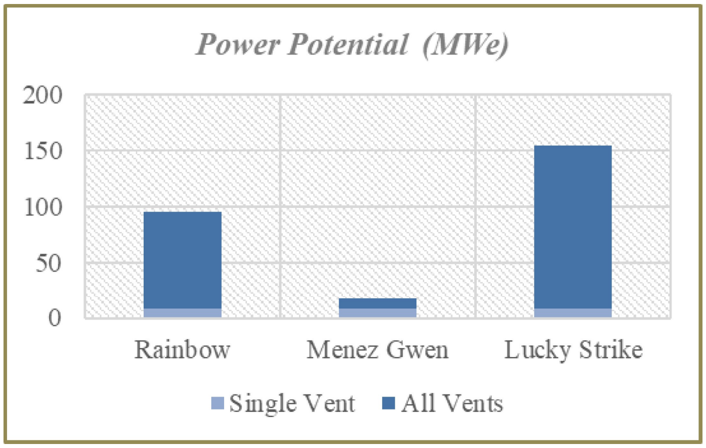

Figure 7: Actual power potential in MWe of single and group of hydrothermal vents in the vent field

5. Conclusion

Many factors affect the power production potential of the vent fields. An in-depth analysis, site surveys and multidisciplinary approach is needed in these kinds of studies in order to make their exploitation for power production a reality. The further part of the study aims at using the obtained data to assess the economic potential of energy extraction from the hydrothermal vents.

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