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Geothermal Energy Use, Country Update for Portugal

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ABSTRACT

In Portugal, the presence of high temperature geothermal resources is restricted to the volcanic islands of Azores Archipelago, which are associated with the triple junction of the North American, Eurasian and African (or Nubian) plates (Figures 1 and 3).

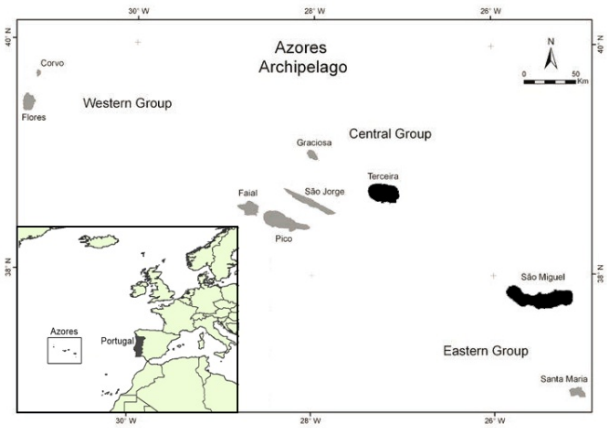

Figure 1: Location of Portugal Mainland, the Azores Archipelago and S. Miguel and Terceira Islands

Present investment projects at the Ribeira Grande Geothermal Field on the island of S. Miguel, implemented by SOGEO (Sociedade Geotérmica dos Açores S.A.), led the installed generation capacity in Azores to a total of 23 MW net, with the contribution of the new Pico Vermelho plant (10 MW net), which went into production in November 2006. Thus, power production from geothermal resources in Azores presently meets 42% of the electrical consumption of S. Miguel, and over 22% of the total demand of the archipelago.

On Terceira Island, deep exploratory drilling at the Pico Alto Geothermal Field during 2003-2010 conducted to a maximum temperature of 312 ºC. New evaluation tests were designed and will be carried out in 2013 to evaluate the capacity of the existing evaluation-production wells.

Geothermal is expected to assume an even more impressive role for electric power self-sufficiency of this Autonomous Region of Portugal, particularly in S. Miguel and Terceira Islands. However, its development is now considered in conjunction with other renewable energy sources, particularly wind energy.

Low-temperature geothermal resources in Mainland Portugal are exploited for direct uses in balneotherapy, small heating systems and heat pumps (Figure 2).

In Portugal, ground source heat pump technology (GSHP) is still not known and has a reduced penetration in the heating and cooling of buildings market.

In 2008, private investors obtained concession rights for exploration of geothermal resources for a total area of 2,655 km^2, aiming the future development of small scale generation projects, but these EGS projects abort and no technical or scientific results are known.

1. Introduction

High temperature geothermal resources in Portugal are limited to the volcanic islands of Azores, where have been used for power production since 1980, at the Ribeira Grande geothermal field. In spite of some minor environmental impacts, the last years were extremely relevant for geothermal in the Azores (Cabeças et al., 2010), as:

• The generation capacity installed at the Ribeira Grande field was expanded from the previous 16 MW, mainly concentrated at the Ribeira Grande plant, to a total capacity of 23 MW, including the Pico Vermelho plant;

• The development of geothermal generation projects on the island of S. Miguel has been well succeeded, with an annual average contribution of approximately 42% of the electricity produced in the island.

Based on this scenario, geothermal gained a renovated interest and assumes a leading position in the renewable energy portfolio of the island of S. Miguel. In the scope of renewable energies utilization expansion in Azores, the regional government considered geothermal as a main player for the development of new projects for electricity generation. The expansion of the installed capacity at the Ribeira Grande field is under evaluation to increase the geothermal penetration on the market.

The geothermal policy in Azores issued by the Azores Government is developed in the field by the regional electric utility EDA – Electricidade dos Açores S.A., through its affiliated companies SOGEO - Sociedade Geotérmica dos Açores S.A. and GEOTERCEIRA - Sociedade Geoeléctrica da Terceira S.A., which concentrate the local effort in the development of generation projects in the archipelago. Considering the high generation costs using fossil fuels, geothermal is a competitive source of energy, providing significant running savings to EDA.

In Mainland, at present, there are no direct use projects running, outside a few existing Bath Spa's, and it is not envisaged the oncoming of new operations based in deep wells.

Portugal like the other Mediterranean countries has more leveled heating and cooling needs than Nordic countries. As a consequence, in Portugal GSHP's are usually reversible, producing heat and cooling. The equilibrium between heating and cooling in a dwelling is important in order to maintain the temperature stability of ground along the years.

In the residential sector, heating needs are higher than cooling needs, what can lead to the ground temperature decrease. However that problem is smaller than in northern and central European countries. Commercial buildings can have more cooling needs, function of the activity developed in the building, so special attention has to be paid to geothermal borehole heat exchangers (BHE) design to avoid the ground temperature increase.

2. GEOLOGY AND HYDROGEOLOGY BACKGROUND

The geology and hydrogeology controls the occurrence of geothermal resources so an updated description of these conditions is provided below.

2.1 Mainland

In Mainland Portugal, classical geothermal resources are generally associated to the following origins: i) thermo-mineral waters related to active faulting and diapirism; and ii) deep circulation in some peculiar structures in the basement and particularly in the sedimentary borders trough permeable formations (e.*g*. Aires-Barros and Marques, 2000; Carvalho, 1995, 1996, 1998, 2006; Carvalho and Carvalho, 2004; and Costa and Cruz,, 2000).

The existing temperatures restrain the utilization to direct uses. Twenty-four springs are officially used in balneotherapy having discharge temperatures between 25 ºC and 76 ºC (Figure 2).

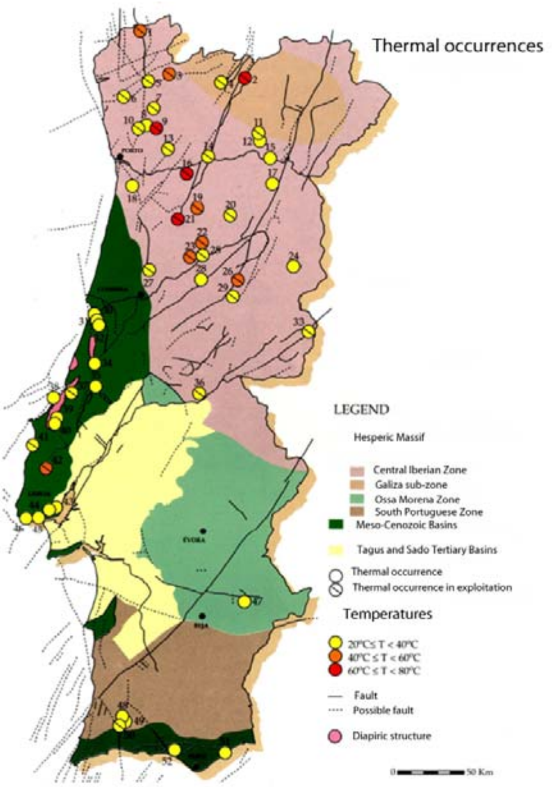

Figure 2: Geological sketch of Portugal Mainland, with thermal occurrences (adapted from Instituto Geológico e Mineiro 1998, www.dgeg.pt)

From the lithological point of view, main rocks are granites of the Variscan orogeny and metasediments pre and post orogenic. Weathering is quite irregular depending on tectonics and present and past climates. Average reported depths to sound rock ranges from 0 to 60 m but in the vicinity of main tectonic axis it is not infrequent to drill up to 300 m of weathered rock.

Naturally available discharging flows from former exploitation systems reached a maximum of 10 l/s. New wells up to 1,000 m depth, drilled after the seventies of the past century, allowed moderate improvements in sustainable production and in temperature (Carvalho, 2006).

Regarding chemistry, the following groups could be considered at the Variscan Massif: (i) hypo-saline waters with total dissolved solids (TDS) less than 150 ppm, frequently under 50 ppm. This less mineralized group corresponds mainly to water circulating in quartzite reservoirs, (ii) sulphurous waters with up to 1,000 ppm and temperatures up to 62 ºC, and (iii) carbonated sparkling waters with TDS up to 2500 ppm and temperatures up to 76 ºC.

The sedimentary borders composed of sequences of post Palaeozoic sediments with thickness up to 4,000 m also present several thermal waters related to deep faulting and diapiric tectonics. These waters are generally of the sodium chloride type and temperature from 20 to 40 ºC.

Synthesis of the Portuguese geological conditions related to mineral water and geothermal is available at the site (www.dgeg.pt) of Directorate General for Energy and Geology (DGEG), the Portuguese authority for those geological resources.

2.2 Azores Islands

The nine islands that form the archipelago of Azores are spread over 600 km in the Atlantic Ocean, along WNW-ESE trend and emerge from the designated "Azores Plateau" (Figure 3), which is defined by the bathymetric line of 2000 m. Being situated at the junction of the American, Eurasian and African tectonic plates, the Azores display an intense seismic and volcanic activity. Since discovery and settlement of the islands, in early 15th century, 26 eruptions were recorded inland and onshore. Volcanic and seismotectonic activity is more concentrated in the Central Group and in S. Miguel Island; the plate boundary between the Eurasian and African plates (Figure 3).

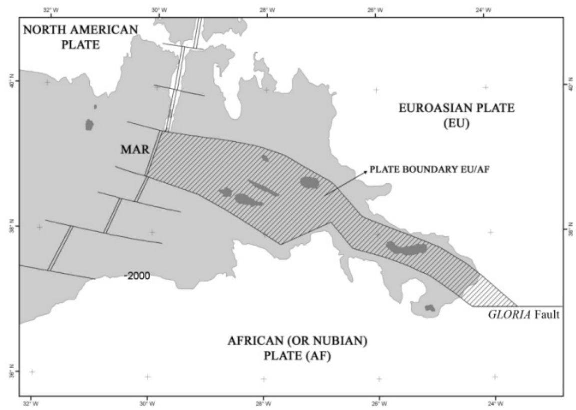

Figure 3: The Azores Triple Junction area. MAR: Mid Atlantic Ridge. Shaded area represents the "Azores Plateau" (adapted from Nunes et al., 2008)

Geochemically, the rocks in the Azores islands belong to the intraplate alkaline series and have a clearly distinct pattern from the toleiitic basalts from the Mid Atlantic Ridge.

On the island of S. Miguel, there are three active polygenetic volcanoes with caldera that produced explosive trachytic eruptions: Sete Cidades, Furnas and Fogo/Água de Pau. On the northern slopes of the Fogo volcano is located the Ribeira Grande geothermal field (Figure 4). The last event on that central volcano was a plinian eruption that took place in 1563 AD. Surface geothermal manifestations are spread in all these three volcanoes, which are particularly impressive at Furnas with the presence of numerous thermal springs and fumaroles.

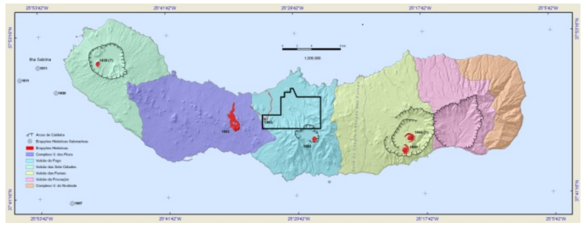

Figure 4: Volcanological map of S. Miguel Island (Nunes, 2004). The Ribeira Grande Geothermal Field concession area is outlined

On Terceira Island (Figure 5), which has a complex tectonic setting, there are four central volcanoes with caldera (Cinco Picos, Guilherme Moniz, Santa Bárbara and Pico Alto – in chronologic order) and the Fissural Basaltic Zone, in the central and SE part of the island (Nunes, 2000). The Pico Alto volcano (the younger polygenetic volcano) is dominated by silicious formations, of pyroclasts and domes and *coulées* of trachytic and pantelleritic nature.

Surface geothermal manifestations are reported in all islands but Corvo and Santa Maria islands. Five Thermal Baths/Spas using geothermal resources are installed in S. Miguel, Faial and Graciosa islands. In addition, the Caldeira Velha and Poça da D. Beija (S. Miguel Island) are also thermal attractions as well-being facilities.

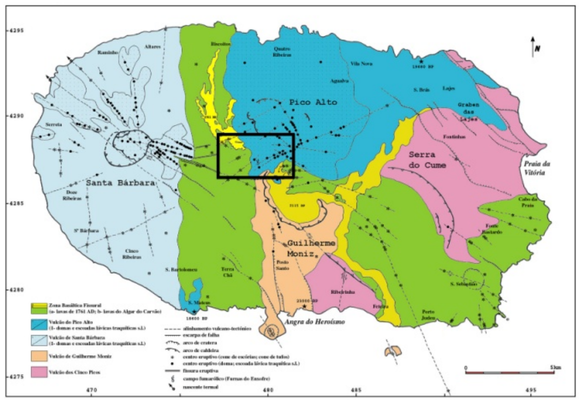

Figure 5: Volcanological map of Terceira Island (Nunes, 2000). The Pico Alto Geothermal Field concession area is outlined

3. Geothermal resources

3.1 Mainland

Geothermal resources (thermo-mineral springs) related to faulting in the Variscan basement (presenting a total available capacity of the order of 28 MW(t)) and diapirism in the sedimentary borders are the leading features of the mainland Portuguese panorama. These capacities refer to an outlet temperature of 20 ºC.

In the sedimentary borders deep aquifers are known as in the Lisbon area where a 1,500 m deep well taped Cretaceous sandstones with 53 ºC - bottom hole temperature (BHT). This well, with a 500 mg/l TDS and 49 ºC water, supplied the Air Force Hospital geothermal project, financed by the VALOREN Program, between 1992 and 2002.

Oil wells in the Tejo and Sado basins (Carvalho et al., 1990) suggest temperatures of 75 ºC at 2500 m in Jurassic limestone, with 5,000 ppm TDS water. The higher geothermal gradient is about 3.5 ºC/100 m (IGM, 1998). Normal gradients are in the range of 2.1 ºC/100 m (Ribeiro and Almeida, 1981), that means average BHT of c.a. 50 ºC at 1,500 m depth.

A. CAVACO (1998) suggested the equation

$$T\,(^{\circ}C) = 0.021 \times \text{Depth (m)} + 17.66 \qquad [1]$$

for the estimation of ground temperature in a given depth (till 1,500 m), in the Portuguese Sedimentary Borders. This linear regression model confirms an average geothermal gradient of 2.1 ºC/100 m with a shallow groundwater temperature of 17.7 ºC.

According to Correia et al. (2002) the regional heat flow density (HFD) is about 60-90 mW/m^2 in the Variscan Massif and 40-90 mW/m^2 in the sedimentary basins.

Potential for EGS projects is not yet scientifically assessed.

3.2 Azores Islands

In the Azores, the presence of geothermal resources is associated to the active volcanism of the archipelago. Although extensive developments have been made at Pico Alto (Terceira island), the Ribeira Grande field in S. Miguel island is the only high-temperature field under exploitation in the archipelago.

The conceptual model has been described by GeothermEx (1996), Cabeças and Henneberger (2001) and later updated by SOGEO and GeothermEx (2008). The Ribeira Grande field is an extensive liquid dominated system located on the northern flank of the Fogo polygenetic volcano, and elongated in a northwestern direction, which is related to a major NW-SE trending pattern of faulting originated by the regional tectonic stress regime. However, the boundaries are not sufficiently delineated considering that drilling has been concentrated mainly in two sectors of the Ribeira Grande field. An AMT survey suggests that the field might extend further than considered previously.

The present geothermal model considers that an up flow of geothermal water enters in the reservoir in the southern area, at more than 250 ºC, and moves to northwest in an extensive zone of several hundred meters thick, in which temperatures exceed 220 ºC. The geothermal water is sodium-chloride type, with TDS of about 6-7 g/l.

Hydrogeochemical and isotopic studies determine a meteoric origin for the geothermal fluid.

On Terceira Island, following the previous exploration studies that included a geoelectric survey and a temperature gradient drilling campaign, deep exploratory drilling and testing was carried out at the Pico Alto field (Figure 5). The results indicate the presence of temperatures in the range of 250-300 ºC but the occurrence of a geothermal reservoir is not still proved. Further long-term testing and other exploration and evaluation activities are in due progress by GEOTERCEIRA to determine the total extent of the reservoir and for characterization of the resource.

In 2006/2007, reconnaissance studies and an AMT/MT survey were developed on selected areas of Sete Cidades central volcano (S. Miguel Island) and in Faial Island, but no drilling programs are now envisaged.

4. Geothermal utilization

Geothermal energy in Portugal is used for electricity production, for direct use in thermal baths/Spas and greenhouses, and in Ground Source Heat Pumps.

4.1 Electric Power Installation and Generation

At the Ribeira Grande field two geothermal power plants – Ribeira Grande and Pico Vermelho – are in operation with a net combined capacity of 23 MW (Table 1). Both plants are based on ORC binary systems.

The Ribeira Grande plant consists of four dual turbo-generators developed in two phases: Phase A (2 x 2,5 MW) installed in March 1994, and Phase B (2 x 4 MW) completed in November 1998.

The new Pico Vermelho plant started in November 2006 and replaced the former 3 MW pilot unit, in operation since 1980. This new project at Pico Vermelho included the construction of a 10 MW power plant and an extensive drilling campaign, to increase the production and reinjection capacity in this sector of the field.

Al the geothermal brines resulting from the operation of the two geothermal power plants are re-injected.

The high productivity wells drilled in 2005 in the sector of Pico Vermelho allowed that the annual production attained 185 GWh in 2011 (Figure 6), representing approximately 42% of the electric consumption in the island of S. Miguel and about 22% in the Azores archipelago.

No direct uses related with the geothermal brines are in operation, as a former INOVA Institute greenhouse operation, financed by the THERMIE Program, has run since 1997 (Rodrigues, 1998) but after 2005 no longer was nourished with geothermal effluent.

Figure 6: Annual geothermal power production in Azores, including data for both de Pico Vermelho and Ribeira Grande power plants (Bicudo da Ponte, 2012)

4.2 Direct Heat Uses

Direct use application in Mainland and Azores is restricted to small district heating operations, greenhouse heating and mainly balneological applications. The situation was reported by Carvalho et al. (2005), Lourenço (2005), Cabeças et al. (2010) and no significant changes occurred afterwards.

4.2.1 District Heating

Two main operations are running normally:

- Chaves, Northern Portugal: a dedicated well, 150 m deep, 76 ºC, TDS of 2500 mg/l, 5 l/s capacity, in metamorphic slates with quartz veins, is used in a small district heating network (swimming-pool and hotel). An independent well (100 m deep, 73 ºC, TDS of 2500 mg/l, 10 l/s capacity), taped hot water in metamorphic slates with quartz veins and feeds the Thermal Bath. A geothermal green house, financed by the JOULE Project, is no more in operation;
- S. Pedro do Sul, central Portugal, the main Portuguese Spa: one inclined well, 500 m deep, 69 ºC, 350 mg/l TDS, 10 l/s with artesian flow, in fractured granite, supply the Thermal Bath and is in use in a small heating operation, financed by the THERMIE Program, in two hotels and inside the Spa.

4.2.2 Greenhouse Heating

One single operation is running at S. Pedro do Sul (Vau). Two km south of S. Pedro do Sul Spa, two wells up to 216 m in granitic rocks (10 l/s at 68 ºC, 350 mg/l TDS) are used in a 2 ha greenhouse producing tropical fruits (mainly pineapple).

The S. Miguel, Azores 6 x 200 m^2 demonstration greenhouses from INOVA Institute formerly heated with the geothermal effluent of Pico Vermelho pilot geothermal power plant (Rodrigues, 1998) is no more in operation. Since 2006 all effluent is re-injected.

4.2.3 Bathing and Swimming

Balneological activities using thermo-mineral waters are quite popular in Portugal for cure and touristic purposes. About 30 Thermal Baths are operating within a legal framework. Most are open only in summer, but some of them are operating normally all over the year. All the balneological activity inside the baths is carried out under strict medical control.

Since 2004 the INOVA Institute and the Azores Government undertake several initiatives and studies allowing the exploitation and valuing of the Azorean low temperature geothermal resources for direct use, including touristic activities and balneology. Resulting from these activities (Nunes et al., 2007) new shallow wells were carried out in Ferraria (S. Miguel), Varadouro (Faial) and Carapacho (Graciosa).

4.3 Ground Source Heat Pumps

There is no data before 2009, but the number of GSHP's registered installations till 2012 is small. At the end of 2012 there were only 13 installed systems registered in APIRAC, the Portuguese Refrigeration and Air Conditioning Association. It is true that in the residential sector a greater number of small installations are performed each year, but are not registered.

At this moment DGEG is preparing new regulations for shallow geothermal purposes, including the obligation to register all new GSHP's installations. In the near future statistical data off new installations will be more realistic.

Three examples of GSHP's installations, from different types, are presented below.

The first example is an installation on the Superior School of Technology of Setúbal (EST Setúbal) from the Polytechnic Institute of Setubal, that was a partner in GROUNDHIT European Project (6th Framework Program), as a demonstration site for high energy efficiency GSHP's. Two GSHP's of 15 KW_{th} for heating and 12 KW_{th} for cooling, each, were installed in the thermodynamics laboratory (Figure 7), to acclimatize 7 office rooms with areas between 13 and 17 m^2 and 2 classrooms with 63 and 65 m^2 and 50 places each.

The project aimed monitoring the prototype of improved energy efficiency heat pumps (COP higher than 5.5) in real conditions in a Mediterranean climate, and test two different Boreholes Heat Exchangers (BHE) types: double-U pipes and coaxial pipes.

The demo site results showed that GSHP's COP is according to the expected ones during the design phase (COP of 5.19 for cooling and 6.05 for heating in real conditions), with a good performance in the terminal units (fan-coils, secondary circuit), boreholes (primary circuit) and GSHP.

The second example is another European project (7th Framework Program) called GROUNDMED, that aims verifying sustainability of heat pump technology for heating and cooling of buildings in a Mediterranean climate.

Figure 7: GSHP's installation at EST Setúbal

The Portuguese GROUNDMED installation is set on a regional authority administration building with offices and laboratories, located in Coimbra city. One GSHP with a heating capacity of 56 kW_{th} and cooling capacity of 61 kW_{th} (Eurovent conditions) serves the building 3rd floor offices (Figure 8). The GSHP is coupled to seven double U, 125 m vertical borehole heat exchangers. The heating/cooling distribution system consists of 33 ceiling Coanda effect fan coil units with high efficiency permanent magnet EC motors, installed in 22 offices, with a total area of 600 m^2. Since all systems were designed to function with moderated temperatures the real cooling capacity is 63.5 kW_{th} and the real heating capacity is 70.4 kW_{th}, resulting in an increased performance.

This project is currently ongoing and there is no sufficient data to give final results.

Figure 8: GSHP installation at Coimbra demo-site

Finally the third example is an installation for heating, cooling and domestic hot water production in Sines Tecnopolo – Business Innovation Centre at Sines city (Figure 9).

Figure 9: BHE drilling at Sines Business Innovation Centre

This complex has an existing renewed building with 251 m^2, a laboratory building with 534 m^2 and an office building with 1,286 m^2, all served by GSHP's.

The existing renewed building is served by one GSHP with a heating capacity of 24.5 kW_{th} and cooling capacity of 18.4 kW_{th}, coupled to 2 simple U, 150 m vertical borehole heat exchangers.

The installation in the laboratory building is formed by one GSHP with a heating capacity of 50.8 kW_{th} and cooling capacity of 38.0 kW_{th}, connected to 3 simple U, 150 m vertical borehole heat exchangers. This GSHP also produces domestic hot water.

In the office building two GSHP are installed, with a total heating capacity of 76.0 kW_{th} and a total cooling capacity of 115.5 kW_{th}, connected to 10 simple U, 150 m vertical borehole heat exchangers.

The heating/cooling distribution system is made by two tube fan coils in all buildings.

5. Conclusions

The below conclusions follow basically those by Cabeças et al. (2010), as no significant events occurred afterwards.

In the Azores islands, close to 30 years after the beginning of the exploitation of geothermal resources for power generation at the Ribeira Grande field, the contribution of this energy source assumes an extremely relevant role. The most outstanding features from the last five years include:

• The installed capacity was expanded from 16 MW net to 23 MW net, with the new 10 MW net Pico Vermelho plant;

• The annual production more than doubled in this period, increasing from approximately 80 GWh to 185 GWh, due to the high productivity wells drilled in the sector of Pico Vermelho;

• The contribution of the geothermal source represents today 22% of the power generated in the Azores archipelago;

• Deep drilling in the Pico Alto geothermal area was developed but the presence of a productive reservoir, at an industrial scale, is not yet confirmed.

Finally, it should be emphasized that the geothermal generation costs are extremely competitive in the Azores, due to its remote location, and allowed significant savings.

In the Mainland, the geothermal exploration and exploitation has been quite stable during the period 2005-2013. Only three "deep" wells were drilled in that period at existing Spas (Carvalhal, 600 m; Unhais da Serra, 750 m; and Fonte Santa de Almeida, 931 m). The results were: (i) a spectacular increase of temperature and flow rate at Carvalhal (from 3 l/s at 44.4 ºC to 6 l/s at 60 ºC (Ferreira Gomes, 2007); (ii) unsuccessful at Unhais da Serra; and (iii) appreciable flow rate and temperature increase (2 to 4 l/s and 19 ºC to 31 ºC) at Fonte Santa de Almeida (Personal Communication Prof. J.A Simões Cortez, 2013).

Concerning GSHP's the potential is huge but not exploited. There are a few installations registered until 2012, but this tends to change due to the preparation of new legislation for regulating shallow geothermal operations. That will allow future statistical data to be more realistic and contribute to ameliorate the quality of the operations.

References

A. CAVACO: Projecto EU Project-DIS-1038-96-IR "To Promote the Use of Geothermal Energy from Proven Aquifers and Match This Energy to Existing or Potential Heat Users". *Report for CEEETA*, Lisboa, (1998), 32 pp. + annexes.

Aires-Barros, L. and Marques, J.M.: Portugal country update. *Proceedings of the World Geothermal Congress 2000*, Kyushu-Tohoku, Japan, (2000), 39-44.

Bicudo da Ponte, C.: Aproveitamento de recursos geotérmicos para a produção de electricidade nos Açores. *Ingenium*, Set/Out, (2012), 64-67.

Cabeças, R.P.M. and Henneberger, R.C.: Dealing with geologic uncertainties in drilling geothermal wells; a case history from the Azores. *Geothermal Resources Council Transactions*, **25**, (2001), 291-296.

Cabeças, R., Carvalho, J.M. and Nunes, J.C.: Portugal country geothermal update. *Proceedings of the World Geothermal Congress 2010*, Bali, Indonesia, (2010), paper #0165, 10 pp.

Carvalho, J.M.: Low temperature geothermal reservoirs in the Portuguese Hercynian Massif. *Proceedings of the World Geothermal Congress 1995*, Florence, Italy, (1995), 1343-1348.

Carvalho, J.M.: Portuguese geothermal operations: a review. *European Federation of Geologists Magazine*, **3-4**, (1996), 21-26.

Carvalho, J.M.: Combination of different heat users: principles and Portuguese case studies. Economy of Integrated Geothermal Projects, International Summer School, Course Text-Book. INOVA, Azores, (1998).

Carvalho, J.M.: *Prospecção e pesquisa de recursos hídricos subterrâneos no Maciço Antigo Português: linhas metodológicas*. Universidade de Aveiro, 292 pp, PhD Thesys, (2006), http://biblioteca.sinbad.ua.pt/teses/2007000122.

Carvalho, J.M., Berthou, P. and Silva, L.F.: Introdução aos recursos geotérmicos da região de Lisboa, in: Livro de Homenagem ao Prof. Carlos Romariz, 332-356, *Secção de Geologia Económica e Aplicada, Departamento de Geologia/FCUL*, Lisboa, (1990).

Carvalho, J.M. and Carvalho, M.R.: Recursos Geotérmicos e seu Aproveitamento em Portugal. *Cadernos do Laboratório Xeolóxico de Laxe*, 29, Corunha, (2004), 97-117.

Carvalho, J.M., Monteiro da Silva, J.M., Bicudo da Ponte, C.A. and Cabeças, R.M.: Portugal country geothermal update. *Proceedings of the World Geothermal Congress 2005*, Antalya, Turkey, (2005), paper #0170, 11 pp.

Correia, A., Ramalho, E., Rodrigues da Silva, A.M., Mendes-Victor, L.M., Duque, M.R., Aires-Barros, L., Santos, F.M. and Aumento, F.: Portugal, in: Atlas of Geothermal Resources in Europe, Hurter, S. and Haenel, R. (Eds.), 47-49, *GGA Publishers*, Hannover, Germany, (2002).

Costa, L.R. and Cruz, J.A.: Geotermia de baixa entalpia em Portugal: situação presente e perspectivas de evolução. *Boletim de Minas*, **37 (2)**, Lisboa, (2000), 83-89.

Ferreira Gomes, L.M.: Elementos construtivos e hidráulicos da nova captação de água mineral das Termas do Carvalhal, Castro Daire. *Boletim de Minas*, **42 (2)**, Lisboa, (2007), 137-148.

GeothermEx, Inc.: Assessment of the geothermal resource supplying the Ribeira Grande Geothermal Power Project, São Miguel, Açores. *Report for SOGEO-Sociedade Geotérmica dos Açores S.A.*, July, 1996.

GeothermEx, Inc.: Update of the conceptual and numerical model of the Ribeira Grande geothermal reservoir, São Miguel, Açores. *Report for SOGEO-Sociedade Geotérmica dos Açores S.A.*, December 2008.

IGM: Recursos geotérmicos em Portugal Continental: Baixa entalpia. *Instituto Geológico e Mineiro*, Lisboa, (1998), 23 pp.

Lourenço, C.: Aproveitamentos geotérmicos em Portugal Continental. *Proceedings of the "XV Encontro Nacional do Colégio de Engenharia Geológica e de Minas da Ordem dos Engenheiros"*, Ponta Delgada, Azores, Portugal, (2005), 9 pp.

Nunes, J.C.: Notas sobre a geologia da Ilha Terceira (Açores), *Açoreana*, **9 (2)**, Ponta Delgada, (2000), 205-215.

Nunes, J.C.: Geologia, in: Atlas Básico dos Açores, Forjaz, V.H. (Ed.), 60-62, *Observatório Vulcanológico e Geotérmico dos Açores*, Ponta Delgada, (2004).

Nunes, J.C., Carvalho, J.M., Carvalho, M.R., Cruz, J.V., Freire, P. and Amaral, J.L.: Aproveitamento e valorização de águas termais no Arquipélago dos Açores, in: O Valor Acrescentado das Ciências da Terra no Termalismo e no Engarrafamento da Água. II Fórum Ibérico de Águas Engarrafadas e Termalismo, Chaminé, H.I. and Carvalho, J.M. (Eds.), 209-230, *Departamento de Engenharia Geotécnica/Laboratório de Cartografia e Geologia Aplicada (LABCARGA), Instituto Superior de Engenharia do Porto*, Porto, (2007), ISBN: 978-989-20-0892-9.

Nunes, J.C., Lima, E.A. and Medeiros, S.: *Carta de geossítios da Ilha de Santa Maria*. 1/50,000 scale. Universidade dos Açores, Departamento de Geociências (Ed.). ISBN: 978-972-8612-47-4, (2008).

Rodrigues, A.C.: Geothermally heated greenhouses at Ribeira Grande (Azores) Portugal, in: Heating Greenhouses with Geothermal Energy. International Summer School on Direct Application of Geothermal Energy, Popovski, K. and Rodrigues, A.C. (Eds.), 433-441, *INOVA Institute*, Ponta Delgada, Azores, (1998).

Ribeiro, A. and Almeida, F.M.: Geotermia de baixa entalpia em Portugal Continental. *Geonovas*, **1 (2)**, Lisboa, (1981), 60-71.

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Tables A-G

Table A: Present and planned geothermal power plants, total numbers

	Geothermal Power Plants		Total Electric Power in the country		Share of geothermal in total	
	Capacity (MW_e)	Production (GWh_e/yr)	Capacity (MW_e)	Production (GWh_e/yr)	Capacity (%)	Production (%)
In operation end of 2012	23	185	*Est* 9000	*Est* 55000	0,25	0,33
Under construction end of 2012						
Total projected by 2015	23	185				

Table B: Existing geothermal power plants, individual sites

Locality	Plant Name	Year commiss.	No of units	Status	Type	Total inst. Capacity (MW_e)	Total running cap. (MW_e)	2012 product. (GWh_e/y)
Ribeira Grande	Ribeira Grande	1994/1998	4	O	B-ORC	15	10	85
Ribeira Grande	Pico Vermelho	2006	1	O	B-ORC	13,5	13	100
total						28,5	23	185

Key for status:		Key for type:			
O	Operating	D	Dry Steam	B-ORC	Binary (ORC)
N	Not operating (temporarily)	1F	Single Flash	B-Kal	Binary (Kalina)
R	Retired	2F	Double Flash	O	Other

Table C: Present and planned geothermal district heating (DH) plants and other direct uses, total numbers

	Geothermal DH Plants		Geothermal heat in agriculture and industry		Geothermal heat in balneology and other	
	Capacity (MW_{th})	Production (GWh_{th}/yr)	Capacity (MW_{th})	Production (GWh_{th}/yr)	Capacity (MW_{th})	Production (GWh_{th}/yr)
In operation end of 2012	1,5	3,9	1,0	3,5	25,3	88,6
Under construction end of 2012						
Total projected by 2015	1,5	3,9	1,0		25,3	

Table D: Existing geothermal district heating (DH) plants, individual sites

Locality	Plant Name	Year commiss.	Is the heat from geo-thermal CHP?	Is cooling provided from geo-thermal?	Installed geotherm. capacity (MW_{th})	Total installed capacity (MW_{th})	2012 geo-thermal heat prod. (GWh_{th}/y)	Geother. share in total prod. (%)
Chaves			no	no	*Est* 0,75			
S Pedro do Sul			no	no	*Est* 0,75			
Alcafache			no	no	A few kw			
Longroiva					A few kw			
total					*Est* 1,5		4,0	

Table E: Shallow geothermal energy, ground source heat pumps (GSHP)

	Geothermal Heat Pumps (GSHP), total			New GSHP in 2012		
	Number	Capacity (MW_{th})	Production (GWh_{th}/yr)	Number	Capacity (MW_{th})	Share in new constr. (%)
In operation end of 2012	13 est.	0,15 – 0,50 est.	0,22 – 0,73 est.	Not available	Not available	Not available
Projected by 2015	n/a	n/a	n/a			

Table F: Investment and Employment in geothermal energy

	in 2012		Expected in 2015	
	Investment (million €)	Personnel (number)	Investment (million €)	Personnel (number)
Geothermal electric power	Not available	Not available	Not available	Not available
Geothermal direct uses	few	few	few	few
Shallow geothermal	few	few	few	few
total				

Table G: Incentives, Information, Education

	Geothermal el. power	Geothermal direct uses	Shallow geothermal
Financial Incentives – R&D	DIS	DIS	DIS
Financial Incentives – Investment	DIS	DIS	DIS
Financial Incentives – Operation/Production	REQ	REQ	REQ
Information activities – promotion for the public	no	no	FP7 GROUNDMED Project
Information activities – geological information	no	-	-
Education/Training – Academic	-	-	-
Education/Training – Vocational	-	-	-

Key for financial incentives:

DIS	Direct investment support	RC	Risc coverage	FIP	Feed-in premium
LIL	Low-interest loans	FIT	Feed-in tariff	REQ	Renewable Energy Quota