Innovative Reservoir Management in Superheated Steam Geothermal System: Micro-reinjection and Push&Pull Production

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ABSTRACT

The Larderello geothermal system is one of the few geothermal systems in the world characterized by a reservoir dominated by superheated steam. The long exploitation history of Larderello, which has been in operation for over 100 years, has led to a general reduction in reservoir pressure, contributing to increase the overheating of geothermal fluid, particularly in the historical area of Valle Secolo. Thanks to these favorable thermodynamic conditions, reinjection has been a fundamental tool for the resource management in Valle Secolo area for over 30 years. In fact, water injection into the geothermal system partially compensates steam extraction and helps to reduce the reservoir pressure decline. The stabilization of electricity production and reduction in pressure decline in Valle Secolo is a check of the effectiveness of reinjection strategy.

High and uniformly distributed permeability is necessary to obtain a significant return in terms of secondary vapor produced by the injected water and to avoid break-through between injection and production. Unfortunately, not all the areas in exploitation in Larderello match this requirement.

In the last few years, Enel Green Power has tested and implemented innovative reinjection methods that allow energy extraction where favorable thermodynamic conditions exist in the reservoir, even where an appropriate homogeneous permeability is absent. In particular, in this paper the Micro-reinjection technique and the Push&Pull strategy are described in details.

Micro-reinjection is based on direct break-through between the reinjection and production wells, while the Push&Pull strategy uses existing unproductive or low steam productive wells that are characterized by high reservoir temperatures. Overall micro-reinjection and Push & Pull applications allow increasing about 10 MW until today.

1. REINJECTION AS STRATEGY FOR SUSTAINING PRODUCTION AT LARDERELLO

The continuing and intensive exploitation of the Larderello – Valle Secolo geothermal system for more than 100 years, gradually depleted the reservoir pressure from starting value of about 3 MPa (Cappetti et al., 1995) to a minimum of about 0.5 MPa in 1980s, although the reservoir temperature remained constant at 240 - 250°C. For this reason, Larderello-Valle Secolo area, which was naturally a steam dominated geothermal system, increased the superheating degree of the fluid in the reservoir.

At the same time, in order to comply with the new environmental legislation, in the 1970s the reinjection of the steam condensate from geothermal power plants started. At the beginning, the fear that a prolonged cold water injection could damage the thermodynamic characteristics of the field, suggested to choose reinjection wells located in marginal areas, far from production zones and sometimes affected by natural cold water inflows. Later specific studies and tests (i.e. numerical modeling and trace tests) began to check the possibility of using cold water to recover the thermal energy stored in the rocks, in particular in those areas characterized by high permeability and high degree of fluid superheating. For these reasons, the first tests about reinjection in the central area of the field started in Valle Secolo area in the shallow reservoir. The results were encouraging allowing the greater part of the water injected recovered as steam from existing productive wells, with an increase of fluid production and a stabilization of the reservoir pressure (Giovannoni et al., 1981 and Cappetti et al., 1982).

The effects of reinjection in the Valle Secolo area have been analyzed by monitoring fluid production characteristics and reservoir pressure in the area affected by injection. In particular, it was evident:

- Flow rate increase for existing productive wells near reinjection pole (Cappetti et al., 1995);
- Sensible reduction in the incondensable gas contents for geothermal fluid (Scandiffio et al., 1992);
- Reduction or stabilization of pressure decline in the shallow geothermal reservoir (Arias et al., 2010);
- Change in the isotopic composition of the fluid produced by the wells before and after the beginnig of reinjection (D'Amore et al., 1987 and Panichi et al., 1995).

Moreover, despite the vicinity of the reinjection wells to production ones, no thermal breakthrough was observed and the fluid temperature remained practically constant. The positive results of the first years of reinjection strategy allowed to increase injected flow rate, widening the perimeter of application and guaranteeing in the Valle Secolo area a stabilization of production. Up today, after about 40 years of reinjection, it continues to be a fundamental tool to guarantee the production sustainability of the field. Currently the injected flow rate in the Valle Secolo area is equal to about 90% of the total fluid extracted from the reservoir. This rate of injection allows maintaining constant the reservoir pressure and it is estimated that the "secondary" steam (generated directly by the evaporation of the injected water) contributes to 60% of the total production in the area (**Figure 1**). These estimates are based on the incondensable gases contents of the produced fluid, assuming that the “primary” steam (which derives from the deep geothermal reservoir) has a content constant over time and are confirmed by water stable isotopes, since reinjected water has an “heavier” signature (+5‰, +10‰ for ^{18}O and ^{2}H respectively) compared to primary steam (-4±2‰, -40±4‰ for ^{18}O and ^{2}H respectively).

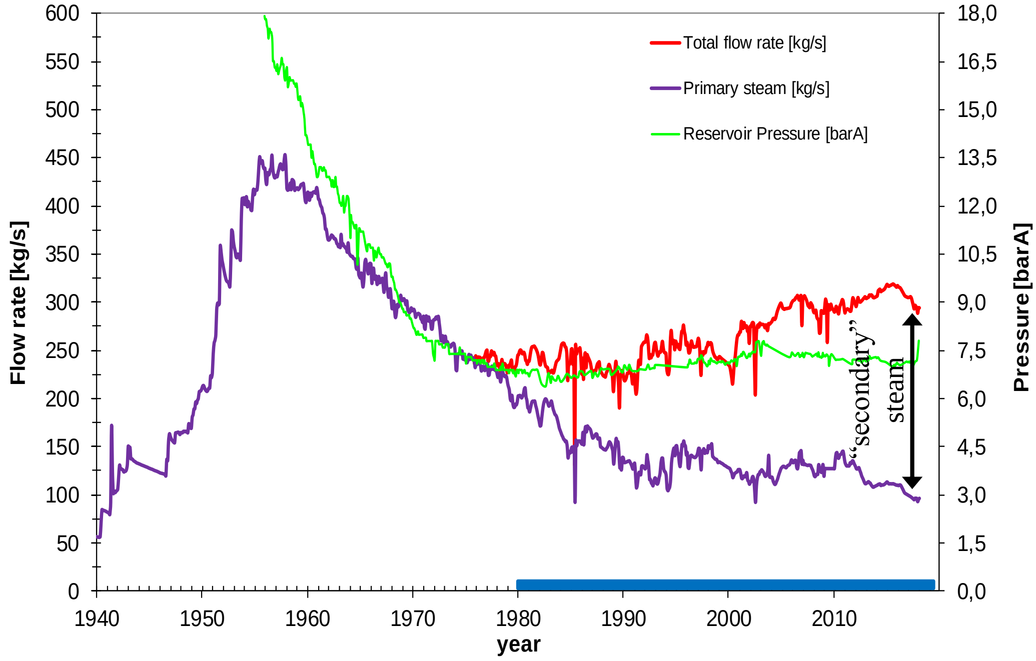


Figure 1: Produced Flow Rate and Reservoir Pressure in Valle Secolo Area.

Although the prolonged reinjection begins to show first evidence of a local and limited cooling of the produced fluid (Figure 2), the reservoir temperature remains high and the superheating degree is still abundantly sufficient to continue with the large-scale reinjection strategy. Therefore, it is believed that the production sustainability in the Valle Secolo area can be guaranteed also in the coming years thanks to the reinjection strategy.

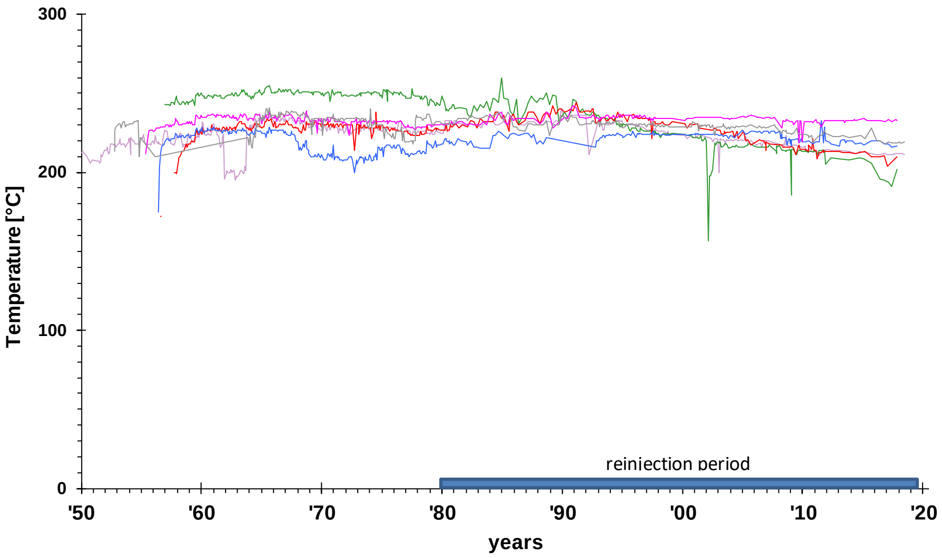


Figure 2: Wellhead Fluid Temperature for Some Wells in The Vicinity of Reinjection Pole.

2. EXTENSION OF THE REINJECTION STRATEGY IN OTHER GEOTHERMAL TRADITIONAL AREAS IN ITALY

The positive experience of reinjection in the Valle Secolo area (Larderello) suggested the possibility of extending this strategy also in other geothermal areas in operation.

At first this was done in areas adjacent to Valle Secolo where similar thermodynamic and petrophysical conditions were present: high superheating degree and high permeability in the reservoir. Experiment results carried out in the Val di Cornia area (**Figure 3**), although with less efficiency and longer response times, were successful. Currently, after having progressively increased the injected flow rate in this area, reinjection has become an essential tool for resource management and decline reducing the decline in the entire geothermal area of the Val di Cornia.

In recent years, the progressive depressurization of the Travale/Radicondoli area (**Figure 3**) due to the intense drilling activity, has suggested the possibility of starting a similar experiment even in the deep metamorphic reservoir that presented saturated fluid conditions before the beginning of the industrial exploitation. After first tests that gave a negative results due to fast breakthroughs with production wells, the injection of over than 100 m^3/h in deep reservoir has been underway for about 1 year with positive results: the neighboring production wells have in fact shown a fluid flow rate increase and a significant reduction in the incondensable contents.

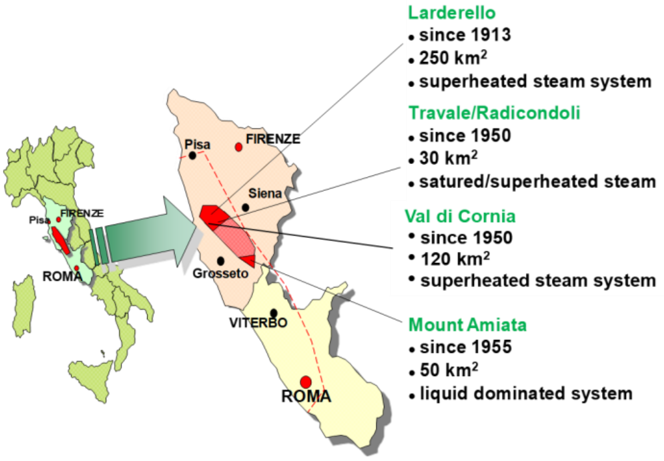


Figure 3: Geothermal area in Italy.

Many studies and tests in progress therefore suggest the possibility of extending the reinjection strategy over all geothermal fields in operation as a fundamental tool for resource management and to guarantee the production sustainability.

Parallel to this strategy, some innovative solutions have been developed with the aim of increasing production or reducing decline even in those areas that do not respond positively to traditional reinjection due to unsuitable thermodynamic or petrophysical characteristics of the reservoir. These include Micro-reinjection and Push&Pull Production methods.

3. MICRO-REINJECTION

Micro-reinjection is one of the innovative tools used to manage our geothermal reservoir and to contrast resource decline. This strategy is based on the same fundamentals of traditional reinjection: the partial reintegration of the mass extracted from the geothermal system by injecting water that vaporizes generating steam, subtracting heat from the rocks. While traditional reinjection realizes this heat exchange by exploiting complex circulation circuits with longer response times, the Micro-reinjection aims to use a direct connection between the production and the re-injection wells, with the consequence of faster response times.

3.1 Difference between Micro-reinjection and traditional reinjection

The difference between traditional reinjection and Micro-reinjection are their objectives. The main purpose of traditional reinjection is to limit the net mass extracted from geothermal system through a water injection distributed as evenly as possible over the entire reservoir volume. In the case of Micro-reinjection, the objective is to increase the steam flow rate of a production well by injecting modest quantities of water into neighboring wells. From this point of view the Micro-reinjection can be assimilated, with due differences, to an EGS system where a natural permeability is present. **Table 1** shows the main differences between traditional reinjection and Micro-reinjection, with their typical parameters for steam dominated fields in Italy.

Table 1: Main Difference between Traditional Reinjection and Micro-reinjection.

	Traditional reinjection	Micro-reinjection
Geothermal Resource decline	✓ (reduction of reservoir pressure decline)	✗ (flow rate increase only for the adjacent wells)
Water injected flow rate	HIGH FLOW RATE	LOW FLOW RATE (5 - 10 m^3/h per wells)
Efficiency	30% - 60%	60% - 80%
Response time	~ 0,1 ÷ 5 years	~ 0,1 ÷ 5 weeks
Incondensable content in geothermal fluid	✓	✓
Effect on fluid temperature	NEGLIGIBLE (< 1°C/y)	IMPORTANT (possible breakthrough between production and reinjection wells)

3.2 Criteria for Identifying Suitable Sites for Micro-Injection

The first examples of this type of reinjection were tested on wells of the same pad where an interference had already been identified during drilling activities or normal operation. The interference between two wells is, in fact, an indication of an interconnection between their fractured zones areas and therefore of a possible positive outcome for Micro-reinjection strategy. The following general parameters are useful to identify suitable sites for Micro-reinjection based on our experience:

- Petrophysical reservoir features

As in the case of traditional reinjection, high local permeability reservoir zones are to be preferred to favor the connection between reinjection and production well and to reduce the response time. Zones with permeability lower than 1mDa are therefore to be excluded. Porosity, on the other hand, is not a valid element for identifying potentially interesting areas for Micro-reinjection.

- Thermodynamic reservoir features

The superheating degree of the fluid in the reservoir is a fundamental parameter that determines the reinjection efficiency. In particular, an adequate superheating degree, generally higher than 40°C - 50°C, must be present. For this reason, high temperature zones (higher than 240°C-250°C) and low reservoir pressure are to be preferred.

- Distance between injective and productive poles

The maximum distance between the fractured zone of the production and reinjection well must not exceed 500 m. This distance can be assessed by projecting on a horizontal plane the axis that joins the fractured zones into the wells.

- Fractured zone depth

Generally, it is desirable that injection and production zones are at the same altitude. When this is not, it is preferable to use the more shallow fracture for reinjection and the deeper for production to favor the interaction between the injected water, which inevitably tends to flow downwards.

3.3 Case Study for Micro-reinjection

In the 1990s, three deep geothermal wells were drilled from a same pad, located in the Val di Cornia area. The first two wells (PW1 and PW2) were poorly productive (steam flow rate less than 10 t/h per well), while the third well (PW3) was idle. The PW1 and PW2 wells identified the production areas at a depth between 1100 m and 1800 m, while the PW3 was drilled up to over 4000 m with the aim of investigating the deep metamorphic reservoir (**Figure 4**). The open hole of PW3 begins at 2154m (depth of last casing shoe) and the fractured zone has been identified at a depth of over 3300 m. An interference between PW3 and the first two was therefore unlikely due to the different depths of the productive horizons.

In order to increase the steam flow rate from production wells through the traditional reinjection strategy, in 2001 water injection into PW3 well started. The test was conducted with an injected flow rate of over 30 m^3/h. Instantly the test determined a flow rate increase of about 10 t/h distributed on PW1 and PW2 with an increase of 1 MW in the geothermal power plant. After only 4 days from the beginning of the reinjection, the two production wells showed a considerable fluid temperature drop with a consequent loss of production in the power plant.

Subsequent well test and logs verified that PW3, had an obstruction at a depth greater than 1500 m and several breaks in the casing in the range between 1000 m and 1500 m (**Figure 5**). Therefore, the water injected into PW3 was not absorbed by the deep fractures present in the open hole, but it came out of the well through the casing breaks, directly interfering with the production zones of the PW1 and PW2. The reinjection in PW3 was then immediately suspended and the traditional injection test ended with a negative result.

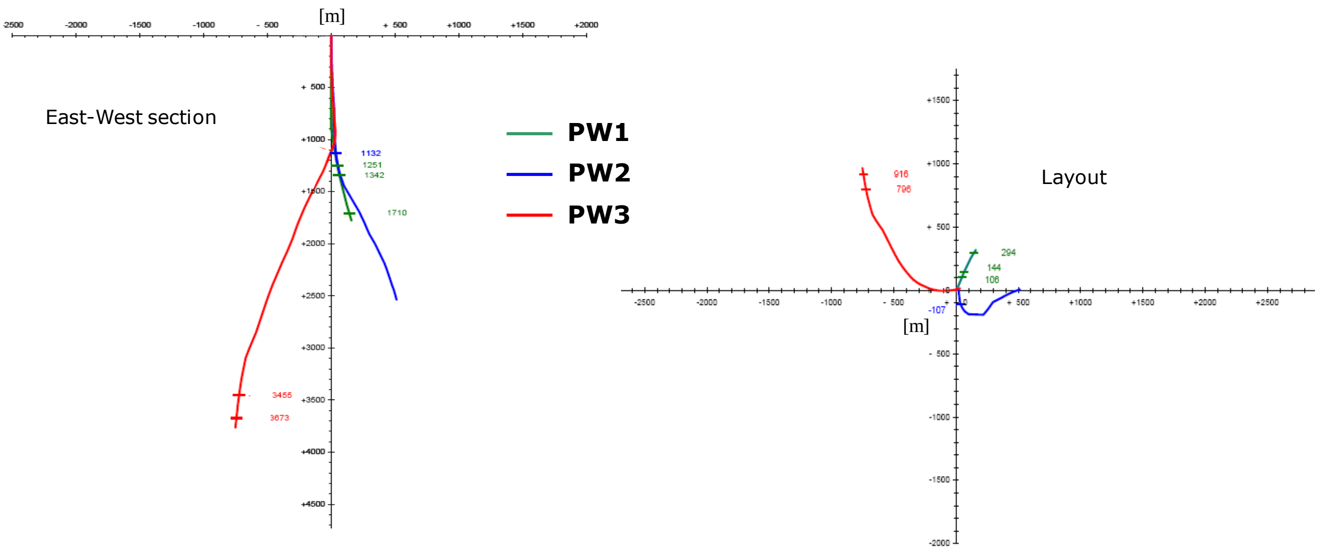


Figure 4: Wells Deviation and Inclination.

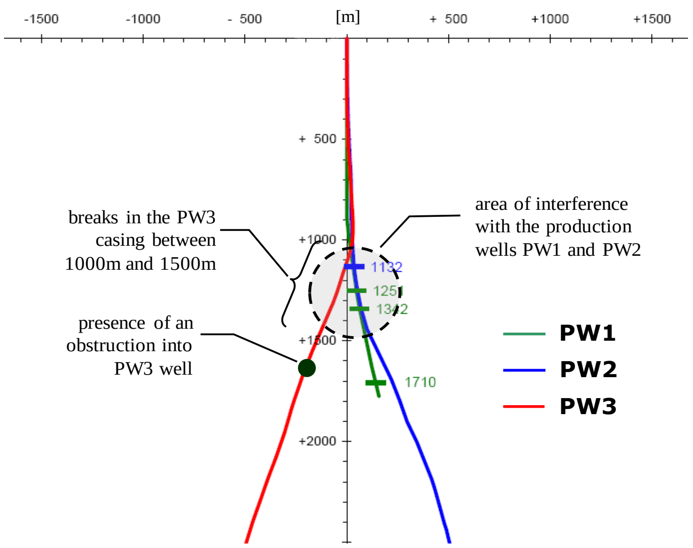


Figure 5: Detailed Situation for Interference Zone.

Given the outcomes from previous test and investigations, recently the three wells were selected for Micro-reinjection application Careful test monitoring was necessary to avoid an excessive cooling of the produced fluid and in particular to prevent the generation of a two-phase fluid in the steam pipeline. A specific and continuous monitoring plan was thus implemented which included a flowmeter for injected water and a gauge for temperature of the fluid coming from PW1 and PW2 (**Figure 6**).

Water injection equipment of PW3

Continuous injected water flowmeter

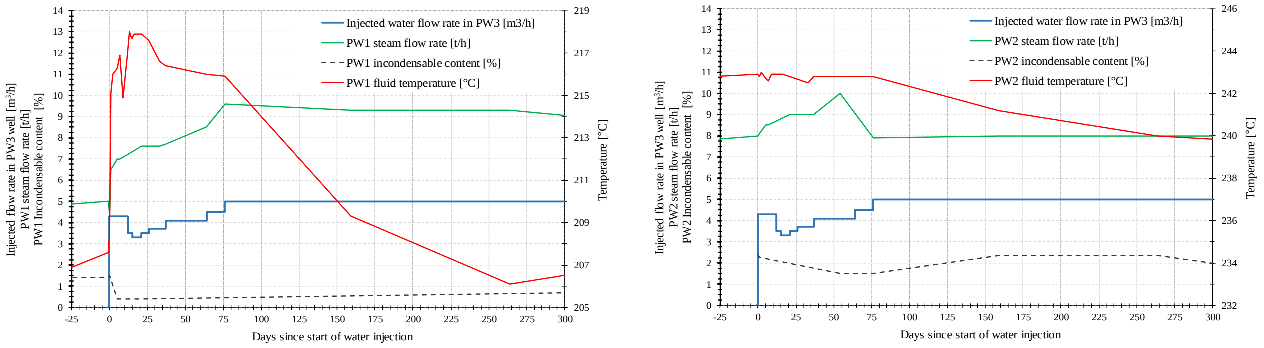
Continuous temperature gauge for total fluid from the pad (PW1 and PW2)

Figure 6: Specific Equipment for Micro-reinjection Monitoring in PW3.

Several adjustments were necessary before finding the ideal injected flow rate that maximized the recovery of steam, without excessive cooling effect. The optimization was reached with a water flow rate of about 5 m^3/h. The main effects (**Figure 7**) of the injection in the PW3 are:

- Increase in steam flow rate of about 4,5 t/h on PW1, with an increase of about 0,5 MW in the geothermal power plant. The reinjection efficiency is therefore 90%. No significant increase in flow on PW2;
- Temporary increase in the temperature of the fluid produced by PW1 due to a transient effect linked to the increase in steam flow rate;
- Significant decrease in the incondensable contents on PW1 well (-50%);

The chemical analysis, carried out subsequently, also showed a decrease in chloride contents on PW1 and PW2 of 40% and 60% respectively, with a significant reduction for corrosiveness issue of the geothermal fluid. Isotopic analysis confirmed that about 80-90% in PW1 produced steam derived from injected water, but also shown that 20-30 % of PW2 comes from reinjection water even if the well did not evidenced an increase in its flow rate. Possibly this is due to PW2 fracture position, higher than the ones in PW1.



(a) (b)

Figure 7: Micro-reinjection Effects on PW1 (a) and PW2 (b).

3. PUSH&PULL PRODUCTION

This methodology has been designed to increase steam flow rate of wells drilled in the deep reservoir that have identified a very low permeability or in any case a limited connection with the rest of the geothermal system reservoir and that have shown a rapid decline in their production history.

A constant water flow rate of about 100-150 m^3/h is injected into unproductive or low productive wells for a short and limited time period. After the injection phase, the well is closed to allow the heating of the fluid due to heat exchange with the hot rock. After one week, the well is then re-opened and fed into the pipeline network with saturated steam production with an increased flow rate.

3.1 Difference between Push&Pull Production and Traditional Reinjection

This strategy is based on the same fundamentals of traditional reinjection: to subtract heat from the rock by injecting water that vaporizes generating steam. The main difference between Push&Pull and traditional reinjection is that the same well is used both as a producer and as a reinjector. The goal, therefore, is not to reduce the geothermal system decline by contrasting the net mass extraction from it, but only to recover the residual heat in a portion of rock that is not well connected with the rest of the geothermal reservoir.

3.2 Criteria for Identifying Suitable Sites for Push&Pull Production

Experiments on this type of activity have only recently begun and the results are encouraging but to be considered partial. In the Push&Pull the sustainability over time is of main importance, and as so two issues must be taken into account:1) the velocity of geothermal reservoir cooling and 2) the well mechanical resistance, which is subject to recurring cooling and heating cycles. Before the injection period, the well undergoes a specific procedure designed to limit thermal shock and to reduce the risk of well damage. Although the short experimentation period, it is possible to identify some features that make a site attractive for Push&Pull method:

- Petrophysical reservoir features

Low permeability with scarce connection with the main reservoir. In any case it must be sufficient to guarantee enough absorbent capacity for the well to avoid fracturing phenomena in the formation.

- Thermodynamic reservoir features

The fluid superheating degree in the reservoir is a fundamental parameter and a value higher than 40°C - 50°C, must be present. Higher temperature (which is a measure of heat amount that can be recovered) means better sustainability over time.

3.3 Case Study for Push&Pull Production

The PW4 well was drilled in the geothermal area of the Val di Cornia in the 1990s with the aim of finding a new resource in the deep geothermal system. The well reached a depth of 2768 m and, after closing, measured a wellhead pressure of about 28 barA. This value, which in static well condition is an indirect measure of the reservoir pressure, was in line with the expected pressure of the deep geothermal field in the Val di Cornia area. After a few years, the well was opened and put in operation with a steam flow rate that rapidly declined from the initial 20 t/h to just over 5 t/h. (**Figure 8**).

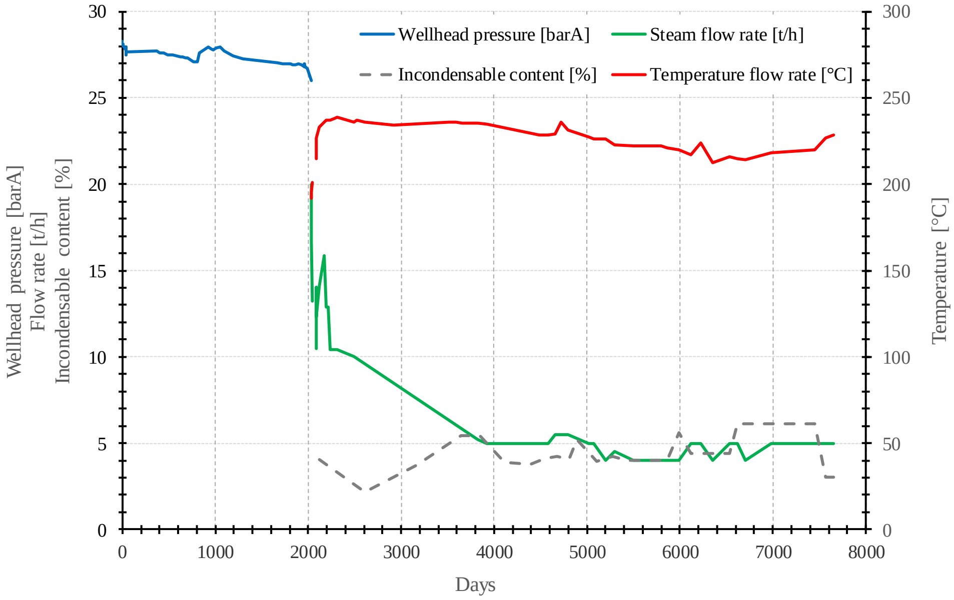


Figure 8: PW4 Production Historical Data.

The well test analysis performed both at the end of the drilling and during the delivery period showed a radial flow in formation with a poor permeability (about 2 Dy·m) confirming the low expectations in terms of productivity. The well was then kept open with constant flow rate until 2 years ago, when it was decided to experiment with Push&Pull to try to increase its production.

The well was closed and reinjection started with a constant flow rate of about 50 m^3/h for 20 days (**Figure 9** - Phase 1): the total injected mass is about 24000 t., and the well spontaneously increased its pressure up to 35 bar, a value higher than that measured at the end of the drilling activity. It is probable that the water injected, vaporizing by subtracting the rock heat, has locally pressurized the reservoir around the well: this is possible because the poor connection with the rest of the system did not allow the injected fluid to move away from the well surroundings.

After interrupting the injection, the well was kept closed for a few days (**Figure 9** -Phase 2) to help fluid heating in formation and to limit as much as possible dragging of a liquid phase in the subsequent opening. After a three-days the well was reopened with an initial steam flow rate of over 35 t/h and a temperature of only a few degrees lower than its historical value (>200°C).

The well, although showing a rapid decline compared to the initial flow rate (**Figure 9** - Phase 3), maintained a steam flow rate higher than the historical values for at least 88 days. The flow rate gain (i.e. the mass difference between produced fluid and historical value of the well) is equal to 5200 t of steam in 88 days, equal to an average flow rate increase of about 2,5 t/h. The reinjection efficiency was therefore equal to over 20%.

For a correct evaluation of the test economic performance it is necessary to consider the production loss during the injection and closure phases: overall the well remained out of service for 20 days for injection and 3 days for heat recovery. If we assume that, if

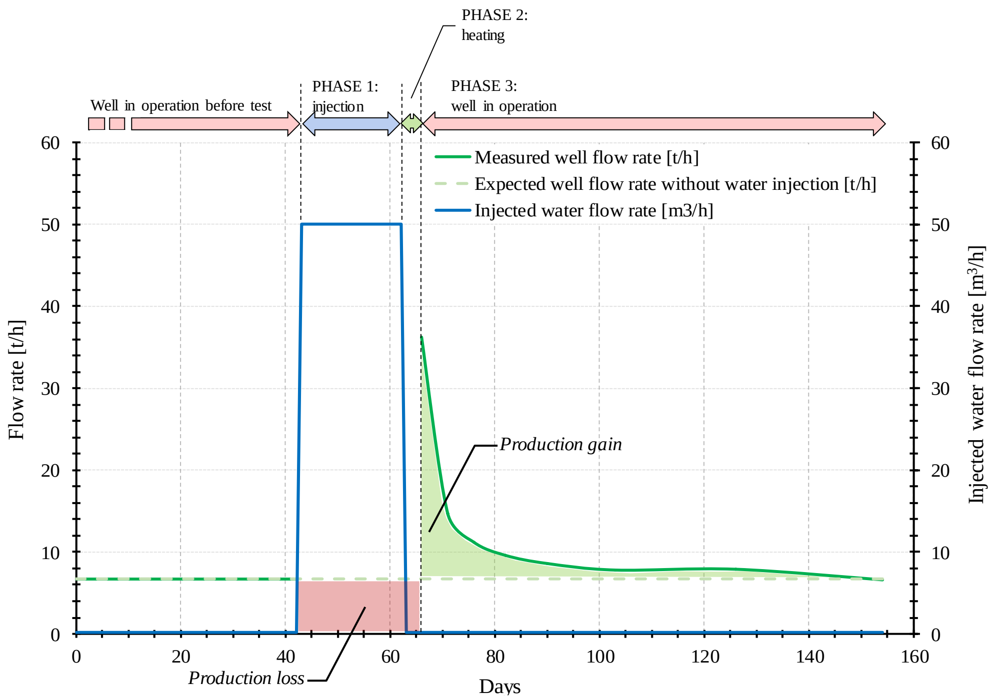


Figure 9: Push&Pull Test Results on PW4 Well.

the test had not been done, the well would have continued to supply constantly about 6,5 t/h of fluid, the total lost mass is about 3700 t. Therefore, the test guaranteed a greater production of around 1500 t of fluid equal to an increase of over 40%.

The second trial involved another well drilled in the same pad of PW4. In this case, however, it was an idle well, not used for production. The well was put in injection for a few months and then opened with a flow rate of over 5 t/h. In this case, Push&Pull tool is even more advantageous since the production loss during the injection and heating phase is zero. Three cycles of Push&Pull were already performed on this well in the last two years with the same results in terms of flow rate. Similar experiments are now underway in other geothermal areas of Larderello.

The next experimentations will be used to optimize the application procedure of the Push & Pull. The use of higher injection rates can allow injecting the same water volume in less time, reducing the closing period of the wells and therefore the production loss.

4. CONCLUSION

The long exploitation history of the Valle Secolo geothermal field (Larderello), which has been in operation for over 100 years, has led to a general reduction in reservoir pressure, contributing to increase the overheating of geothermal fluid. Thanks to these favorable thermodynamic conditions, reinjection has been a fundamental tool for the resource management in Valle Secolo area since ’80 and currently about 70% of steam production comes from water injected. Today the reinjection in Valle Secolo area allows the stabilization of electricity production and reduction in pressure decline. In the last years the reinjection strategy was also applied in the surrounding areas of Valle Secolo and today plays a fundamental role in the management of our steam dominated fields. Unfortunately, not all the areas in exploitation can be supported by reinjection both due to the lack of favorable thermodynamic conditions (low temperature) but also to inadequate petrophysical reservoir characteristics (low permeability). For this reason, in the last few years, Enel Green Power has tested and implemented innovative reinjection methods that allow energy extraction where favorable thermodynamic conditions exist in the reservoir, but homogeneous permeability is absent: the Micro-reinjection and Push&Pull strategy.

Micro-reinjection is based on direct break-through between the reinjection and production wells: low amounts of water are injected in idle or low productive well to increase the steam flow rate in nearby productive ones, without thermal breakthough. The efficiency of this type of reinjection is very high and the steam production increase is extremely rapid. To date this type of process has been implemented on 5 different sites in the Val di Cornia area with a total recovered steam flow rate of 50 t/h, equal to about 7 MW.

The Push & Pull strategy, instead, uses existing unproductive or low steam productive wells that are characterized by high reservoir temperatures but low connection with the geothermal reservoir. These wells, usually closed, are used as injection wells with a constant water flow rate of about 100-150 m^3/h for a short and limited period. After the injection phase, the well is closed to allow the heating of the fluid due to heat exchange with the rock and then is opened and fed into the pipeline network with saturated steam production. To date this type of process has been implemented on 3 different sites, 2 in the Val di Cornia area and 1 in Larderello, with a total recovered steam flow rate of 15 t/h, equal to about 2 MW.

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