

Article

# Power Production Estimates from Geothermal Resources by Means of Small-Size Compact Climeon Heat Power Converters: Case Studies from Portugal (Sete Cidades, Azores and Longroiva Spa, Mainland)

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**Abstract:** Renewable forms of energy are increasingly penetrating the electricity market, particularly, geothermal energy. A wide range of resource temperatures and fluid quality are converted mostly using traditional binary power plants and, recently, using Climeon modular units. Portuguese natural geothermal resources are far from precise estimations. Despite the parameter uncertainties, electric power resource estimations of two natural geothermal reservoirs are presented: a volcanic sourced heated high-enthalpy geothermal reservoir in Sete Cidades, São Miguel Island, Azores; and a low-enthalpy geothermal reservoir linked to a fractured zone in a granitic setting in Longroiva, in the northern part of the Portuguese mainland. Based on the volumetric method, we assessed the power potential of geothermal resources in Sete Cidades and Longroiva using a probabilistic methodology—Monte Carlo simulation. The average reserve estimations for Climeon module were 5.66 MWe and 0.64 MWe for Sete Cidades and Longroiva, respectively. This figure was by far higher when compared to traditional binary technology; those differences were mostly attributed to distinct conversions efficiency factors.

**Keywords:** geothermal; energy; binary power plants; Climeon module; Monte Carlo simulation; reserves

## 1. Introduction

Global warming is compelling Earth's civilizations to move to renewable forms of energy. The use of renewable energy sources promotes local economies through the use of national and local natural resources and protects countries from unstable and unpredictable fluctuations in world energy markets, such as fossil fuels. Moreover, remote zones without access to energy grid systems can be supplied by local renewable energy, such as geothermal energy [1].

Among the renewable energy portfolio, geothermal energy holds a significant resource potential at Earth surface, available to harnesses in housing and industry by converting into electricity or by direct use. Geothermal energy uses heat from the Earth to deliver power. It is a clean, renewable, and stable resource used all over the world directly or by transforming thermal energy into electricity [1–4]. Moreover, cascade use of geothermal energy or hybrid plant systems using other renewable energies can considerably augment the use of this energy source.

Commercial competitive transformation of geothermal heat (i.e., water or steam) into electricity requires a design with good efficiency. Geothermal traditional binary power plants require a geothermal fluid operational minimum inlet temperature higher than 90 °C (with some special exceptions, such as the Chena Hot Springs geothermal power plant in Alaska, with an inlet temperature of 73.9 °C and an outlet of 10.0 °C). Lower inlet fluid temperatures of traditional binary power plants imply low to very low energy conversion efficiency, turning these power plants without commercial feasibility [5]. However, recently, new modular and easy to install small-size compact Climeon heat power converters (SCHPCs) have come on the market, mostly resulting in increased conversion efficiency [6,7]. With medium/low enthalpy inlet water or gas temperature in the range 70 °C to 120 °C, the technology enables excellent efficiency in the range of 10–14% under good conditions, with high inlet temperature and flow combined with a cooling source providing low temperature and good flow. Reasonable efficiency in the range of 5–10% can be obtained even at less favorable conditions, depending mostly on inlet temperature and flow and cooling source temperature and flow. The Climeon technology can be useful in a wide range of use cases, from the early stages to the very end of a geothermal reservoir's exploitation, independent of the size and nature (natural or engineered) of the reservoir.

For large geothermal projects, before the adequate characterization of a reservoir's extractable reserves (enthalpy, fluid quality, and available mass flow), when beginning geothermal exploration, well tests, and designing and fabricating the power plant, the Climeon modules can be quickly installed and powered into the market, thus allowing the owner to potentially generate a profit while waiting on other factors. In addition, modules can be added over time as required.

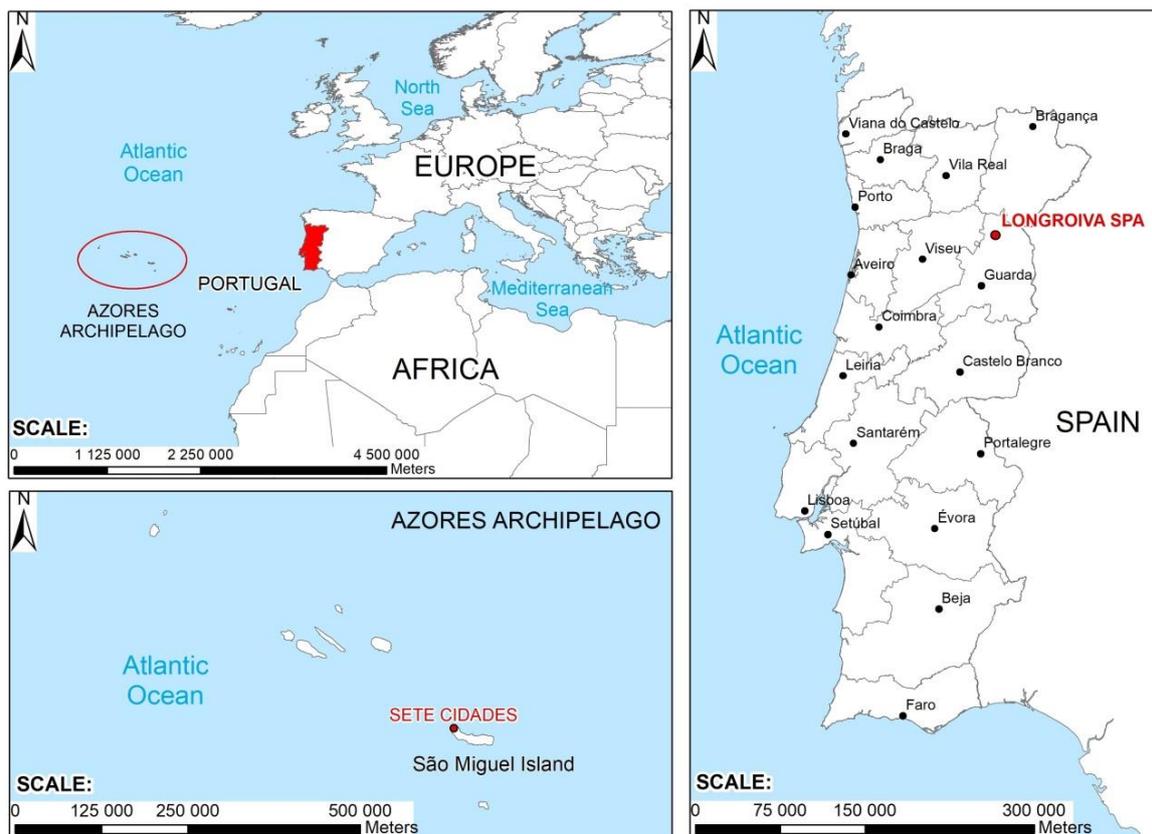
Knowing that most geothermal reservoirs are exploited using a heat mining approach, most of them experience reductions in temperature and pressure (mostly associated with general heat reserve depletion), and power generator modules can solve part of the problem by increasing heat extraction from a reservoir in a wide range of temperatures, particularly in the lower range.

The new Climeon modular power energy systems can also be used in reservoirs where temperatures are in the range 70 °C to 120 °C, the known temperature range (mostly inferred from chemical geothermometers) for most mainland Portuguese natural hydrothermal (geothermal) reservoirs. Moreover, synergies can be obtained by using the hydrothermal fluid in a cascade approach along with the use of rejected heat transferred to the cooling source.

The Climeon modular units can also be used on running power plants, namely, traditional binary power plants, by using hydrothermal fluids before being reinjected into the reservoir. Those fluids, for Azores binary power plants, are reinjected in the temperate range 87 °C to 95 °C, thus, the range of the Climeon units [8,9]. Before system implementation, the chemistry analysis and scaling potential of the pipeline system and reinjection well pipes must be performed, and the availability of the Climeon units' cooling fluids (water) is also important.

In this study, we present an evaluation of the geothermal power potential in two sites in Portugal (Figure 1), with different geological and geodynamic settings, based on a volume estimation methodology using a Monte Carlo approach. The reservoir parameter estimations were based on published papers along with the authors' data and interpretation of the results. We compared both Climeon modules and the traditional binary plants' electric power potentials at the two sites (i.e., Sete Cidades and Longroiva) using different adequate efficiency energy conversion factors.

The investigated sites are located in Sete Cidades in São Miguel Island, Azores archipelago and in Longroiva Spa, in the northern part of mainland Portugal. Sete Cidades is an active large stratovolcano on São Miguel Island, which lies on the boundary between the Eurasia and Nubia tectonic plates [10]. The Longroiva zone, a well-known thermal and spa area in the northern part of Portugal, is traversed by an active large and deep fault zone which crosses the granitic craton, which gives rise to thermal hot springs. The Sete Cidades hydrothermal reservoir, heated by a volcanic source, probably corresponds to a liquid dominated system with temperatures up to 250 °C. The Longroiva Spa reservoir, heated by a natural earth geothermal gradient and the radiogenic heat of local granitic rocks, can attain reservoir temperatures up to 120 °C [11,12].



**Figure 1.** Location of the two investigated sites. Sete Cidades, Azores, Portugal, active volcanic zone; Longroiva Spa, Portugal, granitic craton associated to a regional active fault. Adapted from Portuguese Directorate-General of the Territory (DGT) maps database <http://www.dgterritorio.pt/>. Reproduced with permission from [13]. Portuguese Directorate-General of the Territory, 2019.

## 2. Power Production by Climeon Technology

The Small-Size Compact Climeon Heat Power Converter (SCHPC) converts low temperature geothermal fluids into electric power by exchanging heat from hot water or steam (Table 1). Compared to traditional systems, such as traditional binary power plants (TBPPs), the SCHPC is based on the Rankine cycle, but the condensation side is under vacuum, and no heat recuperation downstream of the turbine is required. The SCHPC runs at low pressure levels, is smaller, more efficient and resilient to weather conditions and can be coupled to a wide range of heat sources [6,7]. The working fluid is of a chemical nature, similar to alcohol, ketone, and even water, has no ozone depletion potential and a global warming potential close to zero [7]. Modules can be fabricated in a wide power range (150 kW to 50 MW) according to source size and flow rate fluctuations, without significantly reducing the efficiency.

Climeon heat power modules have been implemented on a commercial basis in several countries worldwide, mainly in the following three segments, in which strong future growth is expected: geothermal (Wendel in the USA; Baseload Power and Iwana Power GK in Japan; Varmaorka in Iceland), industrial (SSAB steel mill in Sweden), and maritime (Viking Line, in Sweden; Virgin Voyages/Fincantieri shipyard in Italy).

**Table 1.** Basic technical characteristics of small-size compact Climeon heat power converters [6,7].

Characteristics	One Module 150 kW <sub>e</sub>	Power Block 1 MWe (7 Modules)
Module		
Height (mm)	2270	2270
Depth (mm)	2105	2105
Width (mm)	2085	14,700
Total weight (kg)	9000	63,000
Electrical Cabinet		
Height (mm)	2100	2100
Depth (mm)	600	600
Width (mm)	2200	13,600
Total weight (kg)	1200	6100
Heating Circuit		
Module flange connection ISO	DN125/PN10	DN125/PN10
Flow rate liter/second	10–50	70–350
Inlet temperature maximum °C	120	120
Cooling Circuit		
Module flange connection ISO	DN125/PN6	DN125/PN6
Flow rate liter/second	10–50	70–350
Minimum cooling inlet temperature °C	0	0
Maximum cooling inlet temperature °C	35	35
Electrical Specification		
Maximum net output power kW	150	1050
Voltage selectable V	400/690	400/690
Frequency selectable Hz	50/60	50/60

### 3. Case Studies

#### 3.1. Power Potential Evaluation Methodology

Assessment of extractable heat reserves in geothermal reservoirs has been conducted using several approaches, such as the volumetric method and numerical models [14–16]. The volumetric method is by far the most used approach for the assessment of the power potential of geothermal resources, particularly for reservoirs without sound exploration and exploitation data. In order to evaluate the uncertainties of input parameters in the volumetric method, a probabilistic methodology is mandatory, as in the case of Monte Carlo simulation, which includes random numbers and probability by evaluating interactively a deterministic model.

The volumetric methodology estimates the extractable electrical energy of a geothermal reservoir by evaluating the reservoir heat content over a certain reservoir volume, assuming a heat percentage that can be recovered from reservoir to surface and by considering a power machine efficiency on the conversion of heat to electricity.

According to Sarmiento and Steingrímsson [15], the heat content in a reservoir can be estimated by:

$$H = A \times h \times (H_r + H_w) \quad (1)$$

where,

$H$  = Stored heat (kJ).

$A$  = Resource area (m<sup>2</sup>).

$h$  = Reservoir thickness (m).

The  $r$  and  $w$  subscripts symbolize rock and water (fluid).

The heat rock content is obtained by:

$$H_r = (T_i - T_f) \times (1 - \phi) \times C_r \times \rho_r \quad (2)$$

where,

$T_i$  = Average reservoir temperature (°C).

$T_f$  = Base (rejected or abandoned) temperature (°C).

$C$  = Specific heat capacity (kJ/kg °C).

$\rho$  = Density (kg/m<sup>3</sup>).

$\phi$  = Porosity.

The heat contained in the fluid (assumed liquid water at reservoir pressure) is given by:

$$H_w = (T_i - T_f) \times \phi \times C_w \times \rho_w \quad (3)$$

The calculation of the electric power plant capacity is then obtained using:

$$P = H \times R_f \times \eta / (F \times L) \quad (4)$$

where,

$P$  = Power plant capacity (kW).

$R_f$  = Recovery factor.

$\eta$  = Conversion efficiency.

$F$  = Plant capacity factor.

$L$  = Plant life (s).

### 3.2. Sete Cidades Site

The Sete Cidades volcano, located at the westernmost point of São Miguel Island (Azores), lies at the boundary of the Eurasia and Nubia tectonic plates [10,17], close to the Azores Triple Junction: place where the North American, Eurasia, and Nubia tectonic plates meet. The volcano–tectonic setting where the Sete Cidades volcano is located is rather complex. Interpretation of geological, tectonic, and seismic data include inverse, normal, and strike-slip fault mechanisms, thus showing a wide range of stress/strain regimes in the area. Mosteiros graben and caldera wall collapse are two of the most impressive morphological features throughout the region (Figure 2).

São Miguel Island was built by the accretion of diverse volcanic products over the last 0.88 Myr [18] or 4 Myr [19], with a general westward growing trend, from several polygenetic and monogenetic eruptive centers, ranging from low to moderate Hawaiian to Strombolian eruptive styles to highly explosive and dangerous Plinian events [10].

Sete Cidades is the most active stratovolcano in São Miguel Island [20] and has an approximately 6 km diameter circular summit caldera and a maximum elevation at Pico das Éguas (874 m). Several preserved volcanic edifices and landforms can be observed inside (pumice cones, maars, and domes) and outside (cinder and scoria cones; domes) caldera.

The geological deposits on the Sete Cidades volcano reveal intense volcanic activity, thus a repeated input of volcanic heat. Moore and Rubin [21] estimated that 400 years was the average quiescent interval over the past 3000 years, whereas Queiroz data [22], based on the records of 17 intra-caldera eruptions over the last 4600 BP calculated an overall average recurrence time interval of about 144 y, without considering outside volcanic activity. Beier et al. [23] reached the conclusion that the caldera eruptions were triggered by a mixture of deep relatively fast up-flow of basaltic hot magma into upper sited trachytic magma chambers.

Tectonic events on Sete Cidades are a complex superposition of slow and stable movements between the Nubia and Eurasia plates (approximately 4 mm/y in the NE direction) and climactic episodes of volcanic activity. According to Queiroz [22], the actual caldera, with an initial sub-aerial phase around 200,000 BP, was the result of three main collapse phases—36,000 BP; 29,000 BP; and

16,000 BP—the last one involving the north and northeast walls. Around 5000 BP, the activity inside the caldera altered from magmatic to mainly hydro-magmatic, with geological records of 17 eruptions [22]. Regardless of no land eruptions after settlement on the Sete Cidades volcano, offshore, a few eruptions were witnessed, the most remarkable being the Sabrina eruption, which occurred in 1811 (Figure 2) [24].

Recent volcanic eruptions in Sete Cidades along with seismic swarms, including small and major magnitude events, most of them concentrated over the Graben of Sete Cidades, evidence ongoing deformation, most of them by new fault formation and fault reactivation, and hot magma residence [10].

Heat flux transfer of magma to surrounding meteoric water and seawater could occur by small-size magma injections, as dike type or by huge magma chambers shallow sited on polygenetic volcanic systems as Sete Cidades. Machado [25] and later on Beier et al. [23] showed evidence of a probable magma chamber, around 3 km in depth. The cooling process of magma transfers energy to the cold downflowing percolating water, giving rise to a water temperature increase. Rock fracturation and rock alteration over time (the Sete Cidades volcano is almost 200,000 years old) have produced a well-developed geothermal natural reservoir. Sometimes, most of the natural hydrothermal features of those reservoirs (such as hot springs, fumaroles, and degassing) are hidden by the rock suite of volcanic piles and by the buffering systems of huge shallow-sited fresh water aquifers, perched (aquifers located at an altitude controlled mostly by impermeable layers), and basal (shell-like layer aquifers closed to sea-level salt water island interface), making it impossible for the reservoir fluid to reach high zones of the volcano surface. However, there are a few zones where gas emissions, as CO<sub>2</sub> [22], were detected and some hot springs which discharge on sea cliffs, on Mosteiros and Ferrara [26–28].

Surface features such as hot springs, evidence of probable deep-sited geothermal reservoirs, can be observed in two coastal areas with similar geological settings: Ferrara and Mosteiros (Figure 2). Both zones correspond to a basaltic s.l. delta lava flow (locally called Fajã). The hot springs emerge on or nearby the coastline.

In Ferrara, the hot spring water emerges with a temperature of around 60 °C; the pH ranges from 5.4 to 6.2. The Ferrara water, classified as sodium chloride, is a mixture of an up-flowing hydrothermal CO<sub>2</sub>-enriched acid fluid with seawater [27]. The Ferrara water is intensely enriched with Sr and Mn but shows low concentrations in Al, Fe, and As [27]. Recent development and improvement of the Thermal Spa in Ferrara [27] included three shallow exploration geothermal wells, up to approximately 33 m depth. The temperature and chemistry of the water wells are similar to the existing hot springs.

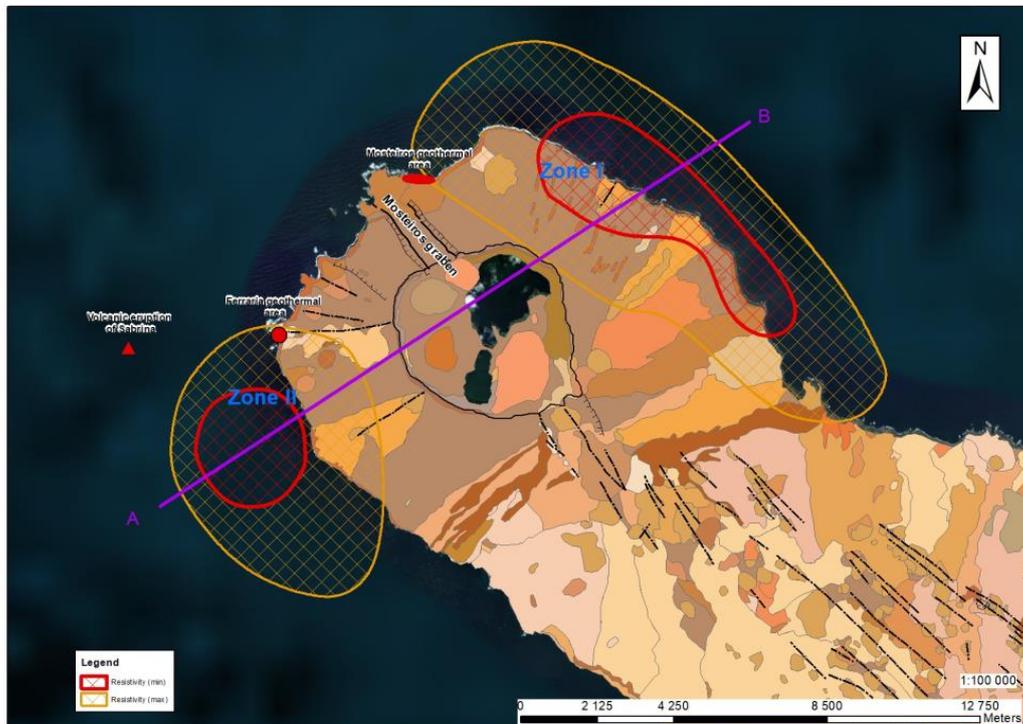
In the Mosteiros area (Figure 2), two hot springs can be found, Mosteiros (43.0 °C) and São Lázaro (32.8 °C), with a similar chemical composition and geological settings as the Ferrara hot springs [26,27].

Menezes et al. [29] performed a broadband magnetotelluric reconnaissance survey across Sete Cidades Caldera and detected a high conductive layer with depths ranging from approximately 600 m deep to 2500 m, indicating the existence of a hydrothermal reservoir, just above the magma chamber inferred by Beier et al. [23].

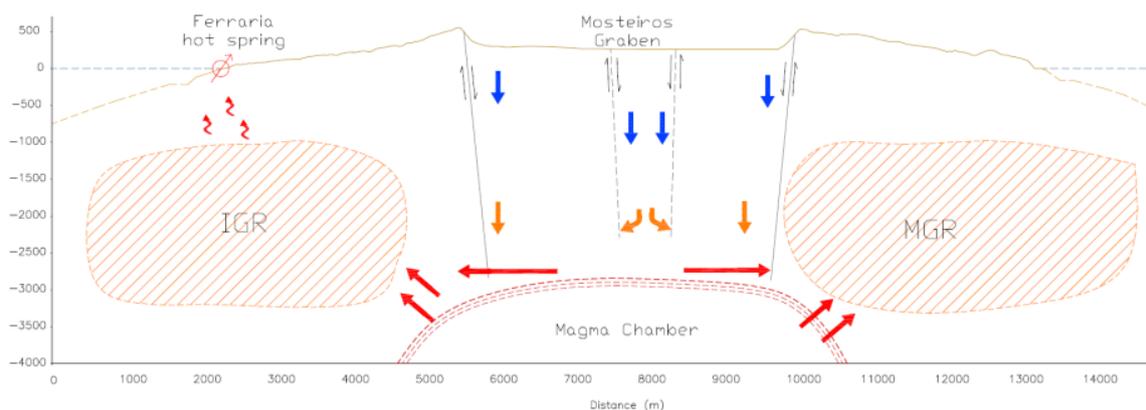
Based on the study by Menezes et al. [29] on local tectonics and on the hydrothermal surface features, we delineated two possible geothermal reservoirs associated to the Sete Cidades active volcano, separated by the Mosteiros Graben. Zone I corresponds to the Mosteiros Geothermal Reservoir (MGR), whereas Zone II corresponds to the Ferrara Geothermal Reservoir (FGR) (Figure 2). At depth, both MGR and FGR could be partially linked. The Mosteiros hot springs and Ferrara hot springs, marginally placed, are probably surface expressions of those reservoirs.

In Figure 3, we present a conceptual model for the Sete Cidades geothermal reservoirs. The heat source is related to the repeated magma injection over the area, inside caldera (record of 17 eruptions in the last 5000 years) and outside (last eruption on Sabrina, year 1811; see Figure 2). The water inflow could have two origins: meteoric water from island high lands and inside caldera; seawater from the Atlantic Ocean. The preferential water inflow could occur along the Mosteiros Graben, a fractured zone probably extended to the southeast, mostly under distension stress behavior. The 3 km top magma chamber will heat the cold inflow water, after which the water is driven by the density difference and ascends to the surface. The long-term alteration of rocks by volcanic gases (mostly CO<sub>2</sub> and H<sub>2</sub>S)

and high temperature will contribute to the rock alteration and leaching processes, thus increasing the porosity, permeability, and an impermeable cap. An exploitable natural geothermal reservoir comprises a significant rock volume size, with appropriate void index, containing extractable fluid at medium to high temperature, and a cap rock to hold the heat.



**Figure 2.** Sete Cidades volcano: geology, tectonics, and hydrothermal features. Zone I: Mosteiros Geothermal Reservoir; Zone II: Ferraria Geothermal Reservoir. Minimum and maximum areas are illustrated (see Table 2).



**Figure 3.** This sketch outlines the hydrothermal reservoir model of Sete Cidades based mostly on the interpretation (see A and B in Figure 2's illustration) of published geological, geochemical, and geophysical data. Reproduced with permission from [22,23,27,29]. Society of Exploration Geophysicists and American Association of Petroleum Geologists, 2017.

Reservoir area. The estimations of the reservoir areas (including the minimum and maximum) are shown Figure 2 and Table 2. The maximum areas were coarsely interpreted from the 10 ohm-m anomaly, whereas the minimum areas were close to the 5 ohm-m [29]. To complete the model, we also used the hot springs' locations and tectonics.

Reservoir thickness. The maximum and minimum thickness of the reservoirs (Table 2) were estimated following Meneses et al. [29].

Reservoir fluid and rejection temperature. According to Carvalho et al. [27], we cannot apply a hot spring chemical geothermometer to calculate the reservoir temperature. Taking into consideration the similitudes of the Fogo volcano to the Sete Cidades volcano [23], we used the temperature range (220 °C to 250 °C) of the Ribeira Grande Geothermal Reservoir for the Sete Cidades reservoirs (Table 2), FGR and MGR [22,30]. Fluid density and fluid specific heat were kept constant (Table 2); the rejection (or base) temperature was linked to the minimum temperature for self-producing wells (120 °C).

Rock density and rock specific heat. Sete Cidades rocks show a wide range of lithology, such as fallout deposits, lava flows, and pyroclastic. Therefore, we considered a range of 2000 to 3000 kg/m<sup>3</sup> (Table 2).

Recovery factor. Recovery factor (Table 2) depends on reservoir parameters, such as temperature, porosity, permeability, and the success of drilling targets in determining the best transmissivities, i.e., maximizing well productivity [31].

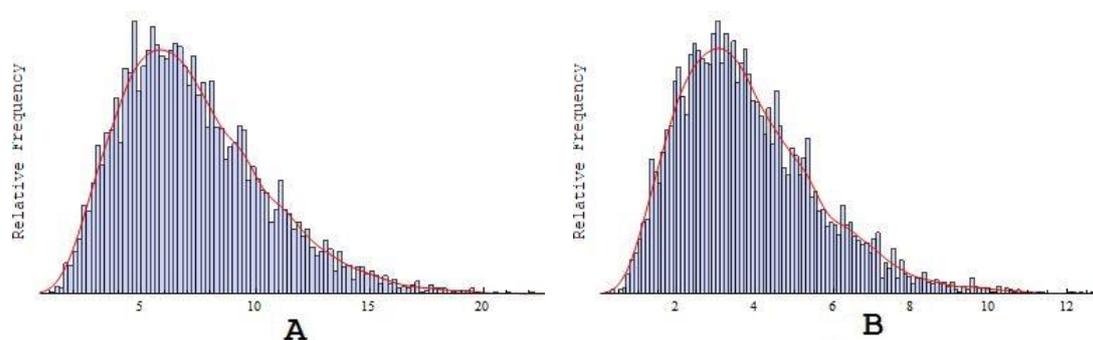
Conversion efficiency. Efficiency of the conversion of heat to electricity depends on several parameters, such as fluid enthalpy, quality, temperature, type of power plant, base temperature, and wellhead pressure. Assuming a cooling fixed-source temperature of 20 °C, and a minimum inlet temperature of 120 °C, we considered a conversion efficiency of 11.5% for the rejection temperature [6]. In order to compare power figures of the Climeon module with binary power plants, we used the temperature formula of Moon and Zarrouk [5] for the efficiency conversion based on inlet temperature. Thus, the efficiency values data input for calculations were 6.3%, 3.6%, and 8.2%, respectively, for the maximum, most likely, and minimum (see the values in brackets in Table 2).

Plant life and load factor. Module or power plant life could extend over decades, depending on several parameters, such as fluid chemistry, climate, maintenance, and power plant characteristics. Here, we considered 30 years for plant life. Load factors on geothermal power plants were high (Table 2).

**Table 2.** Input parameters for the Monte Carlo simulation for the Sete Cidades site (ad = adimensional). The values for binary power plant efficiency are in brackets. Reproduced with permission from [5]. Praise Worthy Prize, 2015.

Items	Units	Most Likely	Min	Max	Probability Distribution
Area (two zones, I and II)	km <sup>2</sup>	53	26	78	triangular
Thickness	m	1000	500	1500	triangular
Rock density	kg/m <sup>3</sup>	2500	2000	3000	triangular
Porosity	ad	0.15	0.1	0.2	triangular
Recovery factor	ad	0.035	0.01	0.06	triangular
Rock specific heat	kJ/kg °C	1			constant
Temperature	°C	230	220	250	triangular
Fluid density	kg/m <sup>3</sup>	827.1			constant
Conversion efficiency	ad	11.5 (6.3)	(3.6)	(8.2)	constant/(triangular)
Fluid specific heat (constant pressure)	kJ/kg °C	4.9			constant
Plant life	years	30			constant
Load factor	ad	0.95			constant
Rejection temperature	°C	120			constant

Figure 4 shows, for both the Climeon module and traditional binary plants, the power potential of a plant in MWe (for a lifetime assumed at 30 years) plotted against a relative frequency histogram. The cumulative frequency distribution can be considered a probability density function.



**Figure 4.** Histogram graph for the power capacity of the Sete Cidades case according to data from Table 2 and based on the Monte Carlo simulation. (A) Climeon module; (B) traditional binary power plants ( $x$ -axis in MWe).

Sanyal and Sarmiento [32] used the cumulative probability of estimated reserve to classify resources as:

- Proven – P90 or 90% probability: the minimum value.
- Proven + Probable – mode (most likely) or median (P50 or 50%).
- Proven + Probable + Possible – P10 or 10% probability: the maximum value.

Table 3 provides the results of the Monte Carlo simulation for the Sete Cidades site. The estimated power potential for the Climeon module was almost twice that compared to the binary plant. The proven reserves of Sete Cidades could produce for 30 years with 38 Climeon modules of 150 kWe each, thus producing a total accumulated amount of  $14.20 \times 10^8$  kWhr.

**Table 3.** Results of the Monte Carlo simulation for Sete Cidades, both the Climeon module and binary power plant.

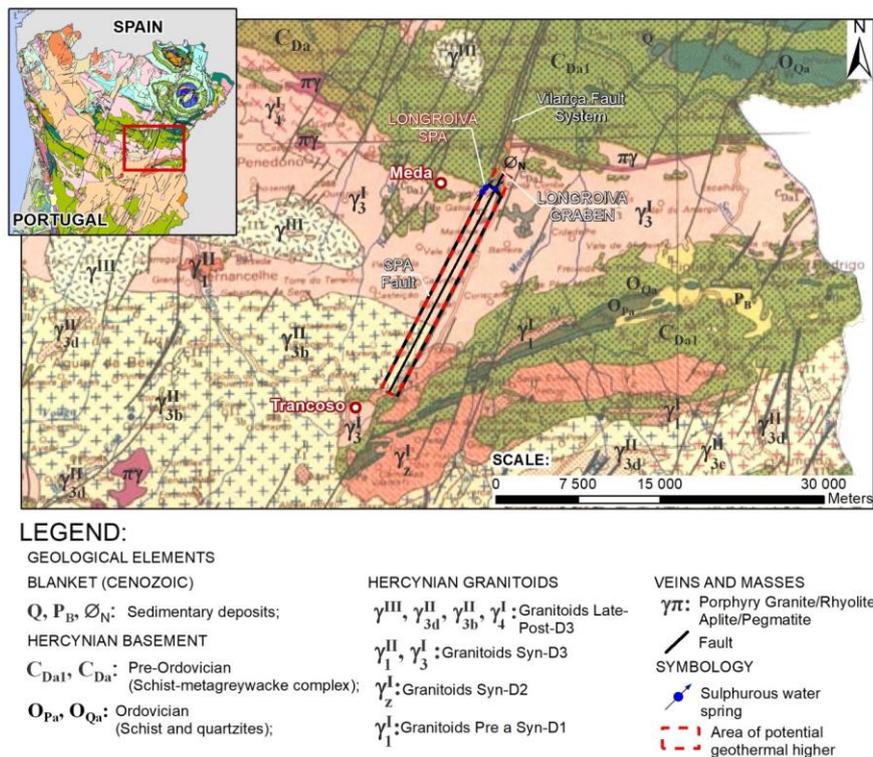
Unit	Proven Reserves (P90) MWe	Proven + Probable (P50) MWe	Proven + Probable + Possible (P10) MWe
Climeon module	5.66	7.03	9.26
Binary power plant	2.04	3.56	6.02

### 3.3. Longroiva Spa Site

The Longroiva Spa is located in the Longroiva village, Municipality of Meda, District of Guarda (mainland Portugal). The geological setting includes the Ancient Massif, which corresponds to the western part of the morphostructural unit of the Iberian Peninsula, called the Hercynian basement, with evident episodes of extensive magmatic intrusions [33]. The region is part of a transition zone among plateaus, which are staggered at various altitudes, and steep slopes. That transition zone is materialized by a major tectonic accident, the Vilarica Fault (Bragança–Vilarica–Manteigas), which divides the region into two large blocks.

The Vilarica intraplate fault, originated by Iberia–Eurasia plate collision, which has been active since the late Cenozoic, plays as an NNE–SSW strike-slip deformation structure [34–38]. This fault zone is considered the most active fault in the Portuguese mainland territory [39–41], being a vertical fault, deep (up to about 20 km) and long (about 600 km), and continuing to the south of Manteigas towards Ponte de Sor [42,43]. The Vilarica Fault accumulates about 5.5 km of horizontal displacement and gave rise to a set of parallel fractures in a wide band of 0.5 to 1 km and subsiding structures, such as the Longroiva Graben (Figure 5). The fracture system shows asymmetric morphology on both sides of Vilarica Fault. The eastern bloc side exhibits a fault scarp of about 150 to 200 m height; the actual surface corresponds to a plateau tilted towards the northwest and to the river Douro, located north of

Longroiva Spa. On the western side, tectonic forces have elevated the land to an altitude of 650 to 750 m where Meda town is located.



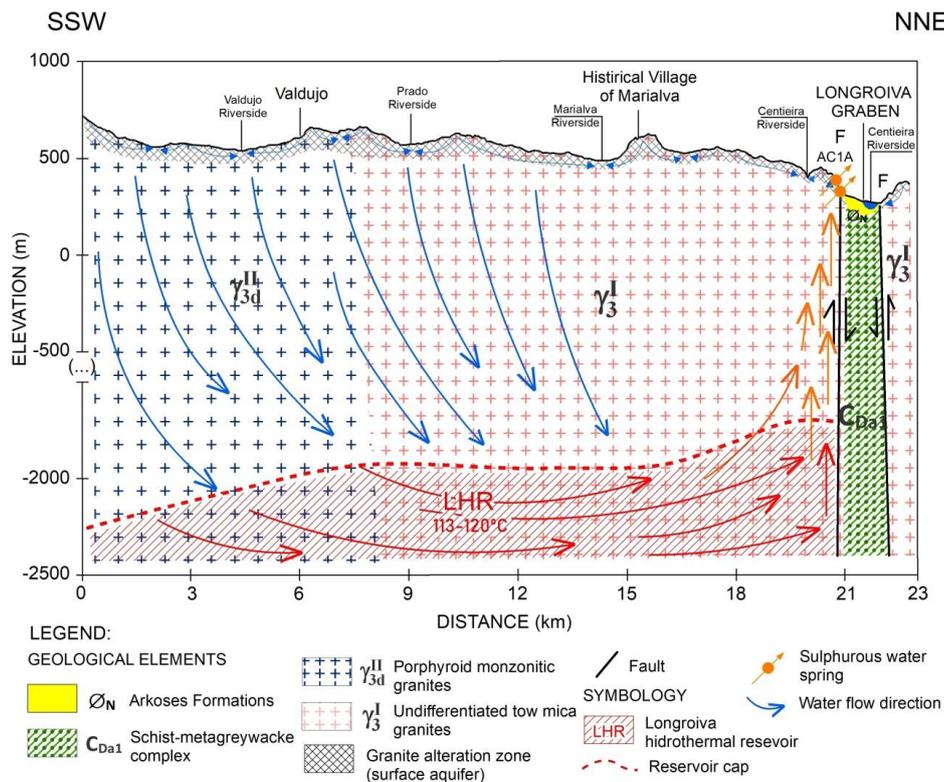
**Figure 5.** Longroiva geothermal area: geology, tectonics, and hydrothermal features. Adapted from SGP and LNEG. Reproduced with permission from [44,45], Geological Services of Portugal. Geological Services of Portugal, 1992.

Along the Vilarica Fault and associated fracture systems, several hot springs occur. According to Ferreira Gomes [46], the Longroiva sulfurous hot spring, approximately 30.8 °C [47], emerges along the Longroiva Spa Fault, a fault parallel to the Vilarica Fault. Based on geological, geophysical, and drilling data, Ferreira Gomes [46] proposed a conceptual hydrothermal model that considers the existence of a probable deep geothermal reservoir between the Longroiva Spa Fault and the Vilarica Fault (Figure 6), i.e., the Longroiva Graben. The recharge water, of meteoric origin, infiltrates at maximum altitudes of 800 m (Trancoso region, on Figure 5), percolates deep into the granitic craton, and gradually incorporates the heat of the Earth's geothermal gradient along with the radiogenic heat content of granitic rocks.

With Longroiva Spa exploration and exploitation projects, several studies were undertaken through shallow drilling. Two wells drilled (TD1, 45 m depth, sealed; AC1, 211.7 m depth, under production) in the Longroiva hot spring area improved the knowledge of the local shallow hot fluid circuit, giving evidence of two different aquifers: (a) an unconfined aquifer, with fresh, low mineralized water, reservoir thickness of approximately 50 m, with local recharge; (b) a confined aquifer of sulfurous water, with deep flow and probably distant recharge.

Well AC1 exhibited artesianism (well head pressure of approximately 1.2 barg) and produces a stable water flow of 6.3 L/s at a temperature of 47.4 °C [12]. Well tests permitted the calculation of the aquifer's parameters: permeability, 0.4 m/day; transmissivity, 5.6 m<sup>2</sup>/day; and storage coefficient, 2.4 × 10<sup>-3</sup>. Well water analysis [48] revealed the chemical stability of an alkaline sulfurous sodium-bicarbonate water type (pH circa 8.8), with a total mineralization of 460 mg/L.

Recent research by Coelho Ferreira [49] anticipated a deep well in the surroundings of Longroiva SPA (1500–2000 m depth), estimating flow rates in the order of 15 to 20 L/s with temperatures up to 80 °C.



**Figure 6.** Conceptual model of the hydrothermal reservoir of the Longroiva Spa site based mostly on the interpretation of published geological and geochemical data (from Ferreira Gomes). Reproduced with permission from [48]. National Library Board Singapore, 2018.

**Reservoir area.** Based on the fault geometry, local geomorphology and geology, and hydrothermal surface features, we designed a maximum probable rectangular area (23.0 km by 1.6 km) for the Longroiva Geothermal Reservoir (Figure 5) of approximately 37 km<sup>2</sup>.

**Reservoir thickness.** Without exploration studies in the area, particularly geophysical, there are no comprehensive data regarding the deep reservoir thickness. We assumed a prudent average reservoir thickness of 400 m.

**Reservoir fluid temperature.** Based on the chemical water composition, Coelho Ferreira et al. [11] and Ferreira Gomes et al. [12], using silica and Na/k geothermometers, estimated reservoir temperatures in the range 113 °C to 120 °C. Taking into consideration geothermal well gradient data [11,12] and heat flow models, Coelho Ferreira et al. [17] estimated the depth of the Longroiva Geothermal Reservoir to be from 1134 m to 2000 m.

**Density, porosity, and rock specific heat.** The reservoir rock is probably made of granitic type. We used the range values of Robertson [50] and Jumikis [51] for rock density (2530 to 2620 kg/m<sup>3</sup>), rock porosity (0.01 to 0.04), and rock specific heat (1.0 kJ/kg °C).

**Recovery factor.** Statistically, there are no sound historical records of the heat recovery factor for natural hydrothermal reservoirs under granitic geological settings in Portugal. Thus, for the Longroiva site, we used a prudent scenario of 5% for the recovery factor (Table 4).

**Conversion efficiency.** As for the Sete Cidades site, in the Longroiva case we used different conversion efficiency values for the Climeon module and binary power plants. For the input temperature range of 70 °C to 120 °C, we used Climeon module conversion efficiencies of 9.6 (1.5), 7.7 (0), and

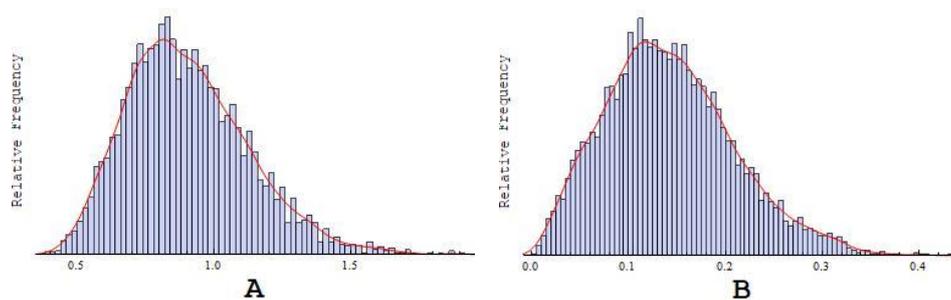
11.5 (3.0), respectively, for the maximum, most likely, and minimum; the values in brackets denote the conversion efficiency for traditional binary power plants (Table 4).

**Table 4.** Monte Carlo simulation for the Longroiva Spa site (ad = adimensional).

Items	Units	Most Likely	Min	Max	Probability Distribution
Area	km <sup>2</sup>	37	30	60	triangular
Thickness	m	400	250	500	triangular
Rock density	kg/m <sup>3</sup>	2600	2530	2620	triangular
Porosity	ad	0.02	0.01	0.04	triangular
Recovery factor	ad	0.05			constant
Rock specific heat	kJ/kg °C	1			constant
Temperature	°C	110	100	120	triangular
Fluid density	kg/m <sup>3</sup>	951			constant
Conversion efficiency	ad	9.6 (1.5)	7.7 (0)	11.5 (3.0)	triangular
Fluid specific heat (constant pressure)	kJ/kg °C	4.2			constant
Plant life	years	30			constant
Load factor	ad	0.95			constant
Rejection temperature	°C	70			constant

Module life and load factor. For the Longroiva site, we considered the same model inputs (plant life and load factor) as for Sete Cidades.

Figure 7 shows, for both the Climeon module and binary plant for the Longroiva Geothermal Reservoir, the potential of the plant in MWe plotted against the relative frequency histogram.



**Figure 7.** The histogram shows the power capacity of the Longroiva Hydrothermal Reservoir according to the data in Table 1. (A) Climeon module; (B) binary power plants (x-axis in MWe).

Table 5 shows the results of the Monte Carlo simulation for the Longroiva site. The estimated power potential for the Climeon module was five times higher compared to the binary plant. The proven reserves of the Longroiva Geothermal Reservoir could stand for 30 years with four Climeon modules of 150 kWe each, thus producing a total accumulated amount of  $1.50 \times 10^8$  kWh.

**Table 5.** Results of the Monte Carlo simulation for Longroiva for both the Climeon module and binary power plant.

Unit	Proven Reserves (P90) MWe	Proven + Probable (P50) MWe	Proven + Probable + Possible (P10) MWe
Climeon module	0.64	0.87	1.24
Binary power plant	0.06	0.13	0.24

#### 4. Discussion

Surface features and exploration studies at the Sete Cidades volcano gives the indication of an important heat resource, probably a hidden deep source natural geothermal reservoir. There is no doubt about the large magma heat flux in the area, evidenced by the presence of several islands (inside and outside the Sete Cidades caldera) and surtseyan eruptions close to the coastline (such as the Sabrina eruption), from at least 200,000 years ago.

Taking into consideration a similar geological setting, namely, eruption and magma source style, the Sete Cidades geothermal reservoir (or reservoirs) might show similarities with the Ribeira Grande Geothermal Reservoir, associated with the Fogo volcano [10]. Thus, the reservoir, with temperatures up to 250 °C (here considered as liquid), could be attained by drilling from 1000 to 2500 m deep. The reserve estimations of 5.66 MWe (Climeon module) may be larger taking into consideration that the reservoir size could be greater and by the fact that we are not considering renewable heat (from the volcano and from well fluid reinjection). Also, depending on the cooling source (sea water, fresh water or cooling tower) and the altitude (for traditional BPP and mostly for CM), the conversion efficiency could augment significantly (we assumed a cooling source of 20 °C). Moreover, recovery factors can be optimized by conducting sound and extensive exploration studies, aimed to discover good drilling targets for the production phase.

The estimated reserve differences between the Climeon module and traditional binary plants are mostly related to conversion efficiency differences—efficiency decrease with input temperature decrease—mostly for traditional binary plants. Depending on the reservoir and well characteristics, a minimum wellhead temperature of 120 °C cannot be sustained if it is self-flowing; in this case, downhole pumps must be implemented.

Evaluation of the reserves for geothermal resources on the Portuguese mainland was mostly based on natural hot springs. However, there may be large hidden natural resources, with reservoir temperatures from 100 °C to 120 °C, which can be attained by drilling on the order of 1.5 to 3.0 km. Except for oil and gas exploration in the sedimentary basins, there has been no complete exploration studies (such as geophysical and deep drilling) to investigate deep-seated geothermal reservoirs. Despite the uncertainties (reservoir thickness) and speculative (recovery factor) approach of some of the input parameters in the calculations, the estimated values can give an order of magnitude of the resources and provide guidance to some of the actual conversion energies systems. Clearly, due to the minimum temperature resource, for the Longroiva site, the Climeon module was by far the most effective machine for the heat recovery (at least five times better than traditional BPPs). Water for the cooling source can be obtained from several sources, such as a shallow fresh aquifer, rainfall, rivers, and brackish and wasted water. Available water for cooling devices is in fact an issue in regions where rainfall is scarce, which is the case for the Longroiva site, nor for Sete Cidades site. The need for cooling water for the Climeon module (and also for binary power plants) depends on several factors, such as cooling water temperature, differential temperature of geothermal source (input and output), and on the size of the Climeon power unit (i.e., number of modules). Cascade use of geothermal resources (swimming pools, greenhouses, and aquaculture) and integration with air conditioning devices (individual dwellings or district heating systems) could transform an issue into a benefit. The heat recovering from the cooling source by means of a heat pump makes possible to reuse the cooling water and therefore reducing significantly the need for external cooling water. Moreover, if necessary, part of the cooling energy can be obtained by air-cooling devices, despite the global energy efficiency reduction. In Portugal, industrial use of water from rivers and aquifers requires previous national/regional authorizations.

For both cases (i.e., Sete Cidades and Longroiva), the Climeon modular unit of 150 kW is crucial for project development, and it must be taken into consideration that the Climeon technology can be easily implemented and adapted to the project phase and resource size, reducing risk.

Every single geothermal project demands an adequate and stepwise development strategy, namely exploration studies, such as geophysical research. Determining the best drilling targets is a crucial issue in geothermal projects, i.e., the recovery factor. Only good well producers can transport heat from the reservoir to the surface, thus raising the recovery factor.

Several hot springs occur across mainland Portugal, such as São Pedro do Sul and Chaves [52], evidencing several exploitable geothermal reservoirs. However, all of them lack a comprehensive reservoir evaluation for desirable exploitation and management, including environmental issues.

## 5. Conclusions

Portuguese natural geothermal resources are far from having a precise assessment. Despite the parameter uncertainties, we made electric power resource estimations for two natural geothermal reservoirs: a volcanic source high-enthalpy geothermal reservoir in Sete Cidades, São Miguel, Azores; and a low-enthalpy geothermal reservoir linked to a fractured zone in a granitic setting in Longroiva, in the northern part of the Portuguese mainland.

Based on the volumetric method, we made the assessment of the power potential of geothermal resources in Sete Cidades and Longroiva using a probabilistic methodology, the Monte Carlo simulation.

For a wide range of input resource temperatures, two conversion technologies can be applied: Climeon and traditional binary technologies. For both cases, the estimated power potential was optimized using Climeon technology. For the high-enthalpy reservoir in Sete Cidades, the estimated reserves using the Climeon module could attain 5.66 MWe, more than twice that of traditional binary technology. For the Longroiva case, the estimation of the reserves was 0.64 MWe, mostly due to the low temperature resource and conversion efficiency factor between Climeon and traditional binary technologies; the difference was greater, attaining ten times more expected electricity, in favor of Climeon technology.

Natural reservoir volume and temperature cannot be changed, only discovered [31]. In order to reduce project risk, a stepwise development phase, namely, exploration studies such as geophysical research, are crucial for success. Defining the best drilling targets will increase the recovery factor. Thus, reducing the parameter range distribution of permeability, porosity, and temperature will improve the reservoir model, possibly producing better reservoir exploitation and management.

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