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Geothermal Potential in Galapagos Islands: Supporting Sustainable Energy Transition

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ABSTRACT

The Galapagos Islands energy system strongly depends on fossil fuels to produce electricity, but also for inland and marine transportation. More than 80% of the energy demand is currently covered with fossil-fuel based power plants. Different efforts to reduce fossil fuel dependence have been implemented on inhabited islands by integrating renewable energies in their isolated power systems. However, energy demand is growing in an accelerated rate, making these efforts negligible for a sustainable energy transition in the long term. Geothermal is a non-variable renewable energy resource that seems to be abundant in volcanic origin islands like Galapagos, which can contribute to achieve the Ecuadorian governments goal of Zero Fossil Fuel for the Galapagos Islands. Therefore, the purpose of this paper is to make a rapid assessment of the geothermal resource by integrating remote sensing, spatial multicriteria analysis, and a review of the energy system in Galapagos in order to estimate the potential, and impact, of geothermal energy in an existing fossil fuel based power system. This study identifies an important potential of geothermal energy, 80 times more renewable energy capacity than needed in the long term. Thus, contributing with open source geospatial information, this approach aims to support energy policy recommendations towards a sustainable energy transition, and thereby the achievement of Sustainable Development Goal 7 "ensure access to affordable, reliable, sustainable and modern energy for all" in natural and protected areas like Galapagos Islands.

1. INTRODUCTION

The Galapagos Islands is an archipelago of 18 volcanic islands distributed in the north and south hemispheres along the equatorial line in the Pacific Ocean, 973 km off the west coast of Ecuador (Figure 1). The ecological importance of Galapagos Islands has been recognized worldwide and strong environmental protection policies have been put in place for its conservation. In 1978 UNESCO recognized the islands as a World Heritage Site, and the Ecuadorian government in 1959 declared more than 97% of the archipelago´s land as a National Park, then in 1986, 70,000 km^2 of the ocean surrounding the islands was declared a marine reserve. However, there are environmental threats such as climate change, introduced plants and animals, land use change, biodiversity loss, and population growths, including tourist who in recent years surpass local population; who demand the scarce resources such as food, water and energy of the Island (CGREG 2015).

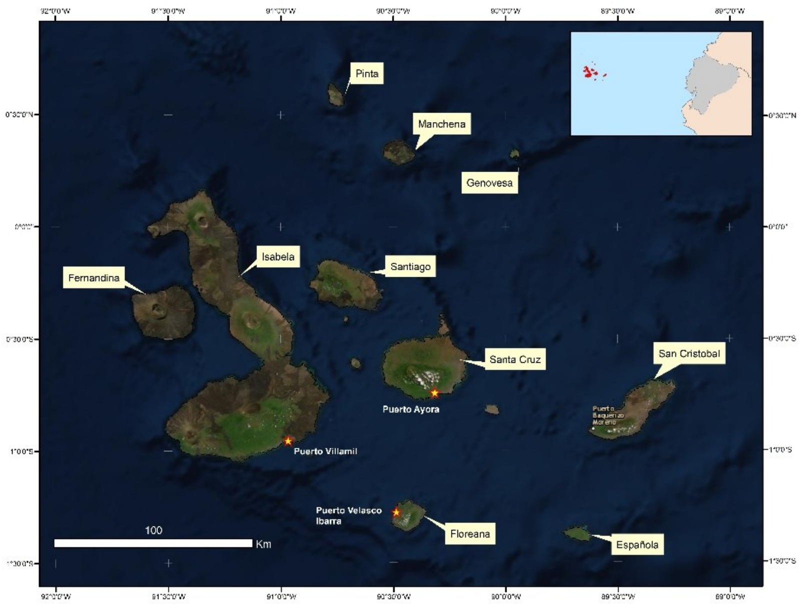

Figure 1: Galapagos Islands

Four islands in Galapagos are inhabited, i.e. Santa Cruz - 15,701 hab., San Cristobal -7,088 hab., Isabela - 2,344 hab. and Floreana - 111 hab. For a total population of 25,244 (INEC 2015), the two former being the most populated and with the highest energy consumption, they consume 90% of the total energy in 2019 (50 GWh/year). Today, the share of renewable energy in electricity production is very low (16% of the total production), and fossil fuel generation is the main source (MERNNR 2019). In this context, the Ecuadorian Government since 2007 has promoted the initiative "Zero Fossil Fuels in Galapagos" to foster a clean energy matrix in the archipelago. However, the complex situation of isolation and lack of funding for infrastructure development has limited the achievement of this goal. According to official projections, energy demand will double by 2027 reaching 100 GWh/year (MERNNR 2019); which means that a considerable increment of renewable energy capacity should be put in place.

For instance, the renewable energy capacity (i.e wind and solar energy) nowadays is 7.23MW, and which will need to be increased approximately to 60MW in order to achieve the goal of 100% of renewable energy in the Galapagos Islands. Considering, that more than 95% of Galapagos´ land is a protected area, plus variable renewable energy projects such as wind and solar require considerable amount of land area and have a negative perception when considerable capacities are put in place (Ioannidis and Koutsoyiannis 2020), they face important social and environmental restrictions for development in the fragile Galapagos ecosystem. On the contrary geothermal energy has the lowest land use (Andrew et al. 2010) and considering that Galapagos Island has a high volcanic activity, geothermal energy seems to be an untapped and unexplored resources that can help towards a sustainable transition of 100% renewable energy in the Galapagos Islands.

There is very high volcanism activity in the Galapagos Islands; however, up to the knowledge of the authors there is scant research on the evaluation of geothermal energy resources in the islands. Studies carried out in the Galapagos Island by Goff et al. (2000), identified a probable geothermal system under the Alcedo and Sierra Negra volcanoes in Isabela Island, where hydrothermal manifestations are observed (fumaroles, hydrothermal alteration), and a potential greater than 100 MW has been estimated. Furthermore, Lloret C. (2015) studied the direct uses of geothermal energy for water desalinization, another scarce resource needed to sustain the growing population of the island. However, in any study reviewing an assessment of the potential of geothermal energy in Galapagos Islands that has been done, an important analysis required for sustainable energy planning in Galapagos Islands has not.

Overall, the aim of this paper is to make a rapid assessment of geothermal potential in Galapagos Islands by integrating remote sensing and spatial multicriteria analysis in Geographic Information System (GIS). A geothermal favourability map of the islands will be developed as a screening tool for the overall assessment of optimal areas for further geothermal development. This analysis will be complemented with a review of Galapagos energy system, in order to do a preliminary assessment of the potential penetration of geothermal energy to reduce the share of fossil fuel based power system in Galapagos islands.

2. METHODOLOGY

2.1 Geothermal potential areas

The geothermal potential was calculated by identifying the potential areas for geothermal development in three of the four inhabited Galapagos Islands, i.e. Santa Cruz, San Cristobal and Isabela depicted through a geothermal favourability map; which, was developed by integrating multicriteria decision analysis (MCDA) in GIS (Figure 2). Floreana was not included due to its size and very low energy consumption that will be supplied with solar energy in the short term (MERNNR 2019). With regard to carried out studies by Abdel Zaher et al. (2018) and Yalcin and Kilic Gul (2017), a decision criteria model was defined to identify favorable areas for geothermal development. The required data to calculate each decision criteria was obtained from official sources and open data. Once the data was collected and revised, each decision criteria was visualized in a GIS with digital processes. To integrate the decision criteria, a normalization was applied. Then, a weight overlay was applied to integrate the decision criteria maps and to estimate the geothermal favourability. The favorability was classified in six classes (very low, low, medium, high, very high and extremely high) using Natural Break Jenks Method.

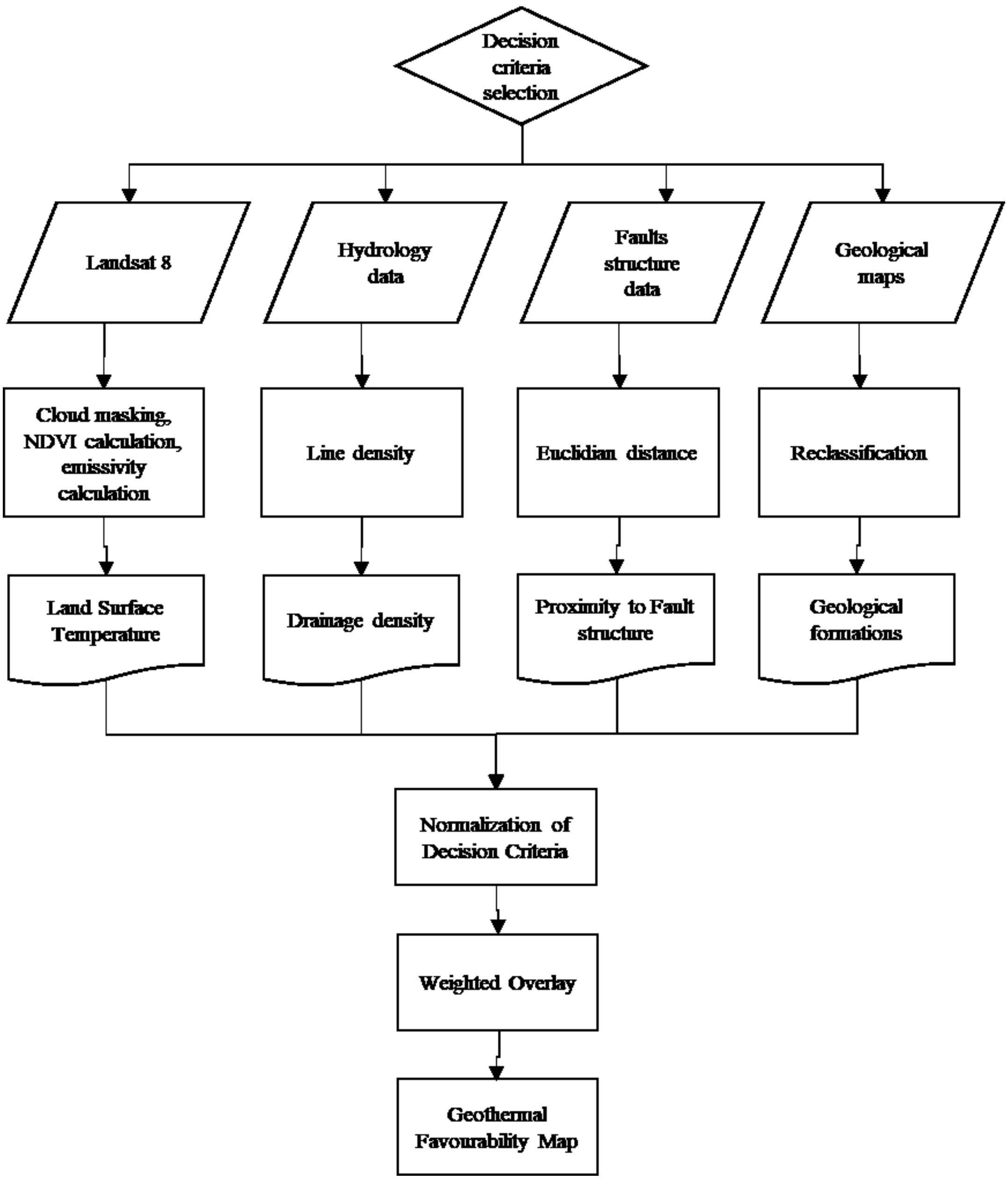

Figure 2: Methodology framework of the study

2.1.1 Land Surface temperature

Land Surface Temperature (LST) can provide information on the geothermal potential of an area (Chan, et. al., 2018; Gupta and Roy 2007). Certain sensors can collect information on thermal information on the land surfaces. Among them are MODIS (Wan et al. 2002), Landsat (Ermida et al. 2020; Jimenez-Munoz et al. 2014), and Sentinel 3 (Yang et al. 2020), which all have a thermal band and support measuring the top of the atmosphere (TOA) radiance, which is emitted by the land surface. Depending on the present land cover, i.e. built-up areas, vegetation or soil types, the radiances varies. As those sensors are optical sensors, data collection is affected by cloud cover disturbances, which can lead to data gaps and reduce availability of long time series of data.

For this study, LST was derived by Landsat 8 OLI images with a 30m resolution (Figure 3). A mean LST was calculated using in total 283 images over a five year period between 2015 and 2020. These were selected based on the applied cloud mask in Google Earth Engine (GEE) for Landsat 8, indicating clear conditions by masking out cloud and cloud shadow pixels. The thermal band of Landsat 8 (Band 10) was integrated to calculate brightness temperature (BT) according to Jeevalakshmi, et.al, (2017). As LST varies depending on the land cover and presence of vegetation, the Normalized Difference Vegetation Index (NDVI) was derived based on the red and near infrared (NIR) bands of the respective Landsat image (Huete et al. 1997). For the estimation of land surface emissivity further the fractional vegetation (fv) was then identified using the NDVI data based on calculations demonstrated in Carlson and Ripley (1997).

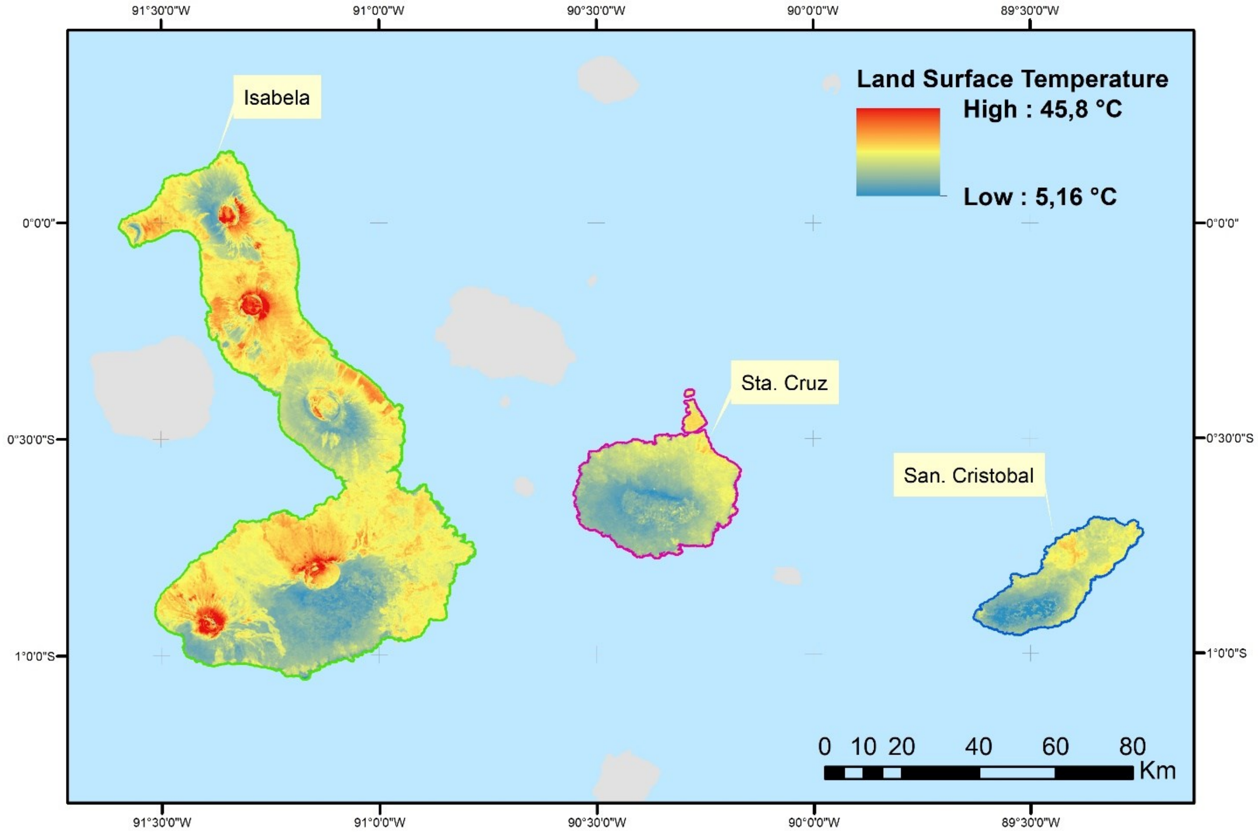

Figure 3: Land Surface Temperature

2.1.2 Drainage density

Water availability in Galapagos Island is a scarce and a critical aspect for human development (d'Ozouville 2017), but also it is important for geothermal exploration (Gupta and Roy 2007); thus its consideration in identifying promising areas for geothermal development is of paramount importance. For this study, drainage density has been used to assess areas for geothermal development and further environmental analysis (Yalcin and Kilic Gul 2017)

Since, there is no field data about hydrology, an approximation has been made using official information about water bodies and infrastructure (CGREG 2015). Based on collected information, Drain lines were mapped, and used as an input in the tool Line density of ArcMap 10.2.1 in order to calculate the Drainage density criteria map, defined as the total length of drain lines in the unit area (1 km^2) (Figure 4).

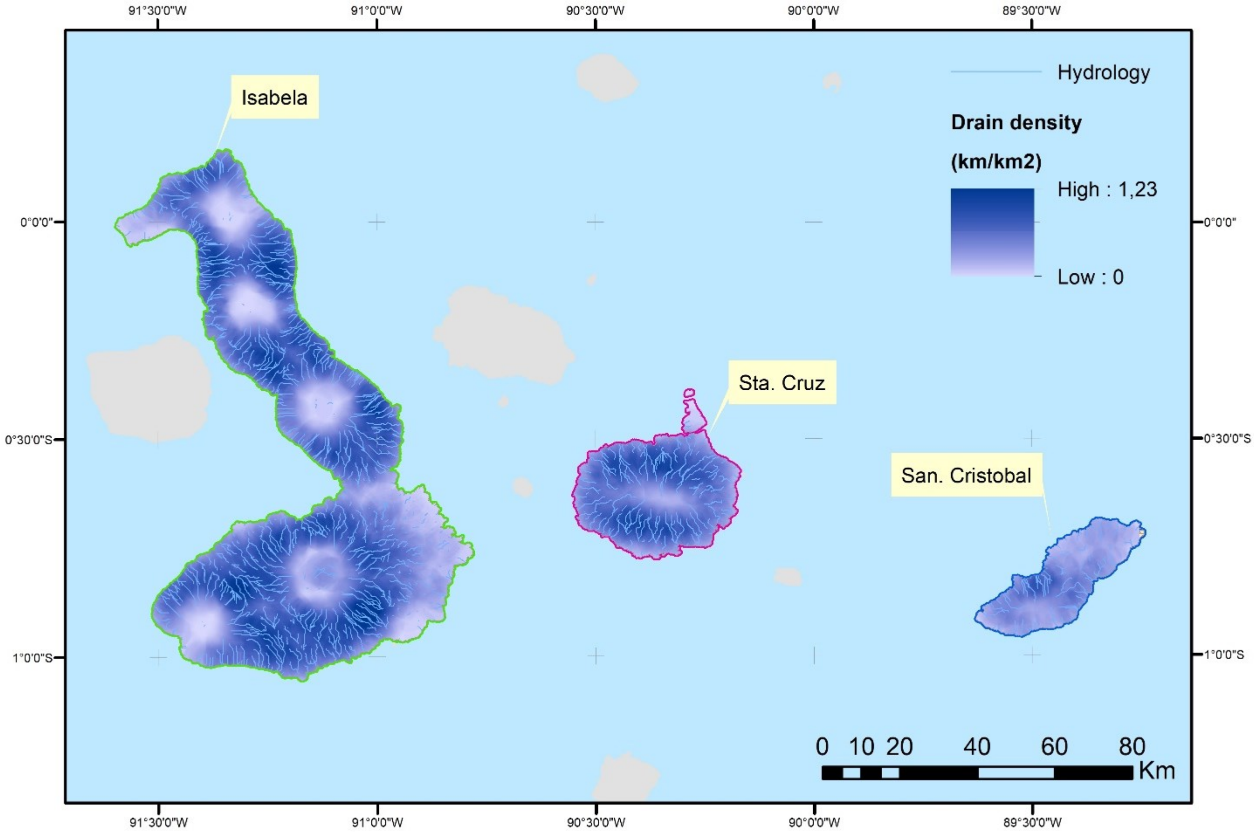

Figure 4: Drainage density

2.1.3 Proximity to fault structures

The presence or proximity to geological fault lines is one of the most important criteria for geothermal exploration and development (Gupta and Roy 2007); because geological faults in an extensional tectonic domain are related with the largest worldwide geothermal power producers (Faulds and Hinz 2015; Hinz et al. 2016).

Since, there is no field data about faults, an approximation has been made using 3 arc second SRTM and collecting previous information from Bagnardi, et. al., (2013); Geist et al. (1994); Reynolds et al. (1995), Vicenzi and McBirney (1990) and D. J. Geist et al. (2005. Thus, four kinds of fault structures related with caldera rings, inferred faults, volcanic and fissure vents were drawn). Moreover, an extensive tectonic setting controls most of these fault structures. For this study the proximity to fault structures map was calculated using the tool Euclidian Distance of ArcMap 10.2.1 (Figure 5)

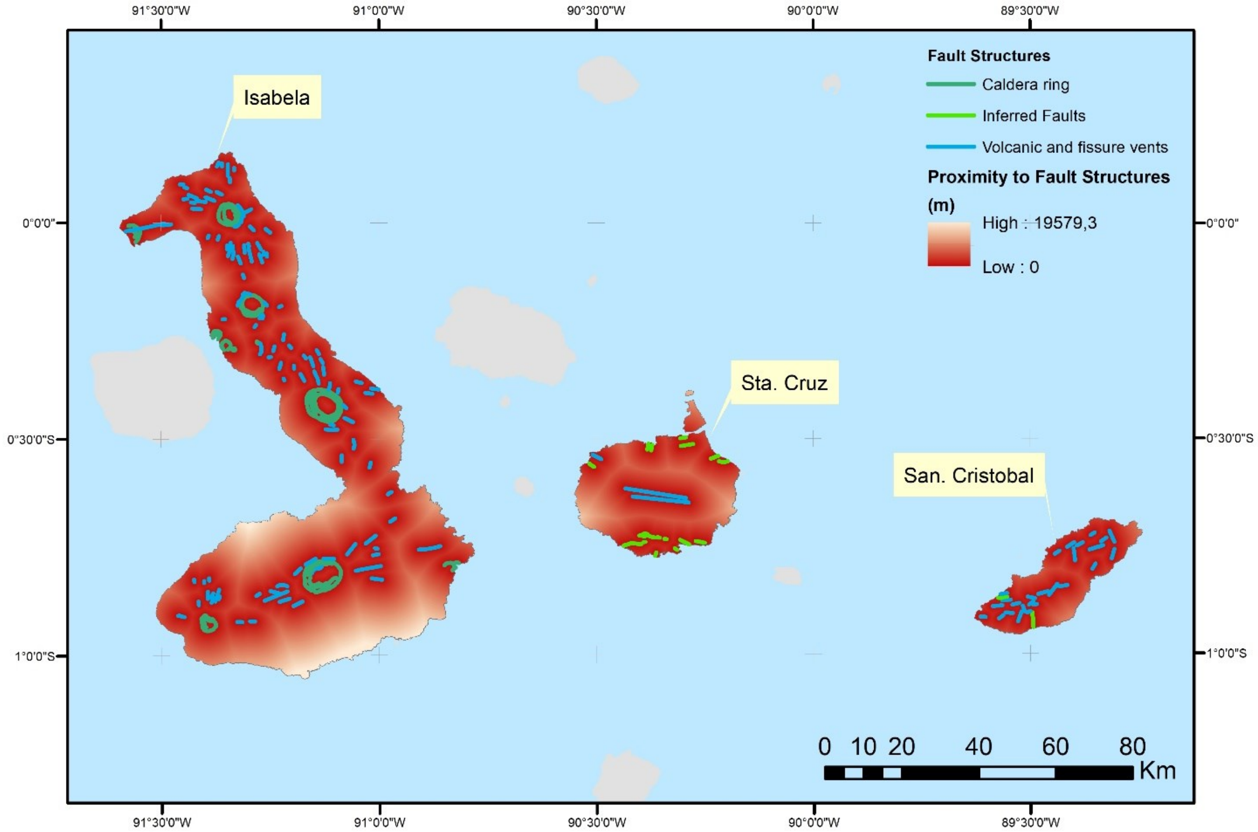

Figure 5: Proximity to Fault Structures

<u>2.1.3 Geological formations</u>

Most of the geothermal systems around the world are hosted in Pleistocene and Holocene calderas (Stelling et al. 2016). In a geologic point of view; the Galápagos Islands are a hot spot, which is likely located in the westernmost islands, Fernandina and Isabela (Neall and Trewick 2008). It comprises several shield volcanoes with more marine erosion at the eastern islands. The last eruption was recorded in January 2020 on Fernandina Island (Vallejo 2020) which is the youngest island (Harpp and Geist 2018). San Cristobal is the oldest one (Mio-Pliocene) followed by Pleistocene Santa Cruz and Floreana islands (Bow and Geist 1992; Harpp et al. 2014; White, McBirney, and Duncan 1993), finally Santiago island is the youngest of the eastern volcanoes with historical activity, including an eruption in 1906 (Siebert, Simkin, and Kimberly 2014)

For this study, geological formations were used as proof of potential geothermal systems presence in the research area. Three geological formations have been identified in Galapagos Islands from the Geological map of Ecuador (IIGE 2017) i.e. Basalt volcano shield-intense volcanic activity, Basalt volcano shield - heavily eroded with raised underwater rocks, and Basalt volcano shield - less volcanic activity, the former being a promising area for geothermal systems. Moreover, hydrothermal anomalies were found mainly in the Isabela Island, where intense volcanic activity occurs (Figure 6).

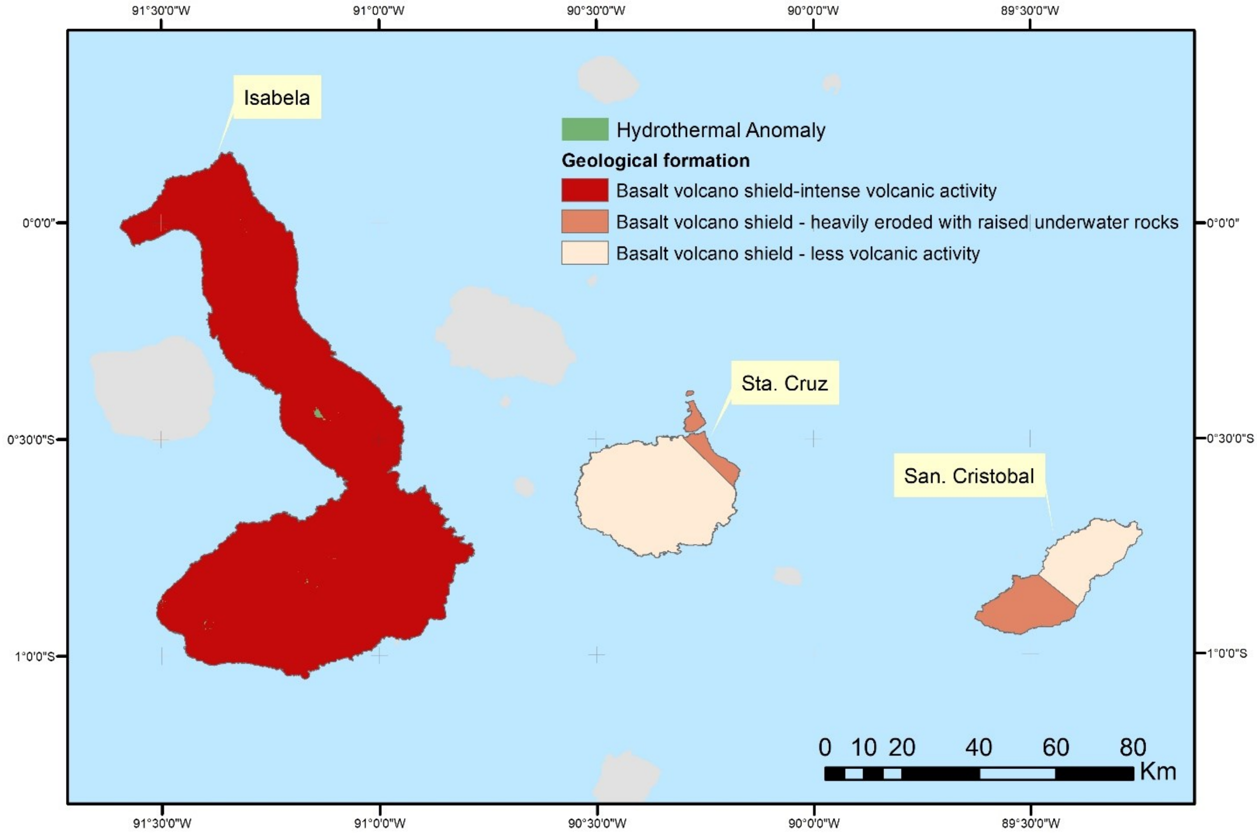

Figure 6: Geological formations

2.1.4 Normalization

A normalization was applied to all decision criteria maps in order to scale them to values, between 0 and 1, allowing their further integration in the next steps. The Maximum and minimum value range method (i.e. value function) was applied (Malczewski 1999; Yalcin and Kilic Gul 2017) in this study. When the highest value for each decision criteria map favors the presence of a geothermal system in the area, equation (1) was used (i.e. LST and drainage density). On the contrary, when the lowest value for each decision criteria map favors the presence of a geothermal system in the area, equation (2) was used (i.e. proximity to fault structure).

$$x'_{ij} = \frac{x_{ij} - x_{min}}{x_{max} - x_{min}} \tag{1}$$

$$x'_{ij} = \frac{x_{max} - x_{ij}}{x_{max} - x_{min}} \tag{2}$$

where x'_{ij}, x_{ij}, x_{min}, x_{max} are, normalized criteria i in location j, the actual value of the criteria i, the minim and maximum value of criteria i respectively.

The application of both equations was done using the Raster Calculator in ArcMap 10.2.1. As a result, all variables for the decision criteria were normalized via the value function to result in a common range of values between 0 and 1, 1 being the more significant value that favors a geothermal system. Furthermore, for the decision criteria of geological formations a classification of 0, 0,5 and 1 was applied to Basalt volcano shield – i.e. less volcanic activity, Basalt volcano shield - heavily eroded with raised underwater rocks, and Basalt volcano shield-intense volcanic activity respectively. Figure 7 shows the decision criteria maps normalized.

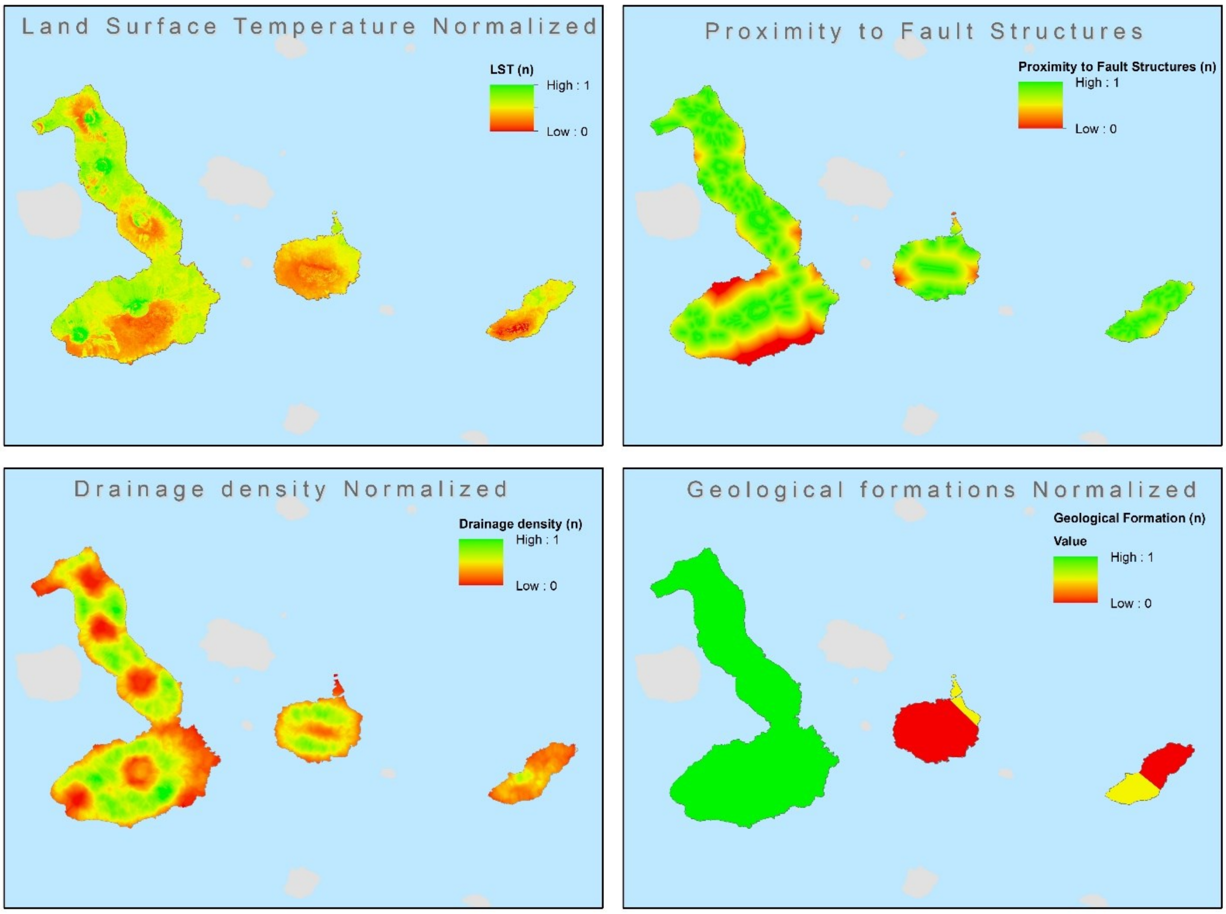

Figure 7: Normalized decision criteria maps

2.1.4 Weight Overlay

A weighted overlay was applied to integrate the decision criteria into a geothermal favorable map. A weight factor was assigned to each decision criteria map according to its relative importance compared to all other criteria see equation (3).

$$GF_j = LST_j * w_{LST} + Dd_j * w_{Dd} + PFS_j * w_{PFS} + GF_j * w_{GF} \quad (3)$$

where GF_j, LST_j Dd_j, PFS_j, GF_j are Geothermal Favourability, Land Surface Temperature, Drain Density, Proximity to Fault Structure, and Geological Formation values, in location j respectively. In addition, $w_{LST}, w_{Dd}, w_{PFS}, w_{GF}$ are the weights factors for Land Surface Temperature, Drain Density, Proximity to Fault Structure, and Geological Formation respectively. After a literature review (Abdel Zaher et al. 2018; Yalcin and Kilic Gul 2017; Yousefi, Ehara, and Noorollahi 2007) and consultations with experts all decision criteria was assigned the same weight (i.e. 0.25). All decision criteria maps were resampled to have the same resolution of 30m in the whole process presented above.

2.2 Geothermal potential and Galapagos energy system review

A simple method to calculate the Geothermal potential for power production (MWe) is a volumetric assessment using area, temperature gradient, and depth; however, due to the lack of this data in this study, the geothermal assessment based on the number of active volcanos from Stefansson (2005) was applied using equation (4).

$$GP_{MW} = 230 + 158 * No.of\ actie\ volcanos_j \quad (4)$$

Then, a review of existing and projected energy demand and production in Galapagos was carried out based on a literature review and expert consultations (i.e. CELEC EP, IIGE, Elecgalapagos). From this analysis the impact of Geothermal Energy was assessed qualitatively, and policy recommendations were defined (Hiremath, et. al., 2007; Pandey 2002).

3. RESULTS AND DISCUSSION

3.1 Geothermal development areas

Figure 8 shows the Geothermal Favourability Map of the three biggest inhabited islands in Galapagos. Results shows that most promising areas for geothermal exploration and development is located on Isabela Island, mainly in-between the volcanos and the shore of the northern part of the island. Considering, that the main settlement of Isabela is located in the southern coast of the island, the favorable areas close to the Sierra Negra Volcano are of great interest. On the other side, the islands San Cristobal and Santa Cruz have manly areas with low or very low potential; though, some high potential areas are located in the northeast part of Santa Cruz and in the center of San Cristobal Island.

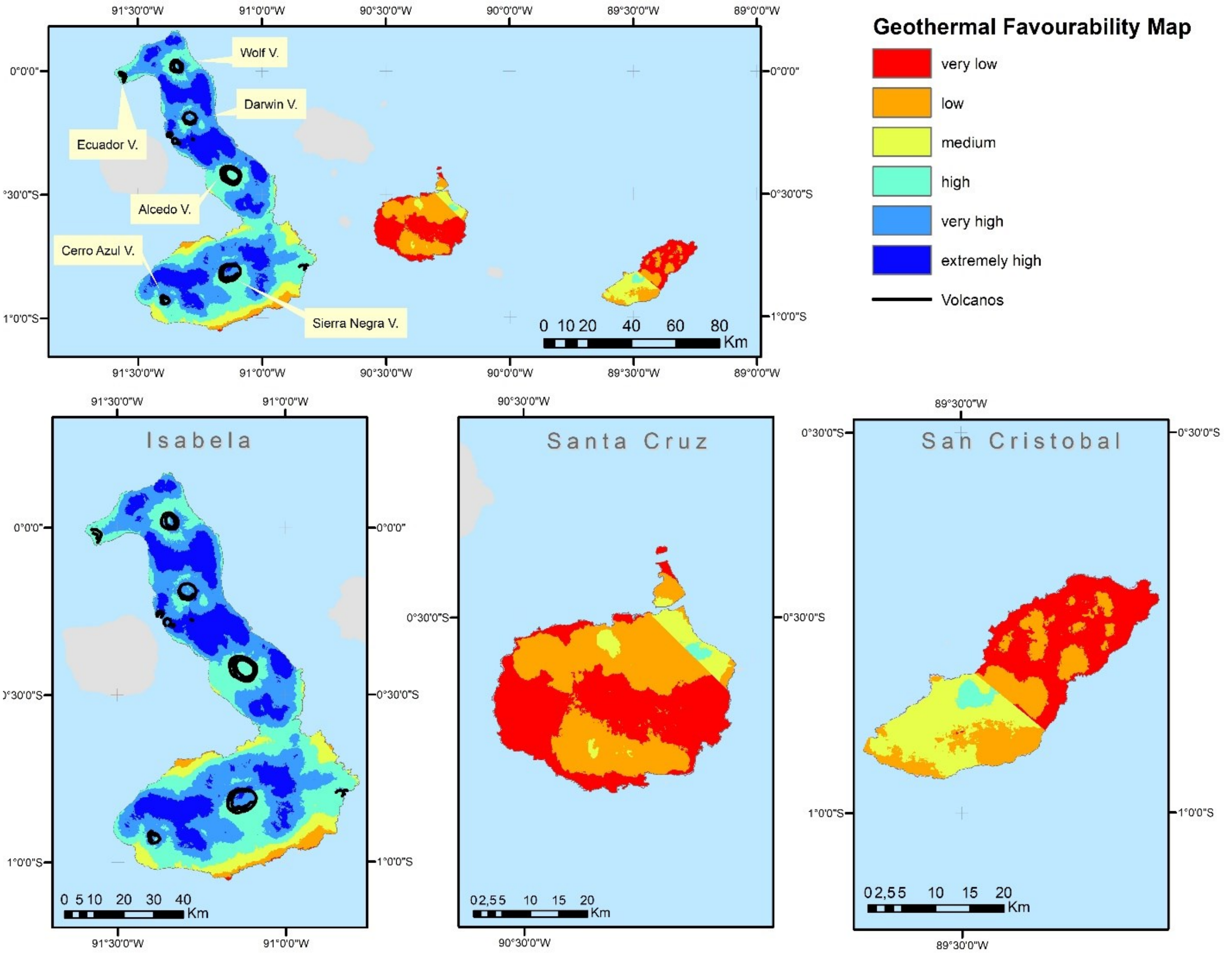

Figure 8: Geothermal Favourability map

This favourability map is an initial screening tool to explore further undiscovered and untapped geothermal resources on inhabited Galapagos Islands. This finding is consistent with other studies Lloret C. (2015), where Isabela Island was identified as the Island with the highest potential, but not defining promising areas for geothermal potential which is a contribution of this study. Furthermore, the favourability maps require validation with ground-level data and field study, especially in terms of geophysical land survey, geochemical sampling, and updated geological data (Abdel Zaher et al. 2018; González and Rodríguez-Gonzálvez 2019; Noorollahi et al. 2007).

3.1 Geothermal potential and contribution to energy transition in Galapagos Island

Based on the number of active volcanos (6) of the Galapagos Islands, which are located in Isabela Island where most of the most promising areas for geothermal development are located, the geothermal potential was estimated at 1178MW according to Stefansson (2005) approach. Figure 9 provides an estimation of energy demand projections for the three inhabited island of this study based on MERNNR (2019). Considering that geothermal power plants have a power factor of almost 100%, in order to cover the whole energy demand by 2027 via geothermal and attain a 100% renewable energy goal, only 10% (i.e. 11.4MW) of the total potential identified needs be developed. Though, this result is a gross estimation of the geothermal potential, it provides a figure and promising areas for further exploration and development of geothermal systems. This results also shows that most of the geothermal potential is located on Isabela Island far away (>100km) from the main centers of consumption, i.e. Santa Cruz and San Cristobal islands. Thus, if this geothermal potential is developed a submarine transmission network is needed to distribute the electricity among islands. Additionally, it can be inferred that direct-uses application of geothermal energy are more suitable for San Cristobal and Santa Cruz island due to their low potential areas and low temperature; and, power production could be more suitable on Isabela Island where higher temperature is observed.

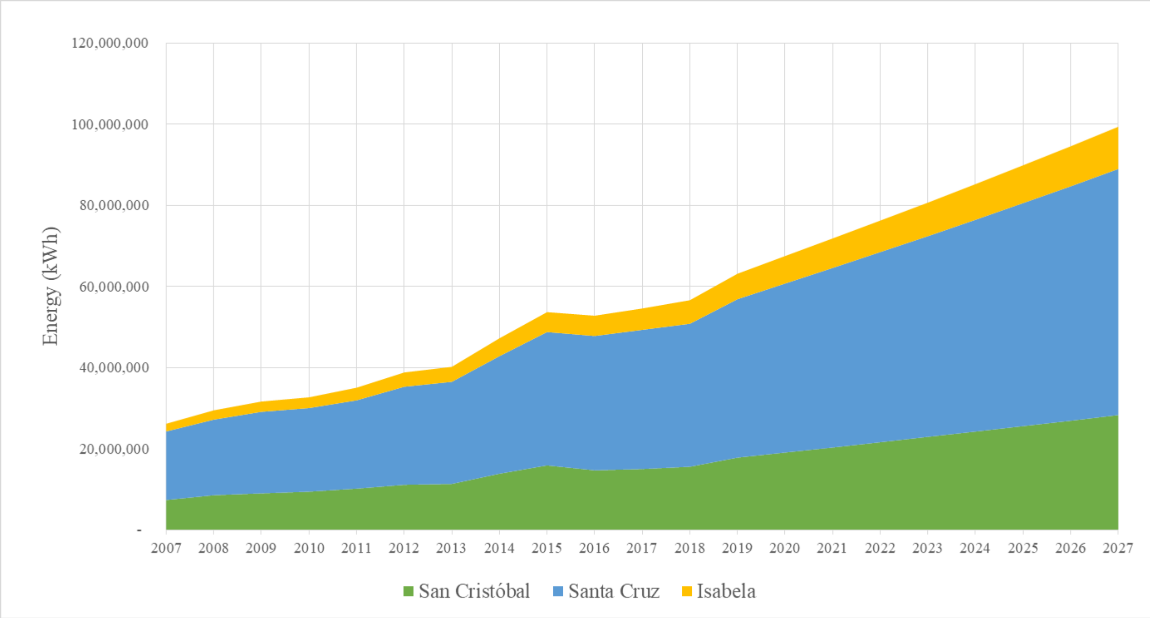

Figure 9: Energy demand projection for Galapagos Island 2007 – 2027

4. CONCLUSION

The approach presented here shows how the geothermal potential can be estimated with free available data and tools. A gross potential of geothermal energy of more than 1200MW has been identified for the Galapagos Islands; located mainly on Isabela Island where most the promising areas for geothermal development are located. The identified geothermal potential is approximately 80 times more the geothermal capacity needed (15MW) to attain the goal of Zero fossil fuels in Galapagos Island. However, this result does not consider land and marine transport energy demand, which nowadays is based mainly on fossil-fuel and which could be electrified in the short term, so a bigger capacity of renewable energy will be needed. Further research on energy balance for Galapagos Islands should be done incorporating geothermal as a non-variable renewable energy generation.

Some challenges have been identified in the proposed approach to identify geothermal potential. Due to high cloud cover optical sensor data as by, Landsat 8, which was used in this research, is not available in dense time series. Here, longer time series and data fusion approaches might be a possibility to overcome data gaps. Further, LST measurements will need ground truth assessment to validate the calculations presented here. Furthermore, the multicriteria analysis proposed will be improved by incorporating other geophysical and geochemical variables important to identify geothermal system. Thus, a ground-level data and field study, especially in terms of geophysical land survey and geochemical sampling, is needed. Future research is needed for validation of satellite data, comparison of existing LST data showed differences, which strengthen the need for local case studies. Estimation of LST variabilities using long time-series of data and data fusion can further help us to understand the stability of geothermal potential.

The Galapagos Islands are facing important threats, among them one of the most important is human activity. Population growth, including tourism, is increasing at a fast rate and therefore so is energy consumption. In addition, water and food scarcity is an issue that is threating human survival and conservation on the islands. In this context, energy is the basis to foster sustainable development, that's why it is needed to strengthen the participation of renewable energy. In addition, the research presented her aimed at the potential of geospatial assessments for geothermal energy provision potential. Current research is ongoing to evaluate integrated variables and improve temporal and spatial scales with available in-situ data.

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