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# Dispatchability Potential of Geothermal Power Plants in São Miguel Island, Azores

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## ABSTRACT

In São Miguel Island, Azores, Portugal, up to 42% of the electricity demand is provided by the operation of the Pico Vermelho and Ribeira Grande ORC geothermal power plants. The available resources are abundant and could support an expansion. However, this will depend on the ability of geothermal to operate in flexible mode to follow the grid demand when it is required. Currently, the average annual base load of São Miguel is around 34 MW, with 20 MW given by geothermal, 10 MW supplied by the thermal plant, operating at its minimum required technical limits to ensure the power system stability, and the remaining 4 MW given by hydro and wind, where wind power is mostly being curtailed at off-peak hours. In the coming years, there are plans to expand the Pico Vermelho plant (+5 MW) and to meet the Ribeira Grande plant nominal capacity (+3 MW). The addition of 8 MW means that some of the geothermal capacity might not be fully loaded at off-peak hours.

In this paper, the operational implications of integrating more 8 MW of geothermal to the power generation system of São Miguel are discussed, and the possibility of turning the geothermal plants to flexible and dispatchable units, that can timely ramp up and down, are analyzed.

## 1. INTRODUCTION

Along with the global energy crisis and the necessity of independence from fossil fuels, as well as environmental issues associated to conventional power plants, a surging interest for renewable systems is being witnessed. With the development of diverse incentive policies in favour of renewables, these clean energy sources have not only become a sustainable solution but also an economically viable alternative. Therefore, the electrical grid has entered a new era with a significant share of intermittent energy sources, like wind and solar, which requires adapting to the changes that these new energy sources impose on the grid and coming up with innovative solutions that enable the transformation to more flexible and yet robust power systems.

Integration of solar and wind power to the grid requires allocating a part of the power capacity of conventional plants for spinning reserve, frequency and voltage control to support the grid reliability against their intermittency and low inertia. If the stable operation of the grid is jeopardized, curtailing of renewables production and consequent loss of the associated economic and environmental benefits are inevitable. Therefore, there is a need for innovative methods to deploy the power generating facilities like geothermal with a firm and continuous production to provide flexible and reliable power, often called dispatchable power.

Nowadays geothermal power plants support other renewable projects with reliable baseload power. While, considering the value that long-term advantages of a flexible and dispatchable geothermal holds, could compensate its development expenses.

On the other hand, historically, the main concerns of turning baseload geothermal generation into a dispatchable electricity source have been associated with the necessary stable character of the heat source supply. Managing the well flow rates with minor variations of their control valve position, which will limit the wellhead pressure changes, avoid the oscillating behaviour of the production and the non-condensable gases build up in some wells of the Ribeira Grande geothermal reservoir. But the results that will be presented in this article show that without intervening significantly with the production parameters of the wells, the power output can be adjusted to some extent. This will allow to add more geothermal capacity to the electrical system of São Miguel Island, and hence reduce the consumption of fossil fuels.

Isolated electrical systems, such as island networks, often are characterized by the dominance of diesel or heavy fuel generators. However, São Miguel island with almost 50% share of renewables is achieving more energy autonomy. During 25 years of geothermal plants operation in this island, they have been exempted from the obligatory provision of operating reserves and ancillary services capacity. The dispatch centre is obligated to inject all net power generated by the geothermal units to the grid and the thermal plants subject to Dispatch, receiving instructions for starting and stopping groups to respond to the load of the electrical system (Unit Commitment).

This study investigates the dispatchability potential (i.e possibility of adjusting the generated electricity aligned with the demand) of two geothermal plants in São Miguel Island (Ribeira Grande and Pico Vermelho plants) in operation by EDA RENOVÁVEIS, the company responsible to harness the endogenous renewable resources of the Azores Islands for electricity generation.

## 2. GEOTHERMAL DISPATCHABILITY HISTORY

Dispatchable or load following operation refers to increase or decrease (curtail) the power output of the plant to meet changes in system electrical demand, Cooley (1996). With the dominance of fossil-fuel electricity generators, the inflexibility of geothermal plants never was considered as a challenge or drawback. However, by the substitution of thermal plants for intermittent renewables in the grid, flexibility of geothermal units is getting more and more serious field of investigation for the remarkable value that it can bring to the grid. However, counting on geothermal units as dispatchable plants is a new path of study with few real examples and therefore literature on this topic is scarce.

In GEOELECT technical report on grid access states that in comparison to other base-load power plants a geothermal unit is more flexible. It needs only 5-6 hours to ramp up from a cold status to full power output. For the same operation a lignite power plant needs 9 h and a nuclear power plant even 50h. Additionally, geothermal power plants can vary their power output within a certain bandwidth and can be used in partial load operation, EnBW Energie Baden-Württemberg AG (2013).

Geothermal plants can be ramped up and down multiple times per day to a minimum of 10% of nominal power and up to 100% of nominal output power. The normal ramp rate for dispatch (by heat source valve) is 15% of nominal power per minute, Matek and Schmidt (2013).

In Puna power plant in Hawaii, the new bottoming unit was added with the objective of participation in the grid's frequency control, enabling the power utility to remotely dispatch the facility like a fossil-fueled generation plant, 24 hours a day, with a ramp rate of 2 MW per minute and a quick load pick-up feature of 3 MW in 3 seconds, Nordquist, et al. (2013).

Another project in the U.S. exploiting geothermal plants to operate on "cycling" or "load following" to resource increases or decreases (curtails) its generation output to meet changes in customer or system electrical demand, was at the world's largest geothermal field - The Geysers, U.S.– that have operated in various modes, including traditional baseload, peaking and load following, Cooley (1996).

In Theistareykir geothermal power plant in Iceland, the facility has been designed to support and contribute to grid abnormal conditions by frequency regulation, black start, and islanding functionalities. The flexibility is achieved with controlling the steam supply pressure via steam control valve and venting the steam to the silencers as well as controlling the level in steam separators. The governor of the turbine and AVR system was designed to respond to the grid unforeseen events. Also, a Power System Stabilizer (PSS) has been installed for supplementary voltage regulation guaranteeing dynamic stability, Hardarson., et al. (2018).

In some studies, conveyed to estimate the additional economical profits that geothermal energy systems could receive by providing operational flexibility in the U.S. grid, concluded that for most geothermal power plants, flexibility is more of an economic issue than a technical one. The plant could provide regulation, load following, spinning, or non-spinning reserve ancillary services with appropriately priced contracts, Edmunds, et al. (2014).

Thus, geothermal power plants are capable to provide both baseload and flexible production with new advancements in this domain. Even providing ancillary services would extend the life of the respective thermal reservoirs. and the reason geothermal power does not currently operate flexibly is that current contracts with geothermal operators did not request or address these ancillary services, Edmunds and Sotorrio (2015).

## 3. POWER SYSTEM OF SÃO MIGUEL ISLAND

The electricity consumption in the São Miguel Island was approximately 436 GWh in 2018, from 131 MW installed capacity, CARE (2018). Prior to 1994, almost all the electricity of the island was generated from fossil fuels and share of endogenous renewable resources was only 13%. In 1900, the first hydropower power plant in the Azores Island started operating in São Miguel with a 100-horse power Francis turbine, providing public lighting to the population for the first time. In 1980, the Pico Vermelho 3 MW pilot geothermal power plant injected its first kWh in the electrical grid from its steam driven turbine, being both projects historical milestones of great importance in the further developments of renewable projects.

Now, the electrical system of São Miguel Island constitutes a complex isolated electrical system with various types of power plants dominated by geothermal. Renewable facilities supply a prominent part of the secure, non-declining and carbon-free energy a region with providing 51% of the electricity demand, (24.5 MW geothermal, 9 MW wind, 5 MW hydro and 2 MW Biogas - intermittent), CARE (2018). Caldeirão Power Station is the only thermal power plant on the island, with an installed power of 91 MW and solely responsible for securing power system stability and grid support services.

## 4. SÃO MIGUEL GEOTHERMAL POWER PLANTS IN OPERATION

As stated in the previous part, geothermal energy contributes significantly to the Azores electricity portfolio.
The geothermal exploitation started in São Miguel Island in 1980 with the operation of a small 3 MW pilot power plant 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, Franco., et al. (2019).

Presently, two geothermal sites, Ribeira Grande since 1994, with 4 production wells, 2 injections well and 4 installed units with a total of 13 MW (two units of 4 MW in 1998 and two units of 2.5 MW in 1994), and Pico Vermelho since 2016, with 5 production wells, 3 injection wells and 1 installed unit (10 MW contracted power, although generating at 11.5 MW), have been providing up to 42% of the electricity needs of São Miguel Island, producing approximately 184 GWh in 2018.

The turbo generator units are two-phase binary recuperated Organic Rankine Cycle (ORC), designed and constructed by ORMAT. Each unit is composed by one synchronous generator coupled to two axial turbines, directly or via gear boxes, hot end heat exchangers (vaporizer and preheater), a heat recuperator, cold end air-cooled condenser and working fluid centrifugal feed pumps, as shown in the ORC simplified diagram of operation (Figure 1).

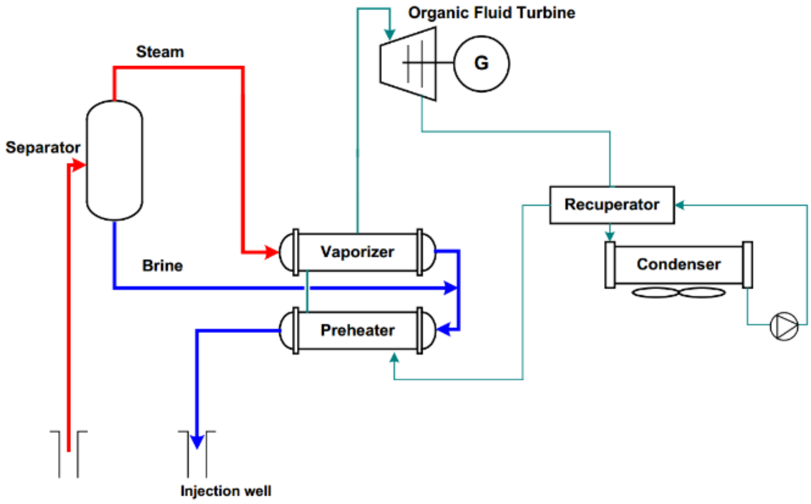


**Figure 1: Two-phase recuperated ORC flow diagram, Kaplan (2007)**

The working fluid is n-pentane, that circulates in a closed loop, receiving thermal energy from the geothermal fluid. It enters the preheater shell side as compressed liquid and leaves the vaporizer as saturated vapour, before its expansion in the turbine, where the energy from the flow is converted into mechanical energy available at the shaft to drive the generator and to produce electricity. From the turbine outlet, the n-pentane vapour passes through the recuperator and finally to the air-cooled condenser, where the remaining heat is released to the atmosphere, condensing the working fluid.

The heat source fluids are saturated geothermal steam, mixed with non-condensable gases, and brine that feeds the heat exchangers tube side. In the vaporizer, the steam exits as a condensate, whereas the non-condensable gases are released to the atmosphere (vented at the vaporizer condensate outlet head). The steam condensate is then mixed with the incoming brine before entering the preheater.

The geothermal reservoir is liquid dominated and harness both plant sites through a series of geothermal wells with depths that ranges from 1 km to 2 km, 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 brine and steam. In each production well pad, the two-phase flow is separated, and the brine and the steam are carried to the power plant headers in separate pipelines, and finally to the ORC heat exchangers.

After transferring its heat into the n-pentane, the geothermal condensate is reinjected back to the high-temperature reservoir, controlling the fluid reinjection temperature to avoid silica scaling, with the reinjection being divided into multiple wells. The reinjection areas have 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.

## 4. GEOTHERMAL POWER PLANTS EXPANSION PLAN

In line with the energy policies of Azores government to increase renewable energies share in the island, it is planned by 2023 to expand the geothermal power generation by 8 MW, that will comprise the installation of one geothermal unit of 5 MW in Pico Vermelho Geothermal Power Plant and meeting the total installed capacity of 13 MW in Ribeira Grande Geothermal Power Plant.

To achieve those targets, a new drilling campaign is planned to be developed during the second semester of 2020 and 2021. In the scope of this drilling campaign, 3 new production wells will be drilled in both Pico Vermelho and Ribeira Grande plant sites, followed by construction of the gathering system piping and the installation of the generating unit(s).

This expansion will avoid the emission of 45,000 ton of $CO_2$ from Caldeirão thermal units in 2023, PEP&O 2019, (2018) and the fossil fuel import costs up to 4.5 M€ but will lead to an excess of geothermal generation capacity during most off-peak hours with minimum load demand.

## 5. GEOTHERMAL DEVELOPMENT EFFECT ON POWER LOAD MANAGEMENT

To guarantee reliability and stability of the grid, even in minimum load hours, at least two fuel oil engines should be online providing voltage and frequency control, spinning reserve, and other ancillary services. On the other hand, the off-peak load of the island is almost half of the peak load and boosting geothermal capacities will contribute significantly in medium and peak hours and the challenge arises in the valley of the load curve. As it has been demonstrated in Figure 2, with the expansion of Pico Vermelho power plant (+5 MW) and meeting the total installed capacity in Ribeira Grande plant (+3 MW), during periods of off-peak, even with all wind power curtailed and two thermal units (15.5 MW and 7.2 MW ) working below their minimum operational limits (40% of their nominal power: ~10MW), surpluses of the power production over the grid load may occur. Thus, in off-peak hours the flexibility of geothermal power becomes more crucial to support the balance between supply and demand. Even currently there are periods of time that the two online thermal units operate under minimum operational limits as load falls to the values lower than 34 MW) which is not an efficient operating condition.

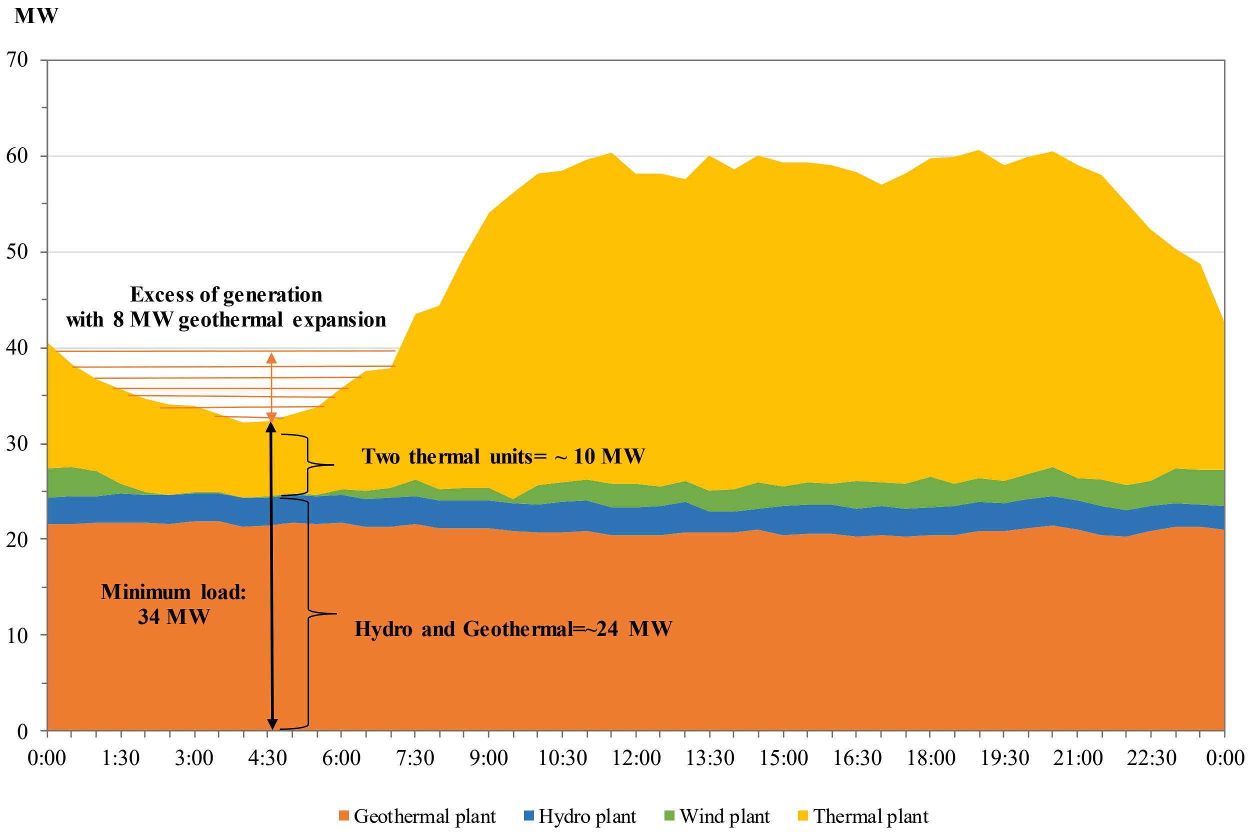


**Figure 2: Daily Load Curve of a typical weekday in Spring 2018 (CARE 2018)**

## 6. PRESENTATION OF THE ALTERNATIVE SOLUTIONS

The objective of this experiment or study was to identify the potential of the units installed in Pico Vermelho and Ribeira Grande plants to follow the load during the off-peak hours (ramp down), which will be a requisite with the geothermal generation expansion of 8 MW, carrying two alternative power output adjustments tryouts in both power plants during intermediate load hour on the 24$^{th}$ and 31$^{st}$ of October 2018.

The power output adjustments of 2 MW in each plant, were made only by controlling the heat source input to the generating units, while limited to the constraints imposed by the production well field of each plant, and following the good practices of wells operation, avoiding significant changes in the wellhead pressure. In fact, from the experience of operation of the geothermal wells in São Miguel, it was found that significant changes in the wells regime of operation tend to increase the time required to stabilize its output and the power generation, plus the non-condensable gases build up in certain wells, when partially closed, greatly impacts the production after the re-opening of the well, so it has not been considered beneficial to vary the load by increasing the wellhead pressure significantly.

ORMAT's generating units in Ribeira Grande Plant are designed with a turbine organic vapor by-pass piping system to the air-cooled condenser, that is mainly a pressure control loop, while in Pico Vermelho it also features a power control loop. Although this loop is not conceived to provide ancillary services, it may allow, for a short period of time, to be operated as a power control mechanism and eventually provide a satisfactory response for load dispatch.

An important condition of the experiments was to manage the power variations limiting or minimizing the need to vent geothermal steam and non-condensable gases to the atmosphere through the plant silencer.

### 6.1. Power output control by wells flow rate adjustment

The power output control by adjusting the wells flow rate was done in Pico Vermelho Plant, where the stable production is typically maintained by the combined production of 3 to 4 of the 5 available production wells. The management of the wells depends mainly on the season and the ambient air temperature, with the aim to generate the same power during the year.

The production wells are prolific and each one produces an average of 100-175 t/h of geothermal fluid with 200ºC temperature at wellhead pressures ranging from 10-25 bar.g, while keeping the steam pressure at the plant header, on average, at 4.5 bar.g. This scenario offers quite a flexible operation of the well field and, since the wells are normally in the partial opening, small variations of their control valves position offers a controllable heat source variation and consequent load change with a stable response.

On the 24th of October 2018, Pico Vermelho plant was generating at 12 MW net, with the contribution of PV3, PV4, PV7 and PV8 production wells, 3 wells were partially closed in steps. For PV8, there is a limitation of the minimum closing position of the wellhead control valve of 15%. A period of about one hour and forty minutes served to observe the response of the gathering system until achieving the load decrease.

The results of the test are presented in section 7.

### 6.2. Power output control by turbine inlet pressure adjustment

The power output control by adjusting the turbine inlet pressure was performed in Ribeira Grande plant generating units, via the power control loop that acts on the steam inlet valve to the vaporizers, which ultimately controls the working fluid vapor conditions into the turbine.

This procedure resulted in the increase of the plant steam header pressure, which is possible in Ribeira Grande since the normal operating pressure is typically below the plant design, due to the shortage of heat source supply.

Moreover, Ribeira Grande production wells have limited flexibility of operation, as only 1 of the 4 wells in the operation allows for a wider range of the wellhead control valve position (CL7), resulting in a significant variation of the wellhead pressure, though.

On the 31st of October 2018, Ribeira Grande plant was generating at 9 MW net, while operating with CL1, CL5, CL6 and CL7 production wells and 3 generating units (1 unit of 2.5 MW and 2 units of 4 MW). Since CL6 is dedicated to one unit of 2.5 MW, the power output changes were made only in the 4 MW units, by individually adjusting the unit power set point.

The results of the test are presented in section 7.

### 6.3. Power output control by working fluid adjustment in the Rankine Cycle

Considering the opportunity of installing dispatchable Binary cycle for future expansion geothermal plants (+8MW) similar to the project done in Puna geothermal site, Hawaii. In this project, addition of a bottoming 8 MW unit capacity to the existing 30 MW facility, enables the fully dispatchable and controllable of plant operation by local utility to adjust its power output quickly in response to the AGC (grid´s Automatic Generation Control that guarantee the frequency stability) with Ramp Rate of 2 MW per minute along with a quick load pick up feature of 3 MW in 3 seconds. To have a rapid ramp rate and to adjust the power output quickly in response to AGC, ORMAT company designedchose to provide bypass for some of the heat input by using a turbine bypass. This would allow some of the heat absorbed by the organic working fluid to be passed around the turbine and dumped directly into the condenser, Nordquist, J., et al. (2013).

To meet up the ramp rate, a certain amount of spinning reserve must be maintained. This spinning reserve (base value: 3 MW) would be achieved by maintaining excess flow of organic vapor from each unit's vaporizer. The excess flow would be bypassed around the turbine directly to the condenser. In the case of ramp up requirement the turbine injection valves would respond by opening and the turbine bypass valve would respond by closing to maintain pressure in the vaporizer, Nordquist, J., et al. (2013).

## 7. RESULTS AND DISCUSSION

The principal point for the discussion of the presented results is the exploratory nature of the trials. The motivation of these tests was to understand the potential and the flexibility of the existing geothermal units in load following, with only slight variations of the production wellhead pressure while avoiding geothermal steam release to the atmosphere, although some venting was required for a short period of time to stabilize the plants steam header pressure.

Also, these trials were authorized to be developed during the intermediate load hours to avoid causing disturbances in São Miguel Island electricity supply, and so the geothermal load was stably compensated by the thermal units in the grid. However, this situation creates the opportunity to perform the load dispatch tests during off-peak hours.

All the provided data are taken from the HMI SCADA system of Pico Vermelho and Ribeira Grande plants.

The power output adjustments in Pico Vermelho plant by adjusting the wells flow rate are shown in Figure 3.

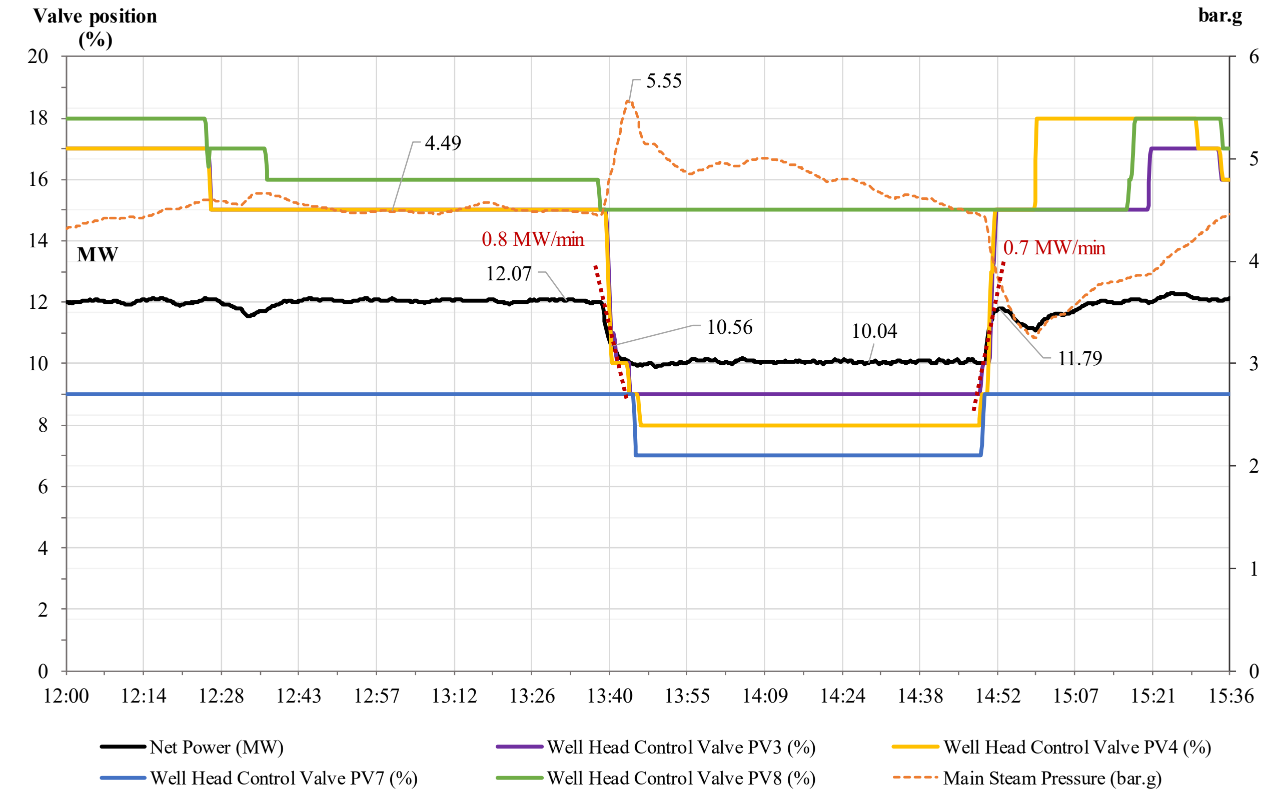


**Figure 3: Pico Vermelho plant power output adjustment varying the control valve position**

The graph indicates the duration of the trial, the generating unit power output variation, the position of the production wells wellhead control valves and the plant main steam header pressure.

The effective power output variation occurred by 13:40, while previously wells PV3, PV4 and PV8 were closed in steps, ramping down the power from 12 MW to 10 MW. The ramp-down rate was 0.8 MW/min and the ramp-up rate is closely the same. Although the rate is not comparable with the required ramp rate of 2 MW/min of ORMAT's dispatchable units in Puna, Hawaii, the value can be seen relevant when performing solely on the heat source supply to the unit vaporizers.

The wellhead pressure was also recorded during the trial. Figure 4 shows the pressure variation of each well following the adjustment of the well flow rate by changing the control valve position at the wellhead.

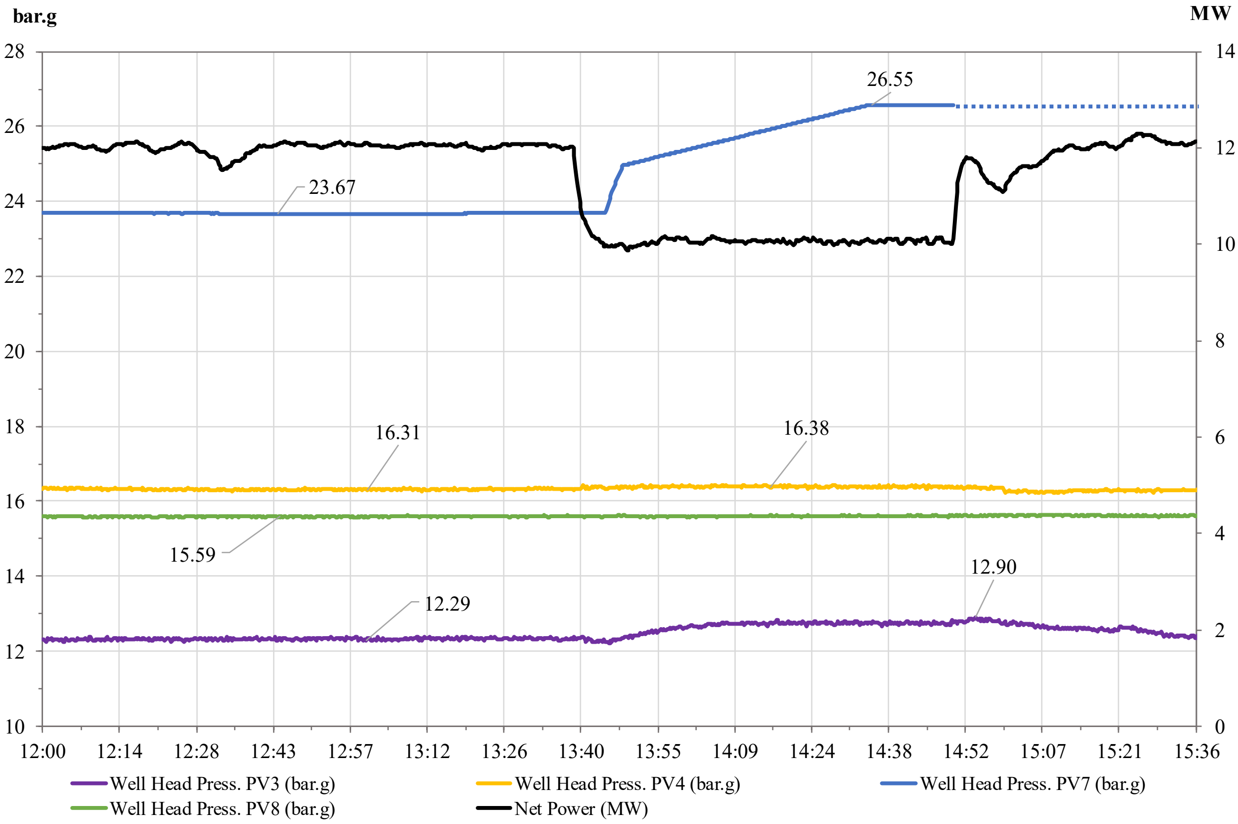


**Figure 4: Pico Vermelho wellhead pressure variation**

Except for PV7 well, which was already significantly restricted by the control valve position, the remaining wells show minor pressure variation during the trial.

At the end of the test, the values of PV7 wellhead pressure were not available.

The maximum and minimum values at wellhead are resumed in Table 1.

**Table 1: Wellhead minimum and maximum pressure**

| | Wellhead pressure (bar.g) | | | |
|---|---|---|---|---|
| | **PV3** | **PV4** | **PV7** | **PV8** |
| **Minimum** | 12.20 | 16.23 | 23.66 | 15.56 |
| **Maximum** | 12.90 | 16.44 | 26.55 | 15.65 |

The power output adjustment in Ribeira Grande plant by reducing the turbine inlet pressure of units 3 and 4 are shown in Figure 5.

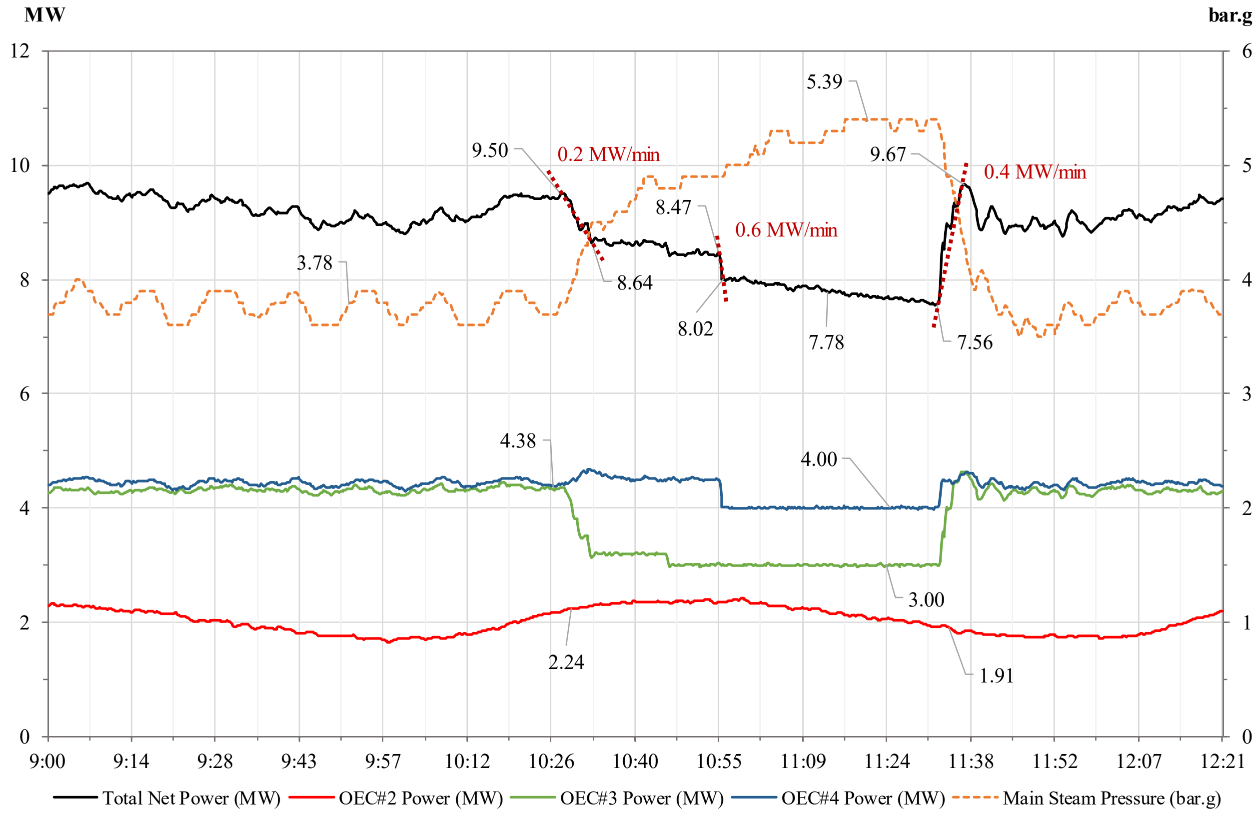


**Figure 5: Ribeira Grande plant power output adjustment**

The graph shows the duration of the trial, the generating units and overall power variations and the plant main steam header pressure. The variation of the main steam header is the direct result of the power output adjustments by closing the steam inlet valve to the vaporizers of units 3 and 4.

The adjustment was done in 3 steps. The 1st step reducing the power set point of unit 3 from 4.3 MW to 3.5 MW and the 2nd step to 3 MW. The 3rd and final step was reducing the power setpoint from 4.4 to 4 MW in unit 4.

Unit 2 could not be part of the test since it is fed directly by the steam produced by well CL6, and adjustments in the power output induces well pressure oscillations, which often leads to the depressurization of the well and loss of production.

It can be identified two ramp-down rates with the higher value equal to 0.6 MW/min., following the 3rd step of the tryout. The ramp-up was 0.4 MW/min.
Both results are not significantly high, but these experiments provided an opportunity to observe that Ribeira Grande plant with the existing equipment and control features and, with only one well that allows for some flexibility, is not suitable to dispatch geothermal load. Differently, Pico Vermelho plant, with the available production well field, with broader conditions of operation, can be used for this purpose.

As referred previously, ORMAT's generating unit in Pico Vermelho is designed with a turbine organic vapor by-pass piping system to the air-cooled condenser that operates as a pressure control loop but also as a power control loop. Although not conceived to provide ancillary services, it may allow, for a short period of time, a satisfactory response for load dispatch, which could be a motivation for further testing, in collaboration with the manufacturer, while keeping the heat supply flow rates to the unit heat exchangers constant.

## 8. CONCLUSIONS

With higher level of penetration of non-dispatchable solar and wind systems installed in modern power grids, the task of balancing electricity demand and power supply over time becomes increasingly challenging. Since firm generation and electrical system inertia are basis of a reliable and stable grid, typically, thermal units are obliged to allocate a part of their capacity as spinning reserves to follow the load in case of their unavailability. In this context the flexibility of base-load energy sources such as geothermal energy will become more and more important to ensure the security of supply.

Dispatchable geothermal operations with possibilities to provide different types of ancillary services such as regulating, spinning and non-spinning reserve, etc. via developing new methods of controlling geothermal fluid, adding new systems to existing technologies, or new control processes and algorithms, will enable geothermal energy to be more widely deployed and economically feasible.

In this study different procedures of achieving flexibility in geothermal power generated by two power plants in São Miguel Island were investigated by only reducing the geothermal fluid heat supply to the generating unit's heat exchangers. As the results show, Pico Vermelho plant load variation rate of 0.8 MW/min is a relevant figure by only adjusting the heat source supply that is provided by a flexible production well field, while Ribeira Grande plant, having only one well that allows for some flexibility, is not suitable with the existing equipment and control features, to dispatch geothermal load.

The trials identified the opportunity and interest to test Pico Vermelho turbines organic vapor by-pass piping system to the air-cooled condenser as a power control loop, to verify the response of the loop as a load following system during off-peak hours, collaborating with the ORC manufacturer to validate the suitability of the installed equipment.

For the foreseen geothermal installed power expansion of 8 MW in São Miguel Island, it will be mandatory to dispatch geothermal power during off-peak hours, therefore the new unit (s) shall allow for plant operation in fully dispatchable and controllable mode and adjust its power output quickly in response to the electrical grid management requirements, by maintaining a certain amount of spinning reserve. This reserve could be achieved if new units would have similar features of flexible units in Puna plant in Hawaii, to meet requirements of the grid by providing 24 hour dispatchable power

In case of São Miguel island electrical system, the possibility of adjusting the power output of baseload geothermal generation to the technically viable extent in combination of another solution such as an energy storage system like Batteries, would improve drastically the stability of the grid by providing ancillary services, reducing the fuel imports by decreasing number of the thermal units on off-peak hours, as well as lowering the curtailment of wind system by storing the excess produced power in the storage systems.

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