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Low enthalpy projects in The Azores Islands (Portugal): a contribution to the enhancement of renewable energy

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ABSTRACT

Surface geothermal manifestations in Azores (fumaroles, thermal springs and wells) are spread around the islands of S. Miguel, Terceira, Faial, Pico, Graciosa and Flores. A few of the existing thermal springs are used in balneotherapy and balneology, at least since the XVIII century. At present, the thermal baths of Ferraria and Caldeiras da Ribeira Grande (at S. Miguel Island) and Carapacho (at Graciosa Island) are operating regularly.

The surface geothermal manifestations of low enthalpy are characterized by thermal springs (discharging from perched-water bodies at altitude and from basal aquifers near the seashore), low-temperature fumaroles, boiling mud-pools and gas (mostly CO_2) ground-emissions.

Geothermal direct uses in Azores are still limited by several factors, including sociological, cultural and demand constrains that did not enable the spreading of the technology.

1. INTRODUCTION

Surface geothermal manifestations in Azores are spread around the islands of S. Miguel, Terceira, Graciosa, Faial, Pico and Flores. Thirty five thermal waters are reported in those islands, and in Pico island only steam emissions occur (Fig. 1). Particularly impressive is the site of Furnas at S. Miguel Island, with the presence of numerous thermal springs and fumaroles. Furthermore, a number of water wells, drilled for water supply purposes, tap thermal water in the islands of Faial, Terceira and Graciosa. The thermal manifestations are largely controlled by active faulting and almost dependent on the high enthalpy geothermal systems, characterized by the presence of boiling deep aquifers.

A few of the existing thermal springs are used in balneotherapy and balneology, at least since the XVIII century. At present, the thermal baths of Ferraria and Caldeiras da Ribeira Grande, at S. Miguel Island, are operating regularly, as well as a number of small thermal occurrences developed as thermal bath touristic attractions (eg Caldeira Velha and Poça da Dona Beija). The Carapacho thermal bath, located at Graciosa Island is also operating normally. The Furnas bath at S. Miguel Island, recently refurbished, is not operating due to administrative and economical reasons. At Faial, the Varadouro bath is closed since 2003.

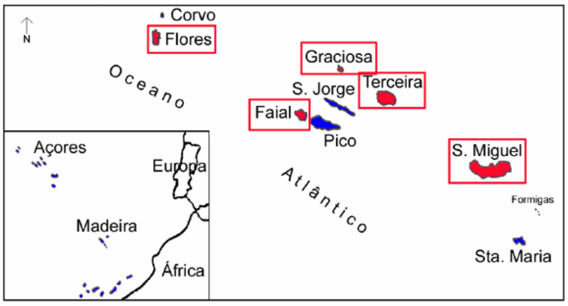

Figure 1: Azores island location. Islands with thermal springs and wells are outlined.

The scientific knowledge of the low enthalpy geothermal occurrences in Azores is quite recent (nineties of the last century) and is due to investigations carried out by the Azores University and by the INOVA, an institute for technological innovation. INOVA is developing a programme in the most significant thermal sites, including volcanological and hydrogeological studies, site investigation (geoelectrical surveys), and sitting and drilling water wells for balneotherapy and geothermal applications. Particularly, this was the case at Ferraria (S. Miguel Island) and Carapacho (Graciosa Island) where small direct uses are in operation (swimming pool and recreation uses).

A number of geothermal feasibility studies were performed showing that those resources are adapted to the geothermal demand and could be an efficient alternative for heating purposes.

No geothermal heat pumps (GSHP) applications are known in the Azores archipelago.

2. HYDROGEOLOGICAL AND GEOTHERMAL CARACTERIZATION

The Azores archipelago is located in a complex geodynamic setting, characterized by the proximity to the triple junction between the North American, African and Eurasian plates. The volcanic and seismic activities are the factors responsible for the occurrence of the geothermal systems.

The surface geothermal manifestations of low enthalpy are characterized by thermal springs, discharging from perched-water bodies at altitude and from basal aquifers near the coast line, low-temperature fumaroles, boiling mud-pools and gas (mostly CO_2) ground-emissions. Figures 2 to 6 show the geographical location and the general volcanic setting after Nunes (2004) of these manifestations, including of several research and exploitation wells for thermal bath utilities promoted by the Azores Regional Government or the INOVA Institute (Ferraria AC2 and AC3 in S. Miguel and Carapacho AC1, PS2 and PS3 in Graciosa), and holes drilled for drinking water supply that have highlighted other thermal events (e.g. Capelo AC4 in Faial, Posto Santo in Terceira and Courelas in Graciosa).

These manifestations are largely controlled by active faulting and almost dependent on the high enthalpy geothermal systems, characterized by the presence of deep aquifers with water at about 150-160°C in Furnas Volcano (S. Miguel), 220-250ºC in the Fogo Volcano (S. Miguel) and 250-300ºC in Pico Alto Volcano (Terceira) – Forjaz (1994); Carvalho (1999), Cruz, et al. (1999); Cruz and França (2006).

These high temperature systems are water dominant, with boiling water in the reservoir and/or boiling during the up flow to the surface, releasing gas and steam into the shallow aquifers, contributing for heating and acidification of the shallow waters.

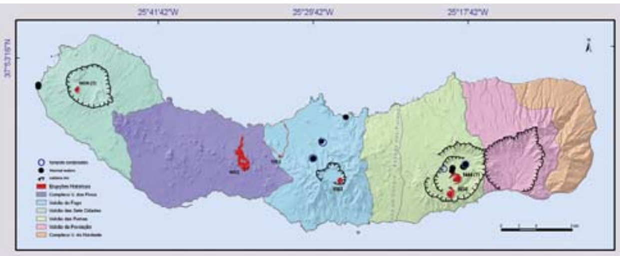

Figure 2: Location of the S. Miguel Island thermal springs, wells and fumaroles. Adapted from Nunes *et al.* (2007). In red/*A.D.* date: historical eruptions.

The physic-chemical characteristics of the thermal water are directly related to the water-rock interactions in the aquifer, the upflow conditions, absorption of magmatic/mantelic volatiles, namely CO_2(g) and H_2S(g), contamination with vapor enriched in these volatiles and mixing with other waters (Cruz et al., 1999, Carvalho, 1999, Cruz 2004, Cruz and França, 2006). The acidification promoted by the acid gas input of mantle origin (Ferreira and Oskarsson, 1999, Carvalho, 1999, Carvalho et al., 2011a, Carvalho et al., 2011b), is suggested to be primarily the cause for extensive rocks leaching. This phenomenon allows the temperature evaluation of the thermal reservoir using aqueous geothermometers.

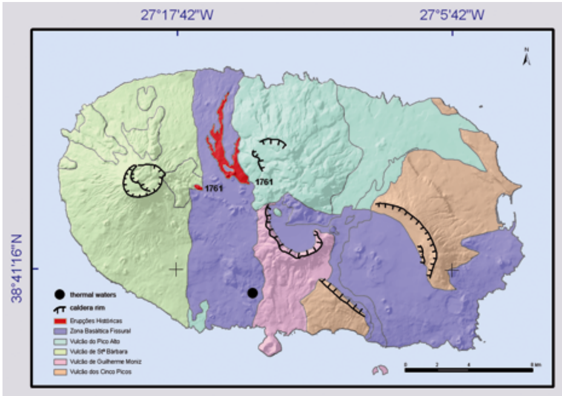

Figure 3: Location of the Terceira Island thermal well. Adapted from Nunes *et al.* (2007). In red/*A.D.* date: historical eruptions.

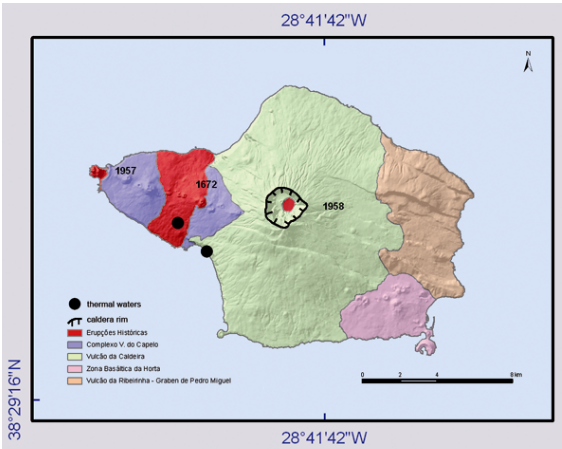

Figure 4: Location of the Faial Island thermal springs and wells. Adapted from Nunes *et al.* (2007). In red/*A.D.* date: historical eruptions.

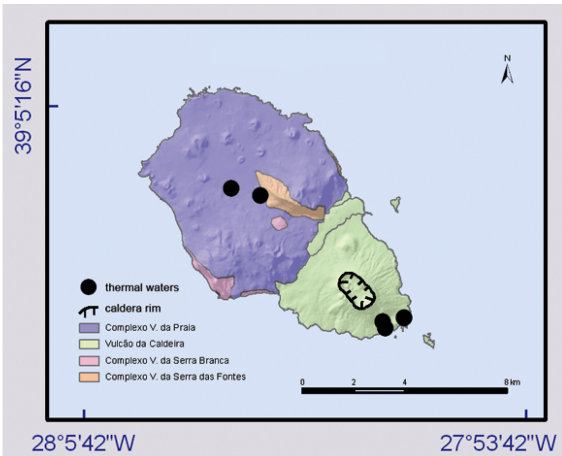

Figure 5: Location of the Graciosa Island thermal springs and wells. Adapted from Nunes *et al.* (2007).

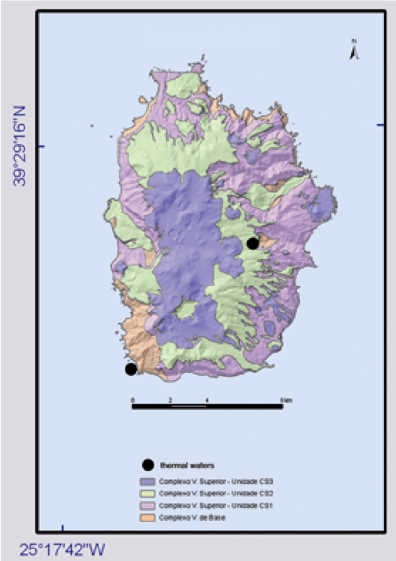

Figure 6: Location of the Flores Island thermal springs. Adapted from Nunes *et al.* (2007).

A detailed description of the characteristics of the Azores thermal waters can be found in Nunes et al. (2007). A brief summary is presented in Tables 1 and 2.

Hyperthermal waters, with temperature between 90 and 100ºC, basic pH, high mineralization showing electric conductivity between 1900 and 2900 µS/cm, HCO_3-Cl-Na type, significant concentration of reduced sulfur species (H_2S, HS^- and S^{2-}) and trace elements present at high levels, especially B and As (Carvalho et al., 2006) are located in Furnas volcano, S. Miguel island (eg Caldeira Grande and Caldeira do Asmodeu – Table 1).

These waters, that had supplied the thermal bath at Furnas village, represent boiling water ascending from a relative shallow aquifer depth of about 165 m and under a pressure of 16 bar, and 160ºC of temperature (Cruz et al., 1999, Cruz and França, 2006).

Thermal waters discharging from perched water bodies are typically steam-heated waters, and the composition is directly related with the acidic leaching, dependent on the amount of volcanic gas dissolved, and residence time. The temperature is usually below 75°C, the pH varies between 4 and 7, medium to high mineralized (electric conductivity between 250 and 1700 µS/cm), depending on the rock-water interaction. These waters are of Na-HCO_3 type (Fig. 7), but enriched in sulfate and reduced sulfur; are characterized also by high concentrations of species easily present in the vapor phase, such as CO_2, H_2S, NH_4 and B, and metals such as Al, Fe, Mn, leached from the volcanic rocks. Caldeira Velha spring (spr) (Fogo Volcano) and Torno, Morangueira and Terra Nostra 2 springs (Furnas Volcano) are examples of this type of waters.

Table 1. Summary characterization of the Azores thermal waters. Data from INOVA and Carvalho, 1999 (1), INTERTEC, 1995 (2), Freire, 2006 (3), Coutinho, 2000 (4) and Azevedo, 1998 (5).

	pH/T ºC	Cond. µS/cm	Tot. CO_2 mg/l	SiO_2 mg/l	Cl mg/l
S. Miguel Island - Furnas Volcano					
Agua Prata	5.4/32.8	322	1092	126	18
Caldeirão	6.43/75.3	479	403	236	32
Terra Nostra I	5.82/41.4	507	693	107	52
Terra Nostra II (Poça da Dona Beija)	5.82/38.7	513	622	108	58
Caldeira Grande	8.05/98.2	2350	524	352	282
Caldeira do Asmodeu	7.03/93.2	2670	506	329	250
Quenturas I	6.6/59.1	1258	1003	223	69
Quenturas III	6.32/57.6	1286	997	257	73
Torno	6.6/39.9	1339	1021	162	84
Grutinha I	6.2/42.3	1344	1277	139	82
Grutinha II – Esq.	6.2/44.5	1155	1093	191	75
Grutinha II – Centro	6.2/44.3	1167	1147	232	75
Grutinha II – Dta.	6.2/42.4	1306	1227	154	80
Água da Poça	6.4/45.1	1450	1198	197	88
Morangueira	6.4/35.4	1601	1249	192	90
Sanguinhal	5.63/36.7	567	1032	163	32
Padre José	5.34/59.5	764	705	267	34
Água Santa	7.65/93.2	897	249	234	77
Caldeira do Esguicho	7.79/97.3	1592	480	278	195
Caldeira dos Vimes	5.35/73	310	497	84	16
S. Miguel Island - Fogo Volcano					
Caldeira Velha (spring)	4.5/33.8	157	562	51.7	15
Ladeira da Velha (1)	4.10/31	290	1227	125	19
Pocinha (Cald. Rib. Grande Férrea)	4.0/27.2	211	699	91.3	20
S. Miguel Island - Sete Cidades Volcano					
Ferraria	6.5/52.8	42000	499	93	17200
Ferraria AC2 well	6.10/58	27000	438	143	10500
Ferraria AC3 well	6.2/62.1	27400	895	181	10300
Terceira Island					
Posto Santo well (2)	6.75/37	1941	32	140.2	90.0
Graciosa Island					
Courelas well	3.7/39.5	6500		19	2500
Pontal well (3)	7.82/27.5	12000			
Carapacho	7.2/40	11100	517	141	3620
Carapacho AC1 well	6.7/45.2	41000	952	147	16535
Carapacho PS2 well	6.5/37.6	11900	641	127	4110
Carapacho PS3 well	6.6/40.8	15400	589	125	5470
Homiziados I (3)	6.37/53.2	43100			
Homiziados II (3)	6.75/38.6	13100			
Faial Island					
Varadouro (4)	6.09/35.1	6570	654	74.85	2016
Capelo AC4 well	6.5/39.6	6700	282	141	1907
Flores Island					
Poio Moreno (5)	6.50/24.8	1255			44
Lajedo	7.04/48	7000	362	82	2470

Table 2. Condensates of the major fumaroles of The Azores. Data from INOVA and Freire, 2006 (1).

	pH/T ºC	Cond. µS/cm	SiO_2 mg/l	Cl mg/l	SO4 mg/l
S. Miguel Island - Fogo Volcano					
Caldeiras da Ribeira Grande	2.46/59.8	1820	240	22	4600
Caldeira Velha	3.47/61.8	357	42	15	25
S. Miguel Island - Furnas Volcano					
Caldeira da Lagoa das Furnas	4.44/94.5	2070	268	17	290
Caldeira Barrenta	2.7/85.5	1394	435	3.7	330
Caldeira da Ribeira Tambores	2.87/96.7	2300	536	125	420
Caldeira Água Santa (1)	?/80.0	2400			786

The thermal waters discharging from basal aquifers systems emerges at the sea level and evolves by mixing with seawater, although processes such as absorption of magmatic volatiles (CO_2) and rock leaching contributes to their chemical composition and very high mineralization. These waters have temperatures between 24 and 60ºC and Na-Cl type; are neutral to slightly acidic (pH<7), with significant dissolved CO_2(g) and strongly enriched in Sr and Mn and, comparatively, low concentrations in Al, Fe and As. The mineralization degree is dependent on sea water mixing and rock leaching, and the dissolved silica varies between 75 and 230 mg/l.

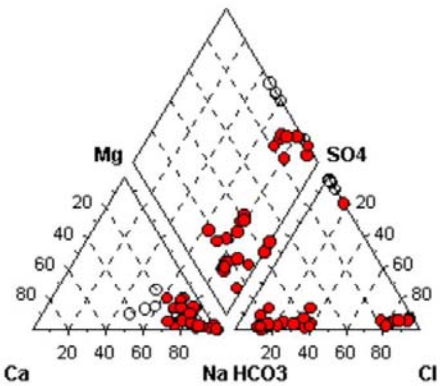

Figure 7: Piper diagram plot of The Azores thermal waters (•) and fumarole condensates (o).

The fumaroles are direct discharge of arising hydrothermal steam and volcanic gases, which condenses on the surface or is mixed with water from precipitation, water runoff and water in soils, and can be represented by Caldeira de Asmodeu, Caldeira da Lagoa Furnas (Furnas Volcano, S. Miguel), Caldeiras da Ribeira Grande, Caldeira Velha fumaroles (Fogo Volcano, S. Miguel) and Furna do Enxofre (Graciosa). The gas composition of fumaroles is strongly dominated by carbon dioxide, with hydrogen sulphide, hydrogen and nitrogen as minor components (Ferreira, 1994). Cooling and oxidation of the steam result in the formation of acid (pH < 3), hot (≈70ºC-90ºC) condensates, extremely high concentrations of sulphate and reduced sulfur species, and very low concentrations of chloride. The condensate display variable degree of mineralisation, as a result of mixing of deep vapours/gases with superficial/groundwater and of the progression of hydrothermal alteration processes in hosting rocks. The representation of the ionic composition of the condensate on a Piper diagram (Fig. 7) clearly shows a Na-Ca-SO_4 type water, quite distinct from all other mineral waters.

The hosted rocks acidic leaching allows the development of thick clay deposits that have been used in some thermal bath facilities for mud-therapy purposes, namely at Furnas and Caldeiras da Ribeira Grande in S. Miguel Island.

3. CARRIED OUT INVESTIGATIONS

Since 2004, the INOVA Institute undertakes 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) – Table 3. Besides the wells indicated in Table 3, other were drilled and cased but not equipped with a pump and monitoring system: wells AC2 in Ferraria (same thermal water as AC3), PS1 in Carapacho (sea water), and PS3 in Varadouro (same water as PS4).

Table 3. Main characteristics of thermal wells controlled by the INOVA Institute.

Well Name/Site	Date	Altitude (m)	Deep (m)	Ø	pH/T (ºC)	Yield (L/s)
AC3 Ferraria	2002	15	30.55	8”/6”	6.2/62.1	5
AC1 Carapacho	2004	89	111.25	6”	6.7/45.2	4
PS4 Varadouro	2004	8	11.5	6”	6.3/21	3
PS2 Carapacho	2007	36	36.5	6”	6.5/37.6	2.5
PS3 Carapacho	2007	28	29.5	6”	6.6/40.8	0.5

In 2013, at Ferraria, a 55 m deep sea water well is being equipped to feed the Thermal Bath and, thus, reproduce (in the inside and outside swimming pools) the thalassotherapy conditions existing in the natural littoral swimming pool, known and used by the populations and visitors since many decades/centuries.

At Carapacho, and taking profit of the ~45ºC AC1 well water, a small recreational structure was emplaced in the littoral swimming area, one of the most visited of the Graciosa Island.

Even not directly related to a specific thermal bath exploitation, INOVA Institute made a detailed physic-chemical and bacteriological characterization of almost all the thermal waters in The Azores (see Tables 1 and 2), with special emphasis on those located in the Furnas volcano caldera (mystic and most visited place of the Archipelago) and Caldeiras da Ribeira Grande and Caldeira Velha recreational areas, on the Northern slopes of Fogo Volcano.

As a very promising thermal spot, INOVA undertook several studies in the Posto Santo well (including a video inspection), located about 2 km NW from Angra do Heroísmo downtown (Terceira Island), the second most populated city and island of the Archipelago. This is a 159 m deep well, drilled in 1995, with thermal water at ~39ºC, 6.86 pH and 1.8 mS/cm electrical conductivity.

4. FEASIBILITY STUDIES AND DIRECT USES

In The Azores, due to the volcanic evidence of the resource and the mild climate of the islands, the prevalent concept among decision makers was that geothermal is only a promising (and proven) technology to produce electricity. So no effective efforts were done, for instance, to utilise the geothermal brines of the geothermal power plants in direct uses in spite of the town of Ribeira Grande (the second in S. Miguel) be located nearby the geothermal power plant of Pico Vermelho. Furthermore in the busiest Thermal Baths as Furnas, Caldeiras da Ribeira Grande, Ferraria and Carapacho the heating facilities, in most cases, were conceived without considering the opportunity of using geothermal energy.

The conception, execution and maintenance of a given geothermal operation is a multidisciplinary, time-consuming and arduous task involving the following main activities: (i) resource investigations, (ii) surface installations design, and, (iii) economical considerations.

Last but not the least, other subsidiary activities play a relevant role for tacking a final decision: monitoring to control performance of reservoir, surface installations and environmental constraints; skills and ability to encourage users, planners and politicians to "embark" in the geothermal venture.

More than a sophisticated amalgam of technologies to provide adequate (technical and economically) answers to promote energetic savings, geothermal operations must be seen as an instrument to help the management of the earth resources, thus increasing quality of life in a medium to long term. So, a good geothermal project is the best compromise between resource and utilization without environmental damages, and allowing the rational use of the natural resource.

An important issue to take in account when developing a given geothermal project is its replicability, say the potential for dissemination of the technology.

The savings, and particularly the energetic savings, play a major role in the study of new geothermal operations. However other points must be considered, as other savings, the positive environmental impacts and also socioeconomic impacts (Bloomquist, 1995).

Among the economic characteristics of geothermal energy are the high capital investments required and the long period of plant amortization. The technical factors determining the success or failure of a project depend mainly on the exploitation of the subsurface (eg flow rate and temperature of the resource). Thus, after drilling, the risk that the geothermal resource will have insufficient production and/or temperature characteristics, rendering the operation unprofitable, is commonly known as the geological, or mining, risk.

In The Azores the geological risk is quite low, and in several sites the resource is already available for balneological or balneotherapic uses, so the lack of utilization in direct use is related to lack of planning at several levels.

Taking into account the difficulties to develop direct use project in The Azores as previously described, INOVA Institute leaded and encouraged the dissemination of this kind of approach in the archipelago. The first attempt was the so called "Ribeira Grande Greenhouses Experimental Field", the INOVA 5 x 200 m^2 demonstration greenhouses complex, financed by the THERMIE Program (Rodrigues and Popovsky, 1996; Rodrigues, 1998).

Running from 1997 to 2005, this complex used geothermal brines coming from the nearby Pico Vermelho Geothermal Plant. Since 2006 and with the new 13 MWe Pico Vermelho power plant all effluent is re-injected and the INOVA greenhouses complex was no longer nourished with geothermal brine.

When operating, the greenhouses complex used waste water at 90ºC from the neighboring power plant (with a flow of 5.5 l/s) in a plate heat exchanger, to avoid incrustation problems inside the installation. In each greenhouse, heating was provided by "fan-jet" air and a soil heating system. Each fan-jet unit consists of a water/air heat exchanger with fan delivering warm air through a plastic pipe positioned below the roof and running the length of each greenhouse. The soil heating installation consists of corrugated plastic pipes buried 0.5 m below ground level in parallel lines, 0.3 m apart. Fully computerized automated regulation of all greenhouse parameters was installed taking into account the outside climate, which was measured by a small local weather station. The production consisted among others, on pineapples, cape gooseberries and melons. A nursery, propagation laboratory, coldstore, storerooms and a geothermal water distribution station were installed (Carvalho 1998).

The idea of install direct uses from the geothermal brines was later on (2003-2004) developed under the scope of the VULCMAC project, financed by the EU INTERREG III-B Program. At the time the rejected brines of Ribeira Grande and Pico Vermelho power plants were about 500 kg/s at 96ºC; that means a considerable capacity that should be used in cascade by several existing or potential users, including touristic purposes, industrial applications and a small district heating network.

The pay-back period for the different considered scenarios was in the range 4-8 years, considered quite interesting according to the Carella (1992) criteria.

Several factors unfavored the utilization of the fluids resulting from the geothermal power plants in direct use: (i) the geothermal brine precipitates – calcium carbonate and silica (Tulinius & Lasne 1993, Carvalho 1999) and also the saturation in iron, resulting in corrosion of the liner and casings of the wells, (ii) the composition of the geothermal fluid, that do not allow its direct use for indiscriminate balneological purposes, as temperature, pH, electrical conductivity, sulphide and arsenium are above the parametric values considered by the Portuguese law, (iii) the mild climate (average air temperature of 17ºC), and (iv) SOGEO, the geothermal operator, does not considers direct use as a priority.

For Ferraria (S. Miguel Island) and Carapacho (Graciosa Island), in 2008, following the drilling of new wells of thermal water to supply the existing thermal baths, INOVA carried out feasibility studies (CEDINTEC, 2008a; CEDINTEC, 2008b) to evaluate the possible execution of small direct uses, including hot tap water, leisure swimming pools and space heating.

Those studies indicate that for the AC1 well (111.25 m deep and located about 300 m North of the Carapacho thermal bath) its 41ºC temperature thermal water represents an available power of 0.3 MWt. At Ferraria, the 62ºC AC3 well (30.55 m deep) ensures an available power of 2.93 MWt. The results also demonstrated that, due to the fact that there was no need to invest in new drillings, the payback period was quite interesting, from 5 years (Carapacho) to 1 year (Ferraria).

It is worth mentioning that similar approaches applied to the Caldeiras da Ribeira Grande and Furnas thermal facilities point out available powers of 0.3 MWt and 1.5 MWt, respectively (Cabeças et al 2010)

Besides the geothermal direct uses, INOVA is promoting an extensive applied research, aiming the use and valuing of the thermal mud associated with the precipitation phenomena of thermal waters, namely from the Caldeiras da Ribeira Grande fumarolic field (eg Quintela et al., 2013). These studies are especially envisaged to the development of dermo-cosmetic formulations that, together with complementary research on pumice exfoliating products (eg soaps) allow the production on "Azorean Made" genuine, differentiate and high-quality products.

5. CONCLUSIONS

Geothermal direct uses in Azores are still limited by several factors, including sociological, cultural and demand constrains that did not enable the spreading of the technology.

However, the geothermal resource is so evident and the technical possibilities are so obvious in certain areas that it is expected in the near future that a number of projects will see the light.

Future projects must consider the global development of the geothermal resource, including balneotherapy and/or balneology, classical geothermal use according to the Lindal diagram (1973) and even pelotherapy and dermo-cosmetic uses.

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