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Energy capacity of the geothermal resource and its integration in the electrical energy demand of the island of Tenerife (Spain)

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Abstract. One of the main strategies to maximize renewable energy penetration in electrical systems is to optimize their dispatchable capacity. One of the benefits of geothermal energy, as a renewable energy source, is its high dispatchability. The isolated electrical energy system of Tenerife (one of the 8 islands of the Canary Archipelago) is highly dependent on fossil fuels. The advanced state of maturity of the geothermal exploration of Tenerife positions the island with a high degree of probability as one of the few regions in Spain with high-enthalpy geothermal resources. This paper reports on a study undertaken of the island's geothermal potential which involved calculation of the heat stored in geothermal reservoirs and the identification of zones of interest for exploitation of this resource and its energy capacity. Among the results obtained, 3 areas of interest were identified for the exploitation of geothermal energy with a total installable electrical power of 117.8 MW, which would increase the renewable contribution to the island's daily demand by over 20% as well as contribute to maximizing the flexibility and stability of the electrical energy supply in a scenario of high renewable energy penetration.

Keywords. Geothermal energy, insular electrical systems, renewable energy, distributed electrical generation, isolated electrical systems.

1. Introduction

One of the weaknesses of the use of renewable energy sources such as wind and solar in terms of its large-scale integration in electrical systems is its low dispatchability. This problem is even more marked in weak electrical systems like those found on islands. For this reason and for such types of renewable resource, the development of estimation and/or prediction models becomes necessary [1]. Geothermal energy is a renewable source that includes among its advantages a high degree of dispatchability, the capacity to supple energy in a constant manner without a dependency on climatological conditions.
The Canary Archipelago (Spain) comprises 8 islands of volcanic origin with a high potential for the exploitation of geothermal energy. The case study presented in this paper focuses on Tenerife, which has the largest surface area of the islands in the archipelago (2034 km^2), a population of 927,993 [2] (42.7% of the total number of inhabitants of the archipelago), and an installed electrical power of 1426 MW [3]. Its electrical system is isolated, with no connection with the other islands or the continent. Its energy mix has a notably high fossil fuel dependency, with 79% [3] of electrical energy coming from conventional thermal power plants. An additional problem with respect to this conventional generation is that it is estimated that by 2030 the useful regulatory life will have expired of 63.2% of the power that is presently available [4]. Moreover, the currently installed renewable technologies are characterized by their non-dispatchability, with the principal sources being wind and photovoltaic solar energy.
The diverse geological [5] [6], geophysical [7] [8], and geochemical studies [9] [10] that have been carried out in Tenerife are indicative of the advanced state of maturity of the geothermal exploration of the island. The results of these studies reveal a high degree of probability of the existence in the island of high enthalpy geothermal resources [11]. These geothermal resources can be exploited for electrical energy generation, which would be in accord with the strategic objectives set out in the Energy Transition Plan of the Canary Islands [4]. In this way, the island's electrical energy system would benefit from the numerous strengths of this renewable and dispatchable energy source. These strengths include the lower levelized cost of energy compared to conventional electrical generation in Canary Islands [12], as well as it being considered a clean energy source in view of its low levels of CO_2 emission per unit of energy generated [13]. In addition, geothermal energy has the lowest ratio between unit of occupied area and unit of energy generated of all energy sources [11]. Finally, a special mention should be made of the significant maturity of geothermal technologies and the potential for cogeneration.
In the work developed in the present paper, zones of interest for the exploitation of the geothermal resources on the island are identified, and an evaluation is made of their

energy capacity and the installable geothermal power. The aim is to facilitate the integration of this energy source in a scenario of advancement of distributed electrical energy generation and high renewable energy penetration.

2. Materials and method

A. Identification of areas with high enthalpy geothermal resources

García-Yeguas et al. [7] generated a 3D interpretation on the basis of magnetotelluric and seismic topographic models developed for the island of Tenerife. The electrical resistivity of the subsoil is obtained from the magnetotelluric model, while its pressure wave (P-wave) velocity is determined from the seismic topographic model. The ultimate goal of this study is to know the internal structure of the island and detect geothermal structures. For this, a joint mesh was generated based on the electrical resistivity and P-wave velocity values at different depths, thereby allowing differentiation between the island's subsoil typologies.

High electrical resistivity and P-wave velocity values are reflected in this mesh in the central region of the island starting at 600 m below sea level (b.s.l.), supporting the conclusion of other authors that the formation of the island is based on a single volcanic source [8] [14].

The internal structure of Tenerife contains a central igneous core divided into three parts [7]: i) *Basalt body; ii) Presence of propylites with chlorite at medium-high temperature*; iii) *Combined effect of shallow aquifers, sedimentary and volcanoclastic multifractured systems.* The latter is of particular interest because, in addition to forming part of the igneous core and, hence, being at a high temperature, it is composed of multifractured rock systems associated to aquifers, confirming the presence of geothermal resources and facilitating their extraction. The horizontal slice at a depth of 2000 m b.s.l. of the 3D model developed in [7] contains various areas with these mineralogical conditions (see Fig. 1). The resistivity of these subsoils is 36 **Ω**·m [7].

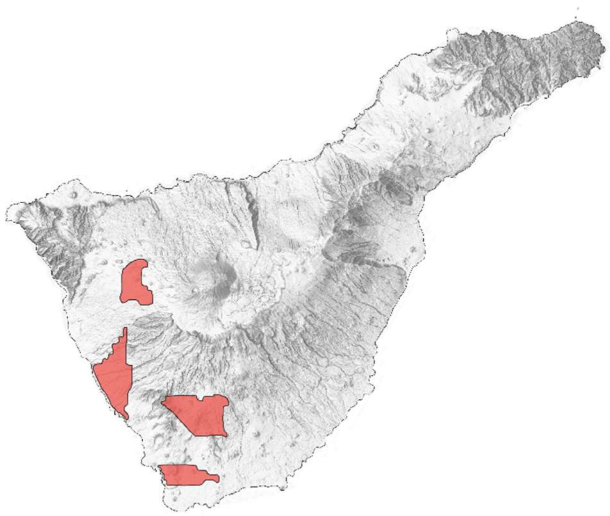

Fig. 1. Areas of combined effect of aquifers and volcanoclastic multifractured systems at 2000 m b.s.l. on the island of Tenerife.

High enthalpy geothermal reservoirs are characterized as permeable zones of multifractured minerals due to hydrothermal alteration [15]. Resistivity is high in this type of reservoir (10-60 **Ω**·m) [15], and the high permeability allows the ascent of geothermal fluids. Given that the areas represented in Figure 1 meet the established mineralogical and electrical resistivity conditions, it is considered that they contain high enthalpy geothermal resources which can be used to produce electricity.

B. Natural protected spaces

Excluded from the calculations are those areas of high geothermal potential situated within the areas of the island designated as Protected Natural Spaces (Fig. 2).

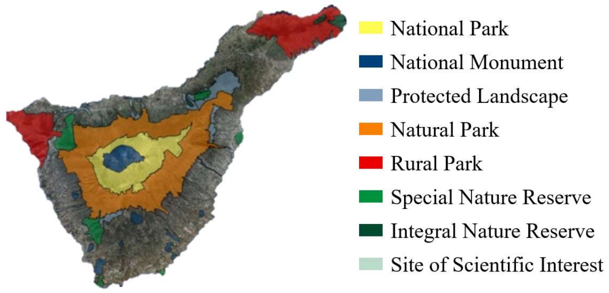

Fig. 2. Protected Natural Spaces [16].

C. Method used to estimate the heat stored in the geothermal reservoir

The volumetric method (see Eq. 1) is one of the most commonly employed techniques to estimate the amount of heat energy stored in a geothermal reservoir [17] [18]:

$$H = [(1-\Phi)\cdot\rho_r\cdot c_r + \Phi\cdot\rho_w\cdot c_w](T_i - T_f)\cdot A\cdot t \quad (1)$$

where:

H: heat stored in the geothermal reservoir (kJ)
$\boldsymbol{\Phi}$: *porosity (dimensionless)*
$\boldsymbol{\rho_r}$: *rock density (kg/m³)*
c_r: *thermal capacity of rock (kJ/kg·°C)*
$\boldsymbol{\rho_w}$: *density of geothermal fluid (kg/m³)*
c_w: *thermal capacity of geothermal fluid (kJ/kg·°C)*
T_i: *average reservoir temperature (°C)*
T_f: *abandonment temperature (°C)*
A: surface area of geothermal reservoir (m²)
t: mean useful thickness of the reservoir (m)

D. Calculation of the installable electrical power

The installable electrical power is calculated through Eq. (2):

$$\boldsymbol{P = \frac{H\cdot RF\cdot \eta}{Lt\cdot CF}} \quad (2)$$

where:

P: installable electrical power (kW)
H: heat stored in the geothermal reservoir (kJ)
RF: thermal recovery factor (dimensionless)
$\boldsymbol{\eta}$: *conversion efficiency (dimensionless)*
Lt: useful life of the installation (s)
CF: capacity factor (dimensionless)

Given that it is not possible to extract all the heat stored in the geothermal reservoir, it is necessary to multiply the gross stored heat (H) by the thermal recovery factor, in this way obtaining the recoverable heat. For its part, the conversion efficiency represents the efficiency of the conversion of the recoverable heat to useful electrical energy.

E. Calculation of energy consumption in seawater and brackish water desalination

The annual electrical energy consumption in seawater and brackish water desalination (Eq. (3)) is:

$$\boldsymbol{e_c = p_c \cdot s_c} \quad (3)$$

where:

e_c: annual energy consumption (kWh/year)
p_c: production capacity (m³/year)
s_c: specific consumption (kWh/m³)

3. Results and discussion

A. Identification of areas of interest and installable geothermal power

The resulting areas of interest for the exploitation of geothermal energy are situated in the south of the island (Fig. 3). The majority are located in the municipality of Vilaflor, followed by Adeje and Arona. Exploitation of the northernmost geothermal reservoir (see Fig. 1) was discarded as its entire surface is situated within the Canary Islands Network of Protected Natural Spaces, or to be more precise in a Nature Park. Likewise, Figure 3 shows the Protected Natural Spaces which partially lie over some parts of the potential reservoirs so that these areas can be discarded in terms of the execution of geothermal projects.
Knowing the subsoil characteristics at 2000 m b.s.l. in the three aforementioned areas, volcanic breccia is chosen as the rock typology in the geothermal reservoirs. This rock typology has a density of 2545 kg/m^3 [19], a thermal capacity of 0.729 kJ/kg·°C [20] and a porosity of 8.5% [21].

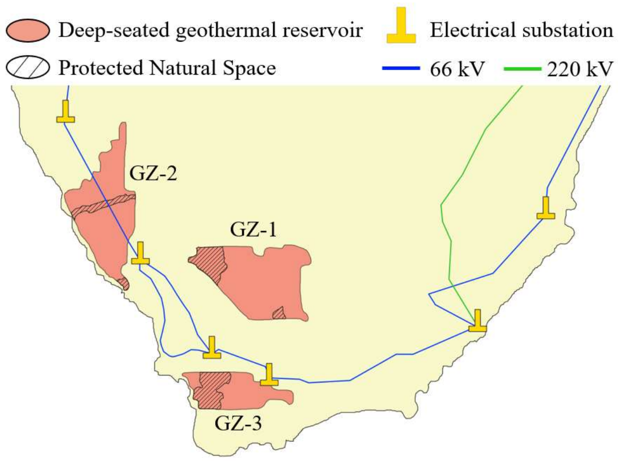

Fig. 3. Plan of the areas of high geothermal potential, electrical substations and high voltage transmission grid.

The high enthalpy geothermal systems found in areas of altered rock and high resistivity (10-60 Ω·m) are usually higher than 200 ºC [15]. In the case study of the present paper, the proposed geothermal reservoirs are considered to be at a mean temperature of 200 ºC. At this temperature, the geothermal fluid, mostly water confined, has a density of 940 kg/m^3 [22] and a thermal capacity of 4.51 kJ/kg·°C. The discharge temperature of the geothermal fluid decreases gradually to the abandonment temperature, which corresponds to the temperature below which a geothermal reservoir will not be produced [23]. Its value depends on the power cycle, and is equal to the pinch point temperature in the case of a binary power plant, which, as justified below, is the most appropriate technology for the case study of the present paper. The pinch point is the place of the heat exchanger where the bubble point of the working fluid occurs and where the temperature difference between the geothermal fluid and the working fluid is minimum, normally 5 ºC [23] [24]. To determine a rough value of the abandonment temperature, a thermodynamic simulation of a possible organic Rankine cycle (ORC) configuration was performed using the free software Termograf [25] with pentane as the working fluid, which is one of the most commonly used fluids in ORCs [24]. It was found that, assuming a geothermal fluid temperature of 200 ºC at the evaporator inlet, the pentane could evaporate at 155 ºC, which would give rise to an abandonment temperature of 160 ºC.
After exploitation of the geothermal fluid, it is reinjected at a sufficient temperature to avoid the cooling and degradation of the useful life of the geothermal site.
The mean useful thickness of the geothermal reservoirs is 700 m, which is the depth range selected for the discretization corresponding to the seismic and electrical resistivity models developed in [7]. That value was applied because the areas of geothermal interest do not vary significantly between the horizontal slices at 2000 and 2700 m b.s.l.
Garg and Combs [23] suggest that the proper range for a thermal recovery factor is from 0 to 0.20, with the latter being the maximum credible value based on worldwide experience. In the particular case of the present paper, as we are dealing with fracture-dominated geothermal reservoirs, a thermal recovery factor of 0.15 is estimated.
The geothermal fluid may contain non-condensable gases which would have a significant environmental impact if emitted into the atmosphere [26]. For this reason, the ORC technology was chosen as being the most suitable in this instance for electrical energy generation. In ORC plants, the geothermal fluid is reinjected into the reservoir immediately after giving up part of its heat energy to a highly volatile working fluid. In this way, the geothermal fluid never enters into contact with the atmosphere. For its part, the working fluid is subjected to the following thermodynamic processes (Fig. 4):

1) *Preheating (process 4-5).*
2) *Evaporation (process 5-1).*
3) *Expansion (process 1-2).*
4) *Condensation (process 2-3).*
5) *Compression (process 3-4).*

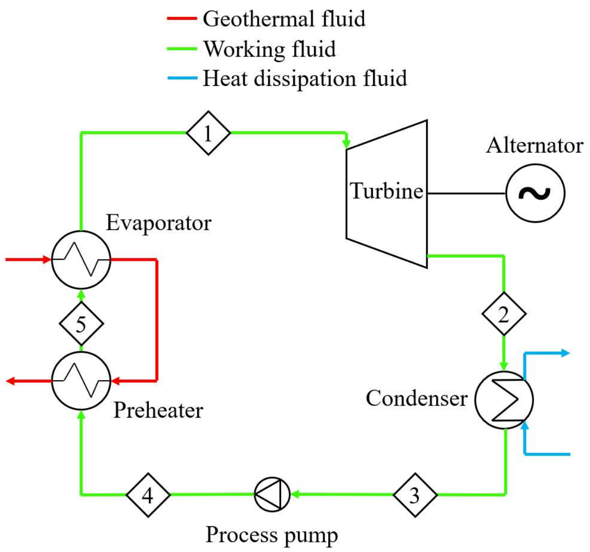

Fig. 4. Layout of an ORC geothermal system.

The preheating and evaporation processes take place in heat exchangers and involve the geothermal fluid giving up heat to the working fluid until the latter reaches vapour state. The expansion process is that in which the evaporated working fluid develops useful work in the turbine. The turbine shaft is coupled to the alternator which is responsible for converting mechanical into electrical energy. In the particular case of the present paper, a conversion efficiency of 13.8% [27] is considered. After expansion, the working fluid is condensed through heat dissipation systems. Finally, the working fluid is compressed using a process pump.

It should be noted that the working fluids normally used in ORC systems are retrograde fluids which have the peculiarity that the slop of their saturation line is positive, allowing them to remain in overheated vapour state throughout the expansion process in the turbine. In this way, formation of humidity is avoided during expansion which would otherwise interfere with the proper functioning of the turbine and the overall efficiency of the system. It is for this reason that retrograde fluids like butane, isobutane, pentane, and isopentane [24] are the most commonly used organic fluids in ORC systems.

The dispatchable generation capacity of geothermal energy enables it to achieve high numbers of full-load-hours in the year. In the present paper, a capacity factor of 0.85 is considered, indicating a significant geothermal operation. The remaining percentage is mostly due to maintenance work of the facility whose useful life amounts to 30 years [27].

The integration is therefore proposed an ORC geothermal plant complex in the island's electrical system under the conditions as set out. Table 1 shows the results for the available useful surface areas, the recoverable heat, and installable electrical power (see Eq. (2)) of the three identified areas in Tenerife with high geothermal potential. The available useful surface areas do not fully occupy any of the Protected Natural Spaces of Tenerife (see Fig. 2), thereby avoiding environmental impacts caused principally by the drilling of the wells required for the extraction of the geothermal resources.

It should also be noted that the three geothermal areas would be close to high voltage lines and electrical substations (see Fig. 3). This would avoid technical and economical drawbacks associated to the incorporation of new electrical infrastructures that would otherwise be required for the integration of the geothermal plants in the island's system.

Table 1. - Results for each of three identified areas in Tenerife with high geothermal potential.

Zone	Surface area (km^2)	Recoverable heat (TJ)	Electrical power (MW)
GZ-1	33.3	288,221.2	49.5
GZ-2	30.5	263,954.4	45.3
GZ-3	15.5	134,065.6	23.0
Total	79.4	686,241.3	117.8

B. Analysis of renewable contribution increase due to integration of geothermal plants in the electrical system of Tenerife

The peak contribution of renewable energies to the electrical energy demand on a typical summer day of 2022 reached 45.2% [28]. At the present time, all this renewable contribution is composed of onshore wind and photovoltaic solar energy.

If an ORC geothermal plant complex were to be integrated into the island's current electrical system, the peak renewable contribution on a typical summer day would rise from 45.2% to 69.3% (Fig. 5). For the case of a typical winter day, the rise could be from 15.9% to 40.9%. The actual demand and renewable generation data were taken from the website of the Spanish electricity system operator [28]. It should be noted that, as geothermal energy is a dispatchable energy source, the maximum contributions that are produced at peak times can easily be regulated for better management of the island's electrical system.

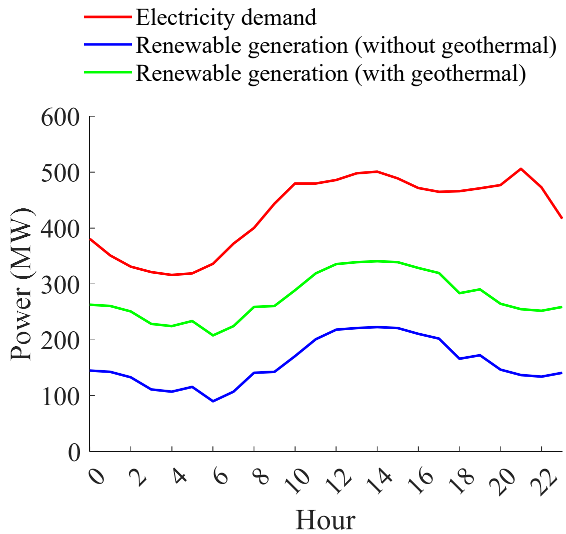

Fig. 5. Electrical energy demand and renewable contribution of a typical summer day in Tenerife.

C. Relationship between geothermal-sourced electrical energy generation and electrical energy demand in seawater and brackish water desalination processes

A significant part of the water demand on the island of Tenerife is satisfied by desalination systems. Currently, reverse osmosis is the most commonly used desalination process. The weight of this water production source has increased in recent years and is expected to grow exponentially in the coming years.

According to the official water management body of the island of Tenerife [29], the sea and brackish water desalination plants have a total production capacity of 77,000 m^3/day, an approximate annual production of 19.20 hm^3. Taking into consideration the envisaged future production capacity increases, as well as the capacity of new desalination plants proposed in the Tenerife Island Hydrological Plan [30], a desalinated water production of 90.82 hm^3 is expected within the time horizon of 2027, of which 78.53 hm^3 will be from seawater and 12.29 hm^3 from brackish water.

Based on historical specific consumption data [31] for the seawater desalination processes used in the Canary Islands, an average specific consumption of 3.5 kWh/m^3 has been estimated, with a corresponding value for brackish water desalination processes of around 2 kWh/m^3 [32]. The envisaged annual energy demand for the desalination processes in 2027 would therefore be 299.44 GWh, of which 274.85 GWh would correspond to seawater treatment and 24.59 GWh to brackish water treatment. In turn, the estimated total installed power in the desalination plants would be 49.8 MW. This total energy consumption and installed power with respect to desalination in 2027 would equate, respectively, to 34.1% and 42.3% of the electrical energy generated and the total power of the ORC geothermal plant complex proposed in this paper.

4. Conclusions

The island of Tenerife has an important high temperature geothermal potential, which can be exploited for integration in the island's electrical system. In the study developed in this paper, 3 areas of interest have been identified for the integration of geothermal plants in the electrical energy generation structure of Tenerife, with an exploitable electrical power of 117.8 MW.

Integration of geothermal power in the island's energy plan would entail a significant increase in renewable power and a more distributed generation scenario, with greater dispatchability and an improved electricity supply in terms of safety and reliability.

Before such an integration can be contemplated, however, certain issues would have to be addressed: i) A lack of specific and precise information about the geothermal resource in the three proposed areas, with greater investment required in terms of exploration activities and the application of geophysical and geochemical techniques to know with greater accuracy different characteristics such as the temperature, presence of liquid-vapour and thickness of the geothermal reservoirs; and ii) The high economic risk of geothermal installations given the high investment costs. Public financing support would therefore be required in the short-to-medium term.

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