Geothermal ORC plant case study in Italy: CastelnuovoPilot Project – Design and technical features

Maurizio Vaccaro[1], Fausto Batini[2], Massimo Stolzuoli[1], Serena Bianchi[3], Ruggero Pizzoli[4], Simone Lisi[2]

[1] GE Oil&Gas Nuovo Pignone, Via Felice Matteucci 2, 50127, Firenze, Italy

[2] Magma Energy Italia, Via Ernesto Rossi 9, 52100 Arezzo, Italy

[3] Graziella Green Power SpA, Via Ernesto Rossi 9, 52100, Arezzo, Italy

[4] Nooter/Eriksen, Via Volta 50, 21010, Cardano Al Campo, Varese, Italy

Corresponding author: maurizio.vaccaro@ge.com

Keywords: Geothermal ORC plant, Castelnuovo Val di Cecina, Pilot plant, Landscape integration, NCG, reinjection, High enthaphy geothermal reservoir.

ABSTRACT

The case study illustrated in this paper is a geothermal ORC power plant, currently designed to be installed in Castelnuovo Val di Cecina (province of Pisa, Italy). The project will be executed by Magma Energy Italia. The power plant will install a turboexpander manufactured by GE Oil&Gas Nuovo Pignone, Florence (Italy).

The solution has been studied to create an innovative "closed loop" power plant, achieved by integrating a binary cycle power plant with a suitable plant infrastructure, respecting the principle of a safe, clean and environmentally integrated system.

This goal is achievable through the combined implementation of the points listed here: Closed loop; Use of non-toxic and non-flammable substances; Total reinjection of fluids and non-condensable gases in the same geological formations from which they are extracted; Adopting an ORC working fluid cooling methodology (air cooler condenser) with no water consumption; Placing the power plant near the production wells and creating the reinjection well on the same drilling pad, avoiding the construction of new pipelines needed to transport fluids to a different site.

This particular ORC application is an innovative case study. The working fluid is R245fa, which is not flammable, and it has a null ODP (Ozone Depletion Potential). The plant is fed by geothermal steam at about 14 bar. Usually in the majority of the geothermal ORC plants, the primary energy source is a liquid (geothermal hot brine, pressurized water). Having a steam condensation in the main heat exchanger is an innovative aspect that characterizes this geothermal project. The main heat exchanger is a geothermal steam condenser, which is used to evaporate and superheat the R245fa. Heat transfer occurs with presence of Non-Condensable Gases (NCG), this adds an additional element of novelty to the project. In order to maximize the sustainability of this project, total reinjection is performed. Both geothermal condensate and Non-Condensable Gases (NCG) are reinjected through a well.

In the paper the optimization of the cycle parameters is treated. The geothermal condensate water, after the heat transfer to the working fluid, is also available for direct use too, being delivered to the return gathering system at about 90 °C. NCG are collected and pressurised in order to be re-injected.

A particular aspect of this case study is the landscape and environmental integration with the surroundings. The paper describes the devices and precautions elaborated in order to minimize the visual impact and harmonize the plant penetration in the surrounding environment. A sustainability analysis and description of the plant is also performed in the paper.

1. INTRODUCTION

Geothermal ORC is not a common practice in Italy yet. Castelnuovo ORC plant could be the first "pilot plant" installed in Italy, with reference to the current Italian Ministry permitting procedure. The plant will be located upon the worldwide known Larderello geothermal field.

Castelnuovo ORC plant will be fed with steam from a high enthalpy geothermal reservoir. Management and total reinjection of the geothermal fluids are peculiar aspects of this project. Although all over the world this has been experienced as a plant strategy, this will be the first plant in Italy having this configuration. The condensate geofluid reinjection will follow the typical practice, while the NCG will be compressed before being reinjected.

As it is shown in the results of the Environmental Impact Study (Golder Associates & Magma Energy Italia, CAS.02.DE.AM.R.005, see References) the plant results to be coherent with the objectives of the national policy about energy production.

The plant described here has "zero emission", as it will have any leakage. Sustainability issues have been faced by optimizing different aspects of the project: the ORC working fluid (R245fa) is not toxic and non flammable; the cooling media is air (so that no water bodies are used for condenser heat removal); reinjection well is located in the same drilling pad of the two production wells (in order to reduce the whole footprint of the project). The ORC plant is designed in order to match the customer's power size (namely 5 MW) and energy production target, this target is typical for the Italian practice of the so called "pilot plants" projects.

The Turboexpander (TEX), single stage, will be provided by GE Oil&Gas (Florence, Italy), having lots of reference of installations in ORC plants for waste heat recovery worldwide. GE Turboexpanders are now mainly used particularly in high temperature waste heat recovery from Gas Turbines (GT) exhaust gases, but also lower temperature ranges can be covered with the same type of equipment.

2. BACKGROUND

In Italy the geothermal resource utilization for electricity generation dates back more than 100 years ago. At present about 900 MWel are installed and operated by ENEL. Recently the market of geothermal electric power generation has been liberalized and several players are now engaged for the exploration and development of new geothermal project in Italy.

The Legislative Decree February 11, 2010 n. 22, amended by Legislative Decree March 3, 2011 n. 28 provides that fluids with medium and high enthalpy are considered of national interest and experimental small size (5 MW) plants with total geothermal fluids reinjection and low environmental impact are promoted on national scale (http://unmig.mise.gov.it/unmig/geotermia/titoli/titoli.asp). Castelnuovo Project is one of the above mentioned experimental plants and it is located in the northern part of Larderello-Travale geothermal system, (Figure 1), where the geothermal resource is well known.

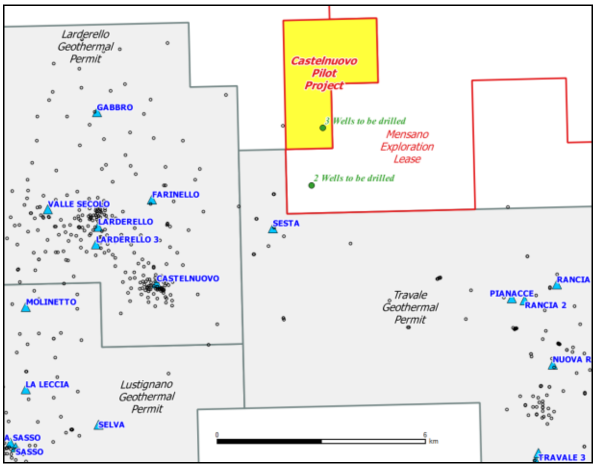

Figure 1: Location of the Castelnuovo Project (yellow) with respect to the Larderello-Travale geothermal Field. Cyan triangles = Power Plants; Black dots = geothermal wells; Green dots: planned wells.

The project is very close to the Gabbro-Sesta area, investigated in the last 20 years with modern geophysical approaches that allowed to drill successfully some deep wells (e.g. Sesta 6bisA, Sesta 6bisB – Barelli 2000, Batini 2002, Cappetti 2005), and to install 20 MW Sesta Power Plant in 2002. Recently additional geophysical surveys (Gravity, Magnetic and MagnetoTelluric) have been executed by Magma Energy Italia through WesternGeco-Schlumberger, as well as a new geo-structural survey by Magma Energy Italia and University of Siena and University of Bari (internal reports, unpublished).

According to the 3D geothermal model of the area built by Magma Energy Italia (Figure 2), there are some 1000 m of clayey formations (Ligurian flysches) covering a complex carbonatic and metamorphic reservoir, whose shallow units (Anhydrites and "Verrucano") locally have no geothermal interest and will be isolated by the casing. The wells will enter the deep metamorphic reservoir down to -3500 m or more, where +250 °C and about 70 bars are expected.

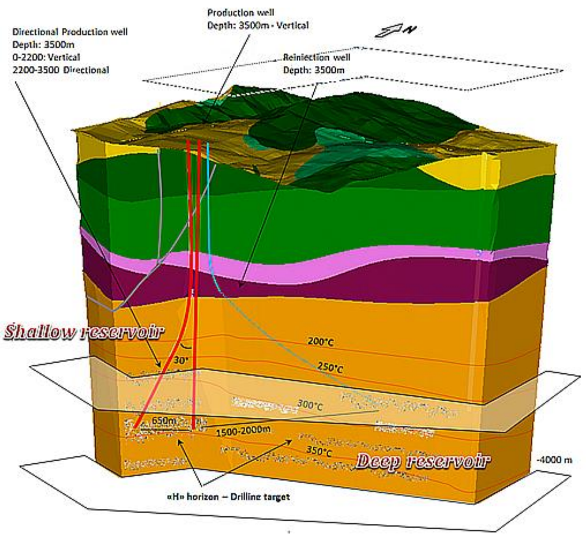

Figure 2: 3D geothermal model of the Castelnuovo Project, showing the profile of the wells.

The objective of the project is to extract high enthalpy geothermal fluids (steam and non-condensable gases, NCGs) to feed an innovative small-sized geothermal power plant (5 MW), and inject the condensed fluids and NCGs back into the reservoir. The expected depth range of the wells is 3000 to 4000 m, with expected temperatures between 250÷300 °C in the reservoir.

The turboexpander that will be used for power generation is a GE product and it will be manufactured in Florence (Italy).

3. BACKGROUND

3.1 Main design data

The main design data considered are indicated in Table 1. The maximum expected value for the chloride is 50 mg/l. The results presented here are based on the assumptions in Table 1, no direct wells data are available at the moment of the issue of this paper.

3.2 Gathering system

The geothermal fluid (steam) coming from the two production wells (180 °C; 10.3 bar) is sent to a scrubber to be washed and to reduce the solid content. A small stream of liquid brine (from the reinjection line) is bypassed to the scrubber to wash the inlet steam. The geothermal steam (after the scrubber) is sent to the evaporator, where it condenses by heating the ORC working fluid (R245fa). The condensed liquid at the evaporator bottom is collected into to the geothermal condensate tank, downstream the evaporator. This condensate tank receives also the drainage from the scrubber and from the NCG (Non Condensable Gases) compression system. The brine from this tank is then pumped to the reinjection line, by a service pump, at 89 °C and 11.7 bar. The NCG are extracted from the evaporator and sent to a compression system, in order to be reinjected. The compression system is fundamental to reinject the NCG (mainly CO_2, as per Table 1) at an appropriate high pressure condition, in order to be pushed down into the reinjection well at the reservoir formation depth. The NCG are compressed at 60 bar (and cooled at 50 °C), before being collected to the reinjection. Materials in contact with NCG have been selected to withstand corrosion phenomena induced by the aggressive stream (high concentration of CO_2 and H_2S).

Table 1: Main design data.

Geofluid inlet		
Mass flow rate (steam)	kg/s	18
Temperature	°C	180
Pressure	bar	10
Geofluid composition		
Water	%w	92
NCG	%w	8
NCG composition		
CO_2	%w	97.5
H_2S	%w	2
Others (H_2, CH_4, N_2, NH_3, H_3BO_3)	%w	0.5
Geofluid outlet (liquid)		
Temperature	°C	89
Pressure	bar	11.7
Geofluid outlet (NCG)		
Temperature	°C	50
Pressure	bar	60
Environment condition		
Temperature	°C	20
Relative humidity	%	60

Both inlet and reinjection gathering pipelines will be appropriately insulated, and they will be provided with expansion loops to absorb thermal stress. A H_2S detection system is foreseen too, both in the wellheads and ORC plant area, able to send an alarm signal to the control system in case of H_2S leakage. The ORC plant area is situated at 9 m higher level respect to the wellheads location.

Figure 3 shows the scheme of the gathering lines, which flow distribution is listed in Table 2. In Figure 4 the overall power plant and gathering scheme are provided.

3.3 ORC plant process description

The geothermal steam enters in the evaporator, here it condenses by transferring heat to the Working Fluid (R245fa). The working fluid mass flow rate circulating in the ORC plant is 173.4 kg/s. At this conditions, the WF expands then in the turboexpander, producing the expected 6.45 MW gross power at generator terminals. The expanded working fluid goes to a recuperator, in which the residual heat of the hot vapour (at about 100 °C) heats the liquid R245fa coming from the pump, raising its temperature up to 71 °C (Figure 4). The WF at vapour state is then condensed in an Air Cooled Condenser (ACC), and the WF circulation pump raises again the liquid R245fa at the high pressure level, before regenerating it in the recuperator (cold side). Figure 4 shows the process flow diagram of the ORC plant. The ACC is made by seven bays, each one with two fans, equipped with VFD (Variable Frequency Drive) system. The calculations of the heat and material balance and check have been performed with the software Aspen Hysys v.8.4.

As the geothermal steam is washed before being sent to the evaporator, the solid content is reduced to an acceptable value. Furthermore, the heat transfer is operated by the geothermal steam, being a cleaner fluid than the brine. In any case the evaporator is suitably designed to allow an off line cleaning of the geofluid side, if needed. Scaling phenomena will be better investigated when direct data about the geofluid will be available from the drilling of the wells (Gunnarsson 2003, Corsi 1986, Axelsson 2010, DiPippo 2008, Huenges 2010).

Table 2: Gathering system, flow data.

	Service	Flow (kg/s)	Operating pressure (bar)	Operating temperature (°C)
1	Geothermal Steam	9.0	10.3	180
2	Geothermal Steam	9.0	10.3	180
3	Geothermal Steam	18.0	10.1	180
4	Steam Condensate	16.6	10.3	94.4
5	NCG	1.4	60.3	50

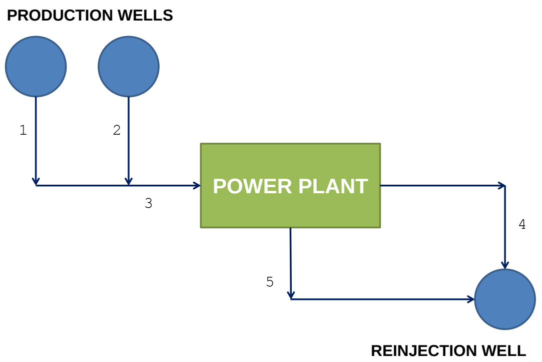

Figure 3: Wells and gathering system.

3.4 Plant layout

The system has been studied to create an innovative “zero emissions” power plant, achieved by integrating a closed binary cycle power plant and a suitable plant infrastructure with the surrounding area, respecting the principle of an environmentally integrated system. The environmental mitigation is implemented, not only on the air, water and soil components, but also in terms of architecture, through studies of landscaping integration.

The layout of the ORC plant and drilling facilities is sketched in Figure 5. The drilling station is situated at a lower elevation respect to the ORC plant (9 m), and a drilling water service pool is also provided next to the drilling area. Geothermal ORC plant will occupy an area of 5500 m^2.

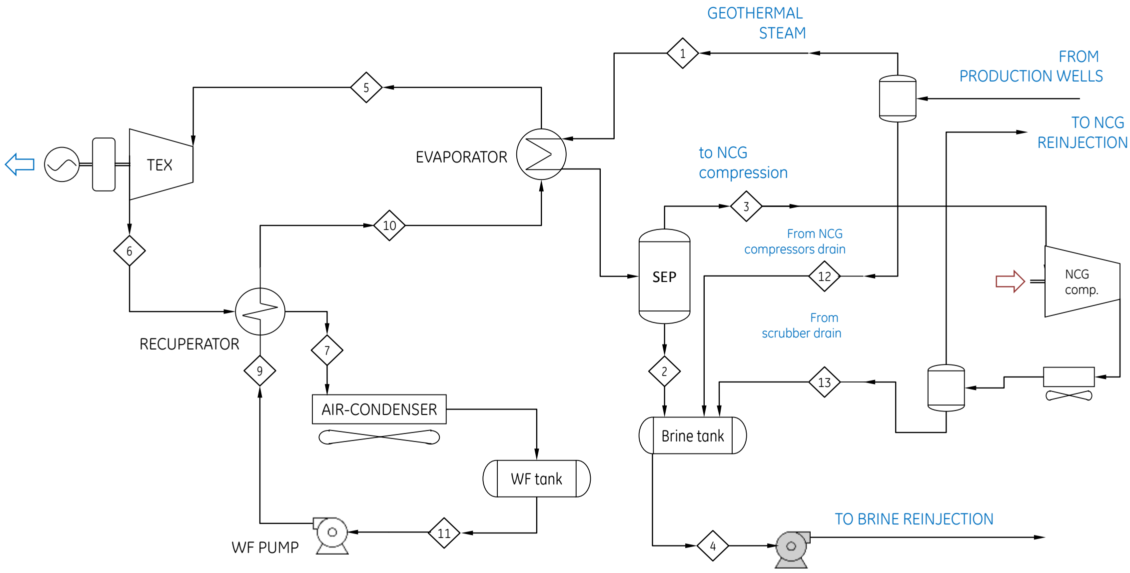

Figure 4: Process flow diagram of the Castelnuovo ORC power plant.

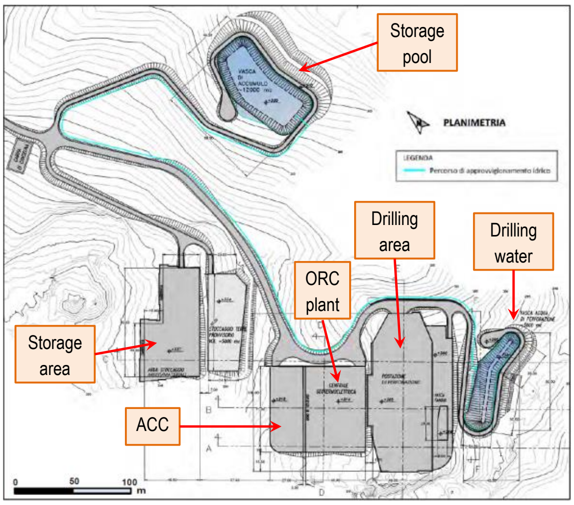

Figure 5: Main layout of the plant and drilling area.

Figure 6: Main layout and rendering of the power plant and ACC units.

The air cooled condenser area will be at a higher height (4 m) respect to the ORC plant area. The architectural design is focused on the creation of a 1560 m^2 curved green roof, covered by vegetation, whose shape could remember the surronding ground (Figure 6). The result is a closed structure, allowing both a mitigation of the plant impact and the containment of the noise emissions. The ORC station (heat exchangers, turboexpander, service and control area, auxiliary systems) will be contained into this single building, of rectangular shape, occupying an area of 1560 m^2.

3.5 Reinjection strategy

The project has been conceived in order to fully reinject the geothermal fluid, by total condensation of the steam and separate recovering of the NCGs. The estimated NCGs content is about 8% weight of the geothermal fluid, mainly constituted by CO_2 (about 98%). All the extracted fluid will be injected in the deep reservoir, within the same geological unit they originate from, by an innovative technology.

GeothermEx (Schlumberger) and Magma Energy Italia developed a dual-porosity numerical model of the geothermal reservoir (Figure 7, unpublished) reproducing the current-state pressure and temperature distribution in the reservoir and allowing the simulation of several conditions of exploitation. The forecasts have been used to define the best strategy of production and reinjection, leading to the design of two production wells and one reinjection well, to be drilled from a single rig site. The selected configuration of the wells and their features are capable of assuring that geothermal fluid conditions (mass flow rate, temperature and pressure) at power island inlet are matching the selected design conditions with adequate safety margins over time. An appropriate range of variability has been considered for the chemical composition of the fluid, derived from published data of the closest production wells.

According to the production forecast, the reservoir is capable to support the combined production of 70 t/h steam rate from 2 wells, totally reinjected in the third well, over 30 years of exploitation. The total reinjection includes the NCGs.

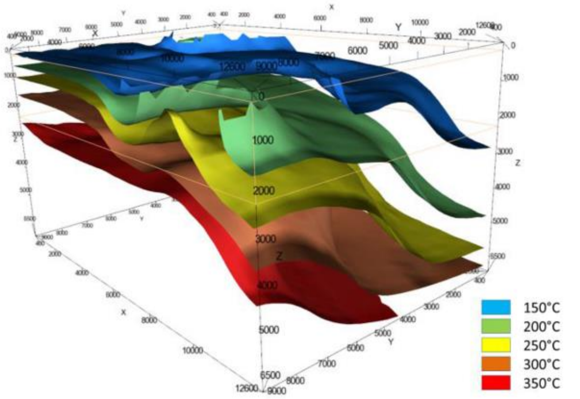

Figure 7: Temperature distribution within the geothermal reservoir.

The total reinjection has a dual purpose. The main one is to recharge the reservoir, in order to support the production over time, keeping the reservoir pressure on the initial values, on average; the second one is to avoid the greenhouse gas emission. The reservoir simulations demonstrate that the pressure reduction at the production wells will be limited to a few bar(a) over plant lifetime. The reinjection has a positive pressure effect on the reservoir but, at once, the propagation front of NCGs does not interfere with the production wells.

Dealing with the gases reinjection, the brine and the NCGs will be released inside the reinjection well by means of concentric pipes, with packers and valves, allowing separate, parallel streams down to the "mixing point", which will be located at few hundred meters in depth as a function of the measured injectivity. At the mixing point a mixture is formed which goes down along the casing of the well down to the leakage fractures in the reservoir, dragging and partially dissolving the gas in the liquid streamflow.

A numerical simulation of the injection system has been executed by Schlumberger Integrated Solutions (SIS), under the guidance of GeothermEx, using the transient multiphase flow simulator "OLGA" (Stacey et al. 2016, submitted). These simulations encompass several injection depths of non-condensable gases (primarily CO_2) into a condensed steam injection stream, demonstrating that the single-well injection system is a feasible approach to bring back both NCGs and water. Several conclusions have been drawn, among which the most relevant are:

1) for all the steady-state cases simulated, no NCG gas backflow due to buoyancy effects was observed;
2) for all the steady-state cases simulated, no counter-current flow will occur;
3) for a wide range of values of well injectivity, the atmospheric pressure is adequate to inject the brine at the wellhead. This ensures the injector well will behave in a way similar to many other injection wells operated in the Larderello geothermal field, and the pressure applied at the fracture in the reservoir is an order of magnitude lower than that exerted during drilling;
4) The NCGs injection pressure is limited to 60 bar, in the worst case, in order to fit the pressure of the brine flow at the mixing point.

4. ORC PLANT PERFORMANCES

This geothermal ORC is designed for 5 MW net power production. The rated performances can be read in Table 3, they are based on the initial data given in Table 1. Figure 8 shows the annual gross energy generation (monthly basis estimation), net energy production will be about 43 GWh per year.

Table 3: Expected performance data in design case.

Design case	kW
Expected gross power	6452
ORC pump consumption	562
NCG compressor consumption	268
Air cooled condenser fan cinsumption	375
Auxiliary systems	60
Net expected power	5180

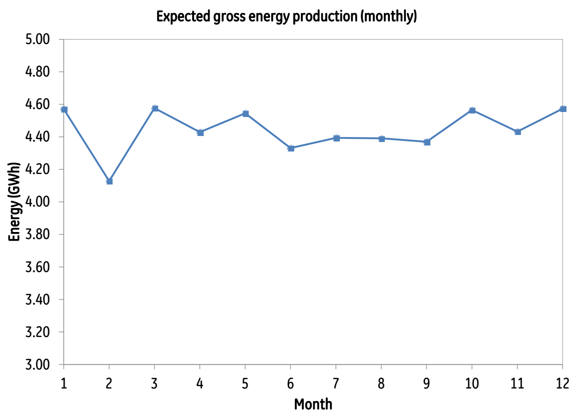

Figure 8: Expected gross energy production (monthly estimation).

A power plant availability higher than 92% will be achieved by installing redundant critical components and control instrumentation, in accordance with a dedicated RAM (Reliability, Availability & Maintainability) study.

5. ENVIRONMENTAL ISSUES

A refrigerant type working fluid has been chosen for this project. R245fa (1,1,1,3,3-Pentafluoropropane, formula: $CHF_2CH_2CF_3$) is not flammable or explosive at ambient conditions. It has a null ODP (Ozone Depletion Potential). It has a not negligible GWP (Global Warming Potential), so that It must be contained, and its emissions to the environment avoided as much as possible.

This geothermal ORC power plant is conceived as a "closed loop" system, with respect to the geothermal reservoir, for total reinjection of the geolfuid and NCG (Kaya 2011, DiPippo 2008, Huenges 2010). For this reason, the exploitation of such geothermal reservoir will be clean, as no leak of geofluid or NCG are allowed during the plant operation. The total reinjection of the brine and gases has the advantage of recharging the reservoir and support the reservoir pressure field, as the reinjection is operated into the same rock formation which feed the production wells. In this way the reinjection is an environmentally friendly method for the disposal of separated geothermal brine and steam condensate (avoiding thermal and chemical problems of pollution of shallow ground water and water bodies).

In order to reduce the footprint due to the reinjection infrastructure, in this project the same drilling area will host also the reinjection well. This well will be fed by the liquid (condensed) geofluid, after being used for heat transfer in the ORC plant, pumped at 11.7 bar (see also section 3.5). The NCG will be reinjected in the same well, but at a different ground level, by introducing an appropriately designed piping with smaller diameter. The high pressure requested for NCG reinjection is due to assure gas injection and avoid bubble phenomena at shallow level. The NCG stream at 60 bar can be also cooled down at 50 °C, after compression. Geothermal fluids exploitation through ORC plants has been mainly practiced using brine as heat source. In this case, as steam is the inlet phase from the reservoir (see Figure 4), the extraction of the NCG must be operated, in presence of phase change at the ORC evaporator (which is both a geothermal steam condenser and a R245fa superheater). NCG must be eliminated from the condensing surface of the heat exchanger, and the same compression service assures the achievement of the appropriate high pressure for reinjection.

The drilling pad area and the ORC plant are close enough to avoid a long pipeline, as it could usually happen in geothermal projects. The possibility of building the power station near to the wells increases the sustainability of this project in terms of territory occupation and pipeline avoided.

The ORC condenser is cooled with ambient air (design temperature is 20 °C, Table 1). No water is consumed to cool down the hot working fluid from the recuperator. Environmental impact is reduced by using air as a coolant, by having the disadvantage of a greater footprint of the ACC unit. The ACC is designed in order to match the full heat transfer capacity in case the TEX must be by-passed (e.g. start-up, stop).

6. CONCLUSIONS

Castelnuovo Val di Cecina will be the first ORC geothermal plant in Italy in the context of the "pilot plants". The net expected power will be 5 MW, based on the current design data indicated by Magma Energy. The working fluid used for the design of the plant is non toxic, non flammable/explosive, and it has a null ODP. The inlet geofluid is at the vapour state, so that a condensation must be performed to transfer the heat to the ORC plant. A total reinjection (closed loop) system is used to bring again the brine to the reservoir formation, and a compression system is used to guarantee the reinjection of the NCGs, while the condensate geofluid could be reinjected at atmospheric pressure. The numerical simulations about the reservoir response to exploitation confirm that the lifetime of the production is possible with the described reinjection strategy. The separate NCG treatment and compression management can be considered has a challenging and innovative aspect, respect to the common practice of geothermal ORC plants. The cooling media for the condenser is ambient air.

The plant is designed to minimize the environmental impact and it matches the objectives of the national policy about energy production. The exploitation of a geothermal steam directly for ORC application is a novel practice in the Larderello reservoir area. It is a challenging and technologically advanced project, and it will probably be the first "pilot plant" to be built in Italy according to the current Italian Ministry permitting procedure.

Acronyms

ACC	Air Cooled Condenser
NCG	Non Condensable Gases
ODP	Ozone Depletion Potential
ORC	Organic Rankine Cycle
RAM	Reliability, Availability & Maintainability
TEX	Turboexpander
VFD	Variable Frequency Drive
WF	Working Fluid

REFERENCES

Golder Associates & Magma Energy Italia, CAS.02.DE.AM.R.005 – Studio di impatto ambientale ridotto (2015). Available at Italian Ministry for Environment website: http://www.va.minambiente.it/File/Documento/160917

Barelli A., Bertini G., Buonasorte G., Cappetti G. Fiordelisi A.: Recent deep exploration results at the margins of the Larderello Travale geothermal system, *Proceedings World Geothermal Congress 2000*, Kyushu - Tohoku, Japan, (2000), paper # R0730.

Batini F., Bertani R., Ciulli B., Fiordelisi A., Valenti P.: Geophysical Well Logging- A contribution to the fractures characterization, *Proceedings 27th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, (2002), paper #SGP-TR-171.

Cappetti G., Fiordelisi A., Casini M., Ciuffi S., Mazzotti A.: A New Deep Exploration Program and Preliminary Results of a 3D Seismic Survey in the Larderello-Travale Geothermal Field (Italy). *Proceedings World Geothermal Congress 2005*, Antalya, Turkey, (2005), paper #0759.

Gunnarsson I., Arnórsson S.: Silica scaling: The main obstacle in efficient use of high-temperature geothermal fluids, *International Geothermal Conference*, Reykjavík, Iceland, (2003), Session #13.

Corsi R.: Scaling and corrosion in geothermal equipment: problems and preventive measures, *Geothermics*, Vol. 15, No. 5/6 (1986) 839–856.

Axelsson G.: Sustainable geothermal utilization – Case histories; definitions; research issues and modelling, *Geothermics*, 39 (2010) 283–291.

DiPippo R.: Geothermal Power Plants, DiPippo R. Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact. 2nd ed., *Butterworth-Heinemann (Elsevier)*, New York, USA, (2008).

Huenges E. (editor): Geothermal Energy Systems. *WILEY-VCH*, 2010.

Stacey R.W., Norris L., Lisi, S.: OLGA Modeling Results for Single Well Reinjection of Non-Condensable Gases (NCGs) and Water. Geothermal Resources Council, October 23-26, 2016, Sacramento, California (Submitted paper).

Kaya E., Zarrouk S.J., O'Sullivan M.J.: Reinjection in geothermal fields: a review of worldwide experience, *Renewable and Sustainable Energy Reviews*, 15 (2011) 47–68.

Acknowledgements

The Authors wish to thank: Michelle Sullera, Stefano Scagliarini and Robert Stacey at GeothermEx / Schlumberger; Vera Trinciarelli, Marco Pucci, Fausto Bellini and Luca Guglielmetti at Magma Energy Italia.