A decade of geothermal commercial production from the Pico Vermelho power plant, São Miguel Island, Azores

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ABSTRACT

Over the last decade, geothermal has become the predominant renewable energy source of the Azores, with a contribution that consistently reaches up to 44% of the power generation in São Miguel Island, where it provides the baseload power needs. Here, the performance of the Pico Vermelho ORC geothermal power plant is a case study, operating 24 hours a day with a steady output that is 15% above the contractual power and with very low operating costs.

This paper presents the production results of the Pico Vermelho ORC geothermal power plant and characterizes its main environmental and economic benefits. Throughout its 11 years of operation, the power plant has achieved remarkable production results, with an annual power generation of about 100 GWh, a steady capacity factor above 95% and availability that is consistently over 99%. Comparing to the heavy fuel oil generation alternative, the geothermal production at Pico Vermelho is environmentally friendly, reducing the CO_2 emissions from power generation in São Miguel Island by 22%. Moreover, the geothermal production at Pico Vermelho has reduced fuel imports by about 25%, resulting in economic savings of more than 100 Million Euros. In a small-scale economy such as the Azores, the geothermal power generation has been of strategic importance, increasing the energy self-sufficiency of this remote Region and reducing its carbon footprint.

1. INTRODUCTION

The geothermal development in São Miguel Island, Azores, has been focused in the Ribeira Grande geothermal field (Figure 1). Here, the geothermal exploitation started with the operation of a small 3 MW pilot power plant (Meidav, 1981; Gandino et al., 1985) in the Pico Vermelho area, consisting in one back-pressure steam turbine designed by Mitsubishi Heavy Industries. The pilot plant utilized steam from only one well (PV1) and, due to its low productivity and to the repeated outages of the well for performing mechanical cleanouts of the calcite deposition inside the production casing, the pilot plant only generated an average net power of 0.8 MW and produced a total of 86,3 GWh (1980-2005). Nonetheless, the pilot plant was an important geothermal school and the learnings from its operation allowed to support the next stages of project development.

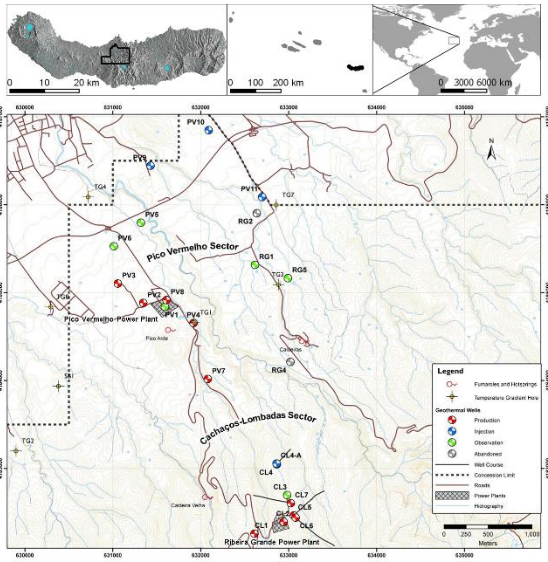

Figure 1: Ribeira Grande geothermal field.

The commercial geothermal power production started in 1994, when the Phase A of the Ribeira Grande power plant became online – 4 MW, and this power plant was later expanded to 13 MW (Phase B), in 1998 (Ponte, 2002; Kaplan et al., 2007). More recently, in 2005 the 3 MW pilot plant was dismantled, and it was replaced at the same site by the 10 MW Pico Vermelho power plant (Kaplan et al., 2007; Ponte et al., 2010), which went online in December 2006, increasing the total geothermal generation capacity in São Miguel Island to 23 $MW_{net.}$ Both utilize ORC binary technology and were provided by ORMAT. Over the last decade, the stable power output from Ribeira Grande and Pico Vermelho power plants have been providing up to 44% of the electricity needs of São Miguel Island (Rangel et al., 2011), operating at the base of the load diagram.

The Ribeira Grande geothermal system is characterized by a 245ºC two-phase liquid-dominated reservoir that can be tapped by relatively shallow wells (1-1,3 km depth). The system is emplaced in the northern flank of Fogo volcano, with the upflow zone inferred to be in the southeastern part of the field. From there, the high-temperature fluid moves northwestward, following the structure of Fogo volcano and probably with some degree of control by fracture zones associated with the graben of Ribeira Grande (Duffield, 1984; Gandino et al., 1985; Henneberger & Nunes, 1990; Granados et al., 2000; Pham et al., 2010). The main outflow takes place along a narrow zone to the west of the scoria cone of Pico das Freiras (Franco et al, 2018) and it ultimately discharges offshore the city of Ribeira Grande. In the Pico Vermelho area (Figure 1), the high-temperature reservoir can be reached by 1 km depth wells, tapping the outflow zone of the geothermal system. The resource is characterized by a fluid enthalpy of 900-1100 kJ/kg, with the total flow rates from the individual wells ranging from 100 to 150 t/h.

In this paper, we summarize the 10 MW Pico Vermelho power plant technology (Figure 2) and its production history, and we characterize its main environmental and economic benefits.

Figure 2: 10 MW Pico Vermelho power plant.

2. PICO VERMELHO POWER PLANT AND WELLFIELD

The Pico Vermelho geothermal power plant is a two-phase binary recuperated Organic Rankine Cycle (ORC), designed and constructed by ORMAT (Israel), in a turnkey contract, for EDA RENOVÁVEIS - the renewable power generation company of the Azores. The binary plant is composed by one turbo generator unit with a rated net power of 10 MW, using an axial flow turbine, and utilizes n-pentane as the working fluid and saturated geothermal steam and brine as the heat sources.

The n-pentane circulates in a closed loop, receiving thermal energy from the geothermal fluid. It enters the heat exchangers as compressed liquid and leaves them as saturated vapour, before its expansion in the turbine, where the kinetic energy from the flow is converted into mechanical energy, rotating the generator shaft and producing electricity. The process flow diagram of the Pico Vermelho power plant is described in detail by Kaplan et al., 2007.

The hot end of the working fluid cycle is given by the heat from the geothermal fluid. In the Pico Vermelho area, the geothermal wells reach 1 km depth, tapping a 235-245ºC resource from a relatively shallow reservoir. The wells are artesian, and the heat is brought to the surface by the geothermal fluid, which corresponds to a mixture of liquid hot water and steam. In each production wellpad, this mixture is separated, and the liquid hot water and the steam are carried to the power plant in separate pipelines, where they feed the power plant shell and tube heat exchangers (two brine preheaters and two steam evaporators). On the heat exchangers, the geothermal fluid flows inside the tubes, whilst the n-pentane circulates in the shell side, receiving the thermal energy from the geothermal fluid.

According to the power plant design (Figure 3), four centrifugal feed pumps pressurize and drive the n-pentane liquid from the condenser hot wells into the recuperator tube side, where it is initially heated by the n-pentane vapour stream from the turbine outlet. The liquid n-pentane is then carried into the pre-heaters, where it will be heated by the geothermal fluid (brine + steam condensate) until saturation and finally follows to the steam evaporator where boiling takes place. Finally, the n-pentane vapour flows into the turbine. After expansion in the turbine, the n-pentane vapor flows into the recuperator shell side and finally to the condenser, where it is air-cooled and condensed, releasing the remaining heat into the atmosphere (cold end of the secondary cycle), before it restarts a new cycle.

On the other hand, the saturated geothermal steam feeding the evaporator condenses and exits the tube sheet as a condensate, whereas the non-condensable gases are released to the atmosphere (vented at the evaporator). The geothermal steam condensate is then mixed the incoming brine before entering the preheaters.

The heat exchangers are fed by the geothermal fluid (steam and brine), produced by five wells (PV2, PV3, PV4, PV7, and PV8), at a temperature of about 150-155ºC (after separation). These are prolific wells, each one producing an average of 100-150 t/h of 200ºC of geothermal fluid at wellhead pressures ranging from 10-16 bar.g. After transferring its thermal energy into the n-pentane, the geothermal fluid (up to 460 t/h, corresponding to 94% of the produced fluids) is reinjected back to the high-temperature reservoir at 87ºC to avoid silica scaling, with the reinjection being divided into multiple wells. The reinjection area has good permeability and it is located at a lower elevation than the power plant, meaning that all the geothermal water is accepted without the need for pumping.

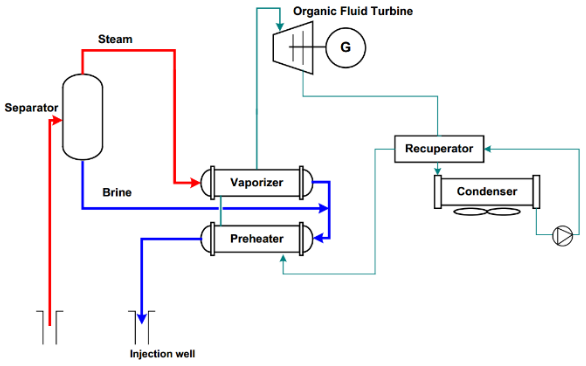

Figure 3: Pico Vermelho two-phase recuperated ORC flow diagram, as per ORMAT design (Kaplan, 2007).

In Pico Vermelho, initially, the reinjection was divided by wells PV5 and PV6 (located at ~500 m from the production area). However, a tracer test conducted in 2007 revealed a high risk of thermal breakthrough of the high-temperature reservoir due to the rapid and strong returns of reinjected fluids to the production area (Pham et al., 2010; and Ponte, 2010). To amend this, three new reinjection wells (PV9, PV10, and PV11) were drilled farther away from the production area (~1 km) and reinjection was relocated into these wells in 2014. The tracer testing was then repeated, and it indicated that reinjection returns were now not only slower but also weaker than of those observed in the 2007 test, confirming that the risk of cooling the production area has been minimized (Rangel et al., 2017).

3. PRODUCTION RESULTS

At the design point, the net power of the Pico Vermelho plant was estimated at 10 MW. This was based on the best information on well production available at the time of the project design phase (essentially discharge data from well PV1, but also from PV2 and PV3). However, the production wells PV4, PV7, and PV8 were drilled in parallel to the construction of the power plant and these turned out to be very prolific wells, with productivities higher than initially forecasted. In addition, for the air condenser cooling system, the selected ambient temperature on the design phase was 22ºC, to assure full capacity generation during summer days. However, as shown in Figure 5, through most of the year the average ambient temperature at Pico Vermelho area is below 20ºC (it ranges from 13ºC in winter to 25ºC in summer), so the performance of the generating equipment turned out to be higher than the predicted in the design phase.

As a result, the Pico Vermelho power plant has been consistently operating above the 10 MW contractual power, delivering an average output of 11,5 MW_{net} throughout its production history (Figure 4). This higher performance derives from the reserve power capacity from the ORC generating unit, and its ability to maximize the excess of geothermal fluid production from the Pico Vermelho wells, while the generator rated output is 13 MW. In fact, the fluid supply from 3 of the 5 production wells is enough to meet the power plant capacity, and this guarantees flexibility in the management of the wellfield.

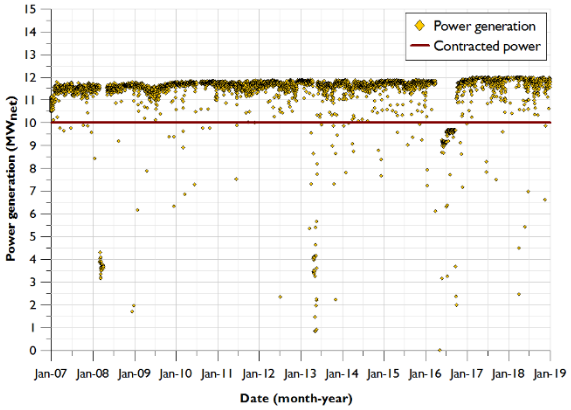

Figure 4: history of power generation at Pico Vermelho.

In the Pico Vermelho area, the production rates withdrawn from the Ribeira Grande reservoir reflect the seasonal variations of ambient temperature, with the peaks of production occurring during the summer (Figure 5). This is related to the lower performance of the air-cooling condensation system when the ambient temperature is higher. Thus, when the parasitic load is higher in summer, there is a higher demand for geothermal fluid to meet the plant generation capacity.

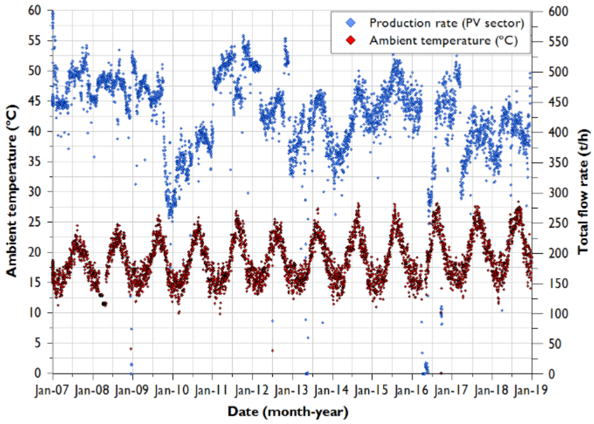

Figure 5: history of the production rate and ambient temperature at Pico Vermelho.

Since 2007, the average annual power generation from the Pico Vermelho plant has consistently been close to 100 GWh/year, with availability over 99% and a steady capacity factor above 95% (Figure 6). The only exception was in 2016 when the power plant was offline for about two months, to perform preventive maintenance works, which included the turbines major overhaul, the generator inspection, and the heat exchangers cleaning.

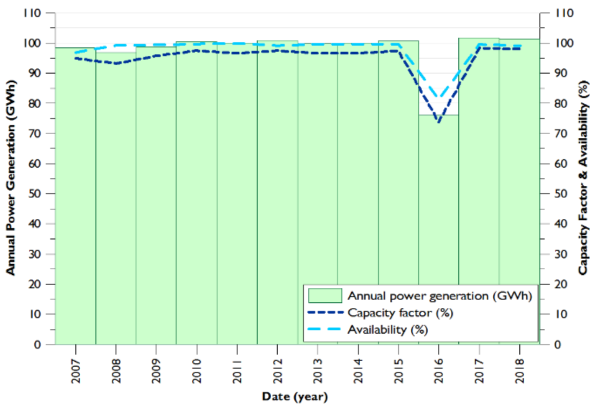

Figure 6: history of production results at Pico Vermelho.

In São Miguel Island, the combined production from Pico Vermelho and Ribeira Grande geothermal power plants provide most of the baseload power needs, and since 2007 it has consistently guaranteed more than 40% of the electricity needs (Figure 7).

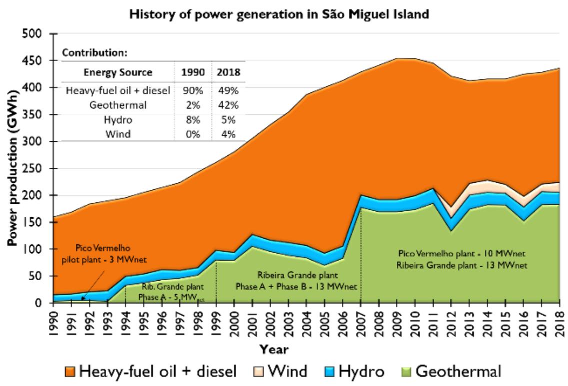

Figure 7: history of the power generation in São Miguel Island

4. BENEFITS OF THE GEOTHERMAL PRODUCTION

Historically, the power generation in the Azores has been based on diesel generators, consuming heavy fuel oil. This option is non-environmentally friendly, as the combustion of fossil fuels results in high gas pollution and high noise levels. On top of that, its generation costs are very sensitive to the fluctuations in the price of crude oil in the international market. In a small power generation system such as in São Miguel Island, the history of diesel generation costs strongly reflects these fluctuations, with the higher costs having been observed when the crude oil price was much higher, particularly from 2008 to 2012, when it reached up to 130 USD/barrel (Figure 8).

In this scenario, the Pico Vermelho power plant provides continuous clean energy, with the geothermal emissions corresponding mainly to benign water vapor and only a small fraction of non-condensable gases being vented to the atmosphere. These are natural volcanic gases, composed mainly by CO_2 (98-99% of the total gases), plus a minor fraction of H_2S and vestigial fractions CH_4, He and H_2. This gas composition is similar of that released in the natural fumaroles of the Azores, but the emissions from the geothermal production are considerably lower than the ones resulting from natural degassing. As an example, the carbon emissions from the Pico Vermelho power plant (~42 tons/day) correspond to 1/25 of that released by soil degassing at Furnas volcano alone - ~1.050 tons/day (Viveiros et al., 2010; Pedone et al., 2015).

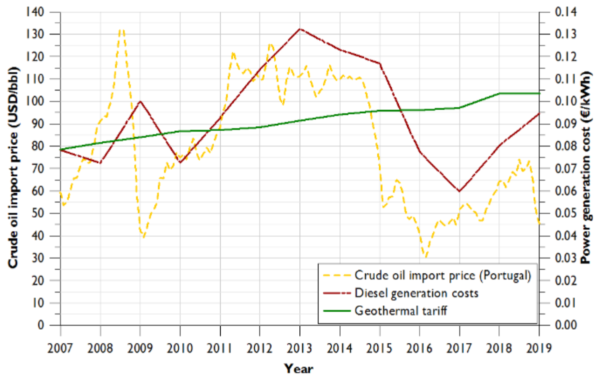

Figure 8: history of power generation costs by energy source and of crude oil import price in Portugal (sources: European Commission, 2019; EDA, S. A., and EDA RENOVÁVEIS, S. A.)

Moreover, as shown in Figure 9, for the same given power generation, the CO_2 emissions from the Pico Vermelho power plant are 1/4 of that resulting from the combustion of heavy fuel oil in diesel generators. Consequently, since 2007 the geothermal production at Pico Vermelho has prevented the emission of about 50.000 tons of CO_2 per year, which otherwise would have been released by the combustion of fuel by diesel generators to meet the electricity demand. Using the reference data for greenhouse gas equivalences from the Environmental Protection Agency from the USA (EPA, 2018), the avoided CO_2 emissions from the Pico Vermelho plant are equivalent to the fuel consumption of 10.000 passenger vehicles or to the energy consumption of 5.900 households for one year.

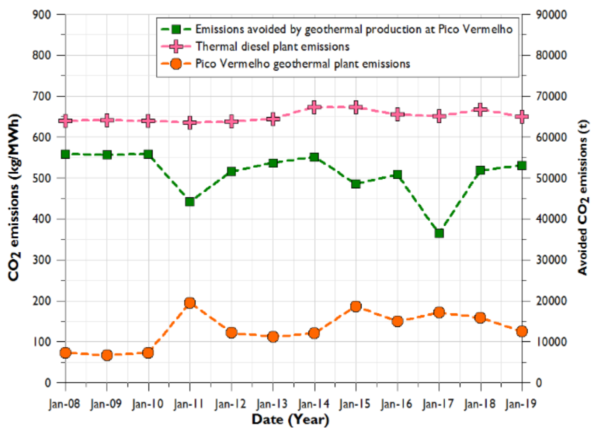

Figure 9: history of CO_2 emissions avoided from PV power plant (source: EDA, S. A., and EDA RENOVÁVEIS, S. A.).

The cost of electricity produced by a diesel generator is relatively high in the Azores, due to the costs of the fuel and its transportation to such a remote area. In this scenario, geothermal energy can be cost-competitive, with the geothermal tariff being often cheaper than the power generation costs from the diesel generators (including the cost of the fuel and the avoided carbon emission taxes).

Very significant are the economic savings from the avoided imports of fossil fuels. Geothermal, as an indigenous renewable energy source, is immune to the fluctuations of the crude oil price in the international market, so its utilization minimizes the dependency on fossil fuels for power generation. Since 2007, the geothermal production at Pico Vermelho has reduced an average of 20.500 tons of fuel imports per year to São Miguel Island, providing savings of more than 100 Million Euros to the Azores (Figure 10).

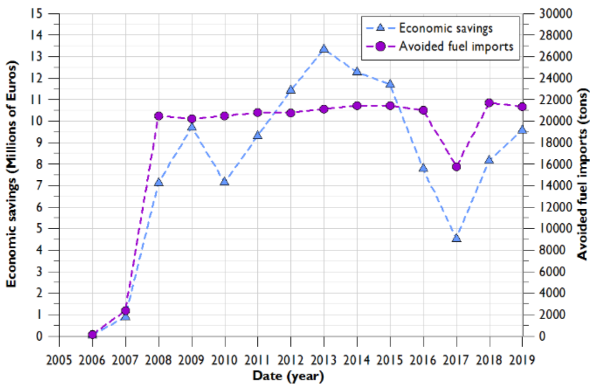

Figure 10: history of savings in fuel imports (source: EDA, S. A., and EDA RENOVÁVEIS, S. A.).

5. CONCLUSIONS

The Pico Vermelho geothermal power plant is a case study of high availability and high reliability, with an annual power generation of about 100 GWh, an availability that is consistently over 99% and a steady capacity factor above 95% every year. These remarkable production results show that when properly developed and managed, geothermal is a sustainable and reliable source of renewable energy and they confirm its position as the predominant renewable in the Azores.

The geothermal production at Pico Vermelho is environmentally friendly. Since 2007, it has avoided the emission of about 50.000 tons of CO_2 every year, which otherwise would have been released by the combustion of heavy fuel in diesel generators. Moreover, the Pico Vermelho production replaces a significant part of the diesel power generation, allowing to reduce the imports of fuel to São Miguel Island by an average of 20.500 ton/year. Thus, the Pico Vermelho plant operation has originated economics savings to the Azores Region of more than 100 Million Euros over the last decade.

Geothermal power provides stable electricity prices, immune to the fluctuations in the price of crude oil in the international market. In a small-scale economy such as the Azores, the environmental and economic benefits of geothermal energy are therefore of strategic importance, as they improve the energy self-sufficiency of the Region and they reduce the carbon footprint from the generation of electricity.

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