Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

The Cerro Pabellón Geothermal Project (Chile): from Surface Exploration to Energy Production

Guido Cappetti[1], Nadia Giorgi[2], Alessia Arias[2], Gianni Volpi[3], Germain Rivera[3], Maurizio Cei[2], Maurizio Fedeli[2], Giuseppe Di Marzio[3], Martino Pasti[3], Stefano Massei[2] and Francesco Baccarin[2]

[1]Geotermica del Norte, Av. Santa Rosa 76, Santiago, Chile

[2]Enel Green Power, Via A. Pisano 120, 56122 Pisa, Italy

[3]Enel Green Power Chile, Av. Santa Rosa 76, Santiago, Chile

guido.cappetti@enel.com

Keywords: Cerro Pabellón, Apacheta, geothermal field, liquid dominated reservoir, hydrothermal alteration, environment, high enthalpy binary power plant.

ABSTRACT

Cerro Pabellón is one of the most challenging geothermal project so far developed worldwide. Located in the northern part of Chile, 120 km north-east of Calama city (Antofagasta region), on the Pampa Apacheta, it represents the first commercial power plant in South America and is also the first utility-scale geothermal plant built worldwide at 4,500 meters a.s.l.. The geothermal field is located in a volcanic area, beside the Apacheta-Aguilucho volcanic complex, in correspondence of a well-defined graben structure characterized by a recent volcanic dome (about 50.000 yrs.).

Since the geothermal field is considered as blind – with only two volcanic fumaroles on the top of Cerro Apacheta – a shallow borehole (187 m depth) drilled by Codelco (Corporación Nacional del Cobre, Chile) for water research represented the main indicator to activate a geothermal project, as it found steam (88°C) instead of tapping the expected cold water aquifer. In this area, the complete exploration and development of the geothermal project was conducted by Geotérmica del Norte (GDN), starting in 2002 with the assignment of the exploration mining lease (330 km^2). During all the phases of the project, a great attention was put both in the environmental aspects and in the relations with local communities, in a logic of sustainable development.

After a phase of shallow exploration surveys (geology and geophysics) and a corehole of 560 m depth, four deep commercial diameters exploratory wells were drilled in 2009-2010, showing the presence of a geothermal reservoir with temperatures of 250-260 °C at depths over 1500 m. According to these positive results, a development program was implemented, including the drilling of additional wells for production and reinjection purposes, the construction of a power plant, the gathering system and 80 km high voltage transmission line (220 kV) that connects the plant to the main transmission network. Because of the remote location and the extreme characteristics in terms of altitude and climatic conditions, a project's base camp was built about 25 km from the project area at an elevation of 3,850 m a.s.l., powered by an innovative system of photovoltaic energy production and storage. The construction activities of the Cerro Pabellón project began in July 2015 by GDN and in March 2017, the plant started its commissioning phase. The 48 MWe gross ORC power plant is composed of two twin units (24 MWe each) and represents one of the few examples of high enthalpy binary power plant in the world, selected in accordance with the resource characteristics and with the extreme climatic operating condition.

Cerro Pabellón will avoid the emission of more than 166,000 tons of CO_2 into the atmosphere per year and it will contribute to diversify Chile's energy mix and to mitigate the country's dependence on fuel imports. Considering that the fluid production and the reinjection capabilities currently available from existing wells exceeds the power plant capacity, the construction of an additional 33 MWe gross unit, same binary cycle type, is scheduled to start in the second half of 2019.

1. INTRODUCTION

Cerro Pabellón is the first geothermal project developed in Chile and in all South America so far (Lahsen et al., 2005; 2010; 2015). It is located in the northern part of Chile, in Ollagüe district, Antofagasta region (Figure 1) and was developed by Geotérmica del Norte S.A. (GDN), at present a joint venture between Enel Green Power (EGP) 84.6% and Empresa Nacional del Petróleo (Enap) 15.4% shares.

The project is a green field one, in a geothermal area characterized by surface "blind" condition with only two fumaroles on the top of the surrounding volcano Cerro Apacheta that did not allow an easy recognizing of the resource potential. GDN initiated the shallow exploration in 2006 arriving at the commissioning of a 48 MW power plant (CP-I and CP-II units) in 2017.

The purpose of this work is to describe the different phases of the geothermal project, starting from the first exploration activities up to the production, but above all to highlight the peculiarities of the Cerro Pabellón (Co. Pabellón in the following) project due to its particular location.

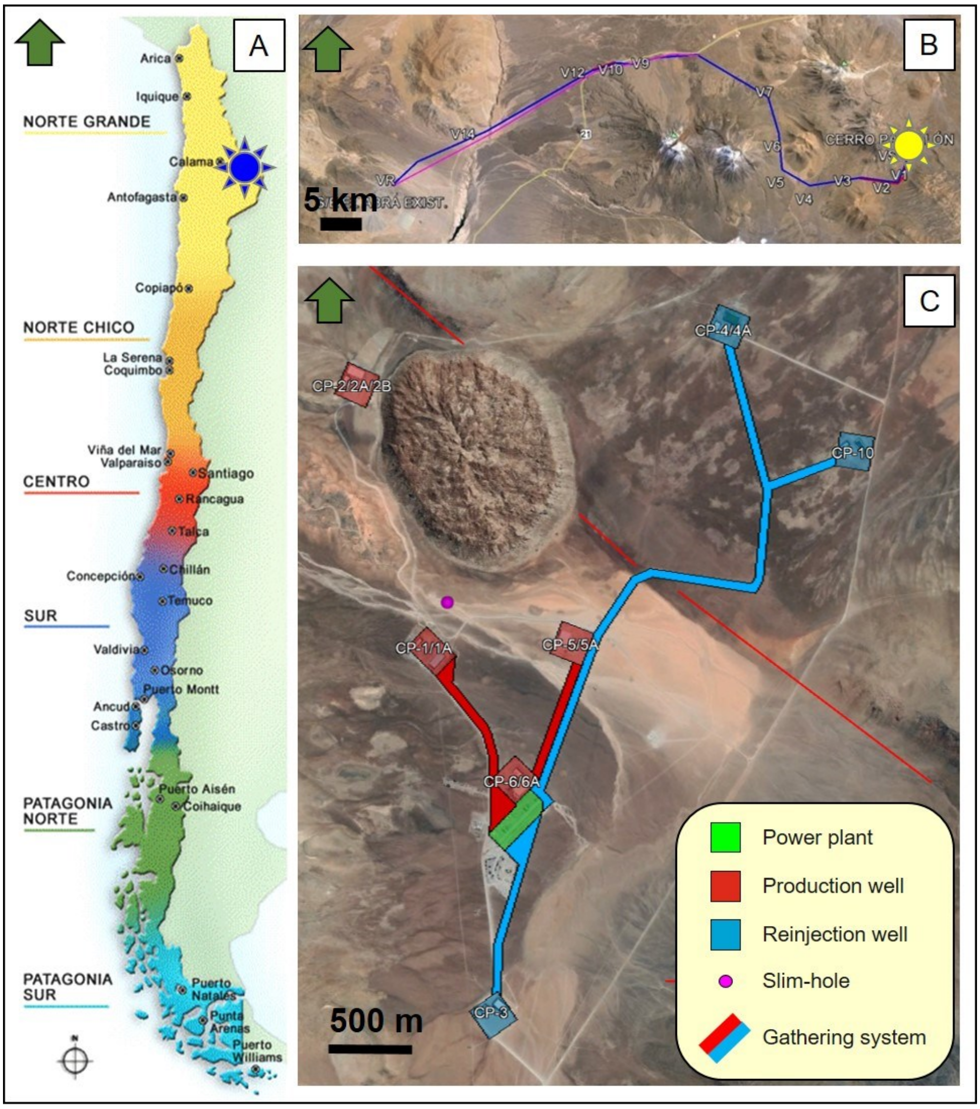

Figure 1: (A) Location of Cerro Pabellón project in Northern Chile. (B) Layout of the transmission line (yellow star indicates the Cerro Pabellón geothermal field). (C) Detail of the geothermal field in Pampa Apacheta, with the present assets (drilling pads, power plant and gathering system).

2. PROJECT DESCRIPTION AND HISTORY

Evidences of thermal activity in the Pampa Apacheta area began to appear in 1993, when Codelco drilled a well for fresh water research near the Co. Pabellón Dome: without tapping the "water table", the well started producing a small amount of steam at 88 °C and 187 m depth.

At the end of '90s, Enap and Unocal conducted the first geothermal-oriented geological surveys in the area. Furthermore, the existence of two superheated fumaroles (109-118°C) at the top of Apacheta Volcano suggested that some kind of thermal anomaly should exist in Pampa Apacheta, especially in correspondence (or within) a well-defined graben structure, clearly visible from aerial photos and satellite images (Figure 2). Based on geochemical sampling and analysis of gases of the fumaroles, Urzua et al. (2002) inferred the presence of a deep geothermal reservoir at temperature in the order of 250 – 325°C, while Aguilera et al. (2006) found in the same fumaroles magmatic signatures (HCl and SO_2) not compatible with a geothermal source.

On December 2000 was constituted the company GDN, as a Joint Venture between Enap (51%) and Codelco (49%), with the aim to explore the geothermal resources in the northern Chile, including the area of Apacheta among others. The first geothermal exploration lease in the Apacheta area is dated 2002. In 2005, Enel Green Power joined the company buying most of the Codelco shares, with a progressive increase of participation in the following years. At present, EGP owns 84.6% and Enap 15.6% of shares in GDN.

2.1 Prefeasibility Stage: Surface Exploration

During 2002, at the beginning of the exploration lease validity, some geological, geochemical and geophysical surveys were carried out by GDN, ending with the very first conceptual model of the area (Urzua et al., 2002). In 2005, with the entry of Enel Green Power, new field surveys were executed, including an extended 3DMT study of 120 sites and a detailed geo-structural study, with the aim to update the conceptual model of the Co Pabellón geothermal system. To put some constraints into the model, in 2007 a corehole of 560 m depth was drilled (slim-hole in Figure 1). The results were encouraging with temperature values in excess of 200 ºC measured at the well bottom. The favorable geo-structural conditions (Apacheta Graben in Figure 2), the interesting MT survey data and the thermal results of the corehole allowed constructing a solid conceptual model in 2008. On the base of this model, GDN took the decision to continue investing in the Co Pabellón project with a deep exploration phase consisting in four wells of commercial diameter up to about 2,000 m depth.

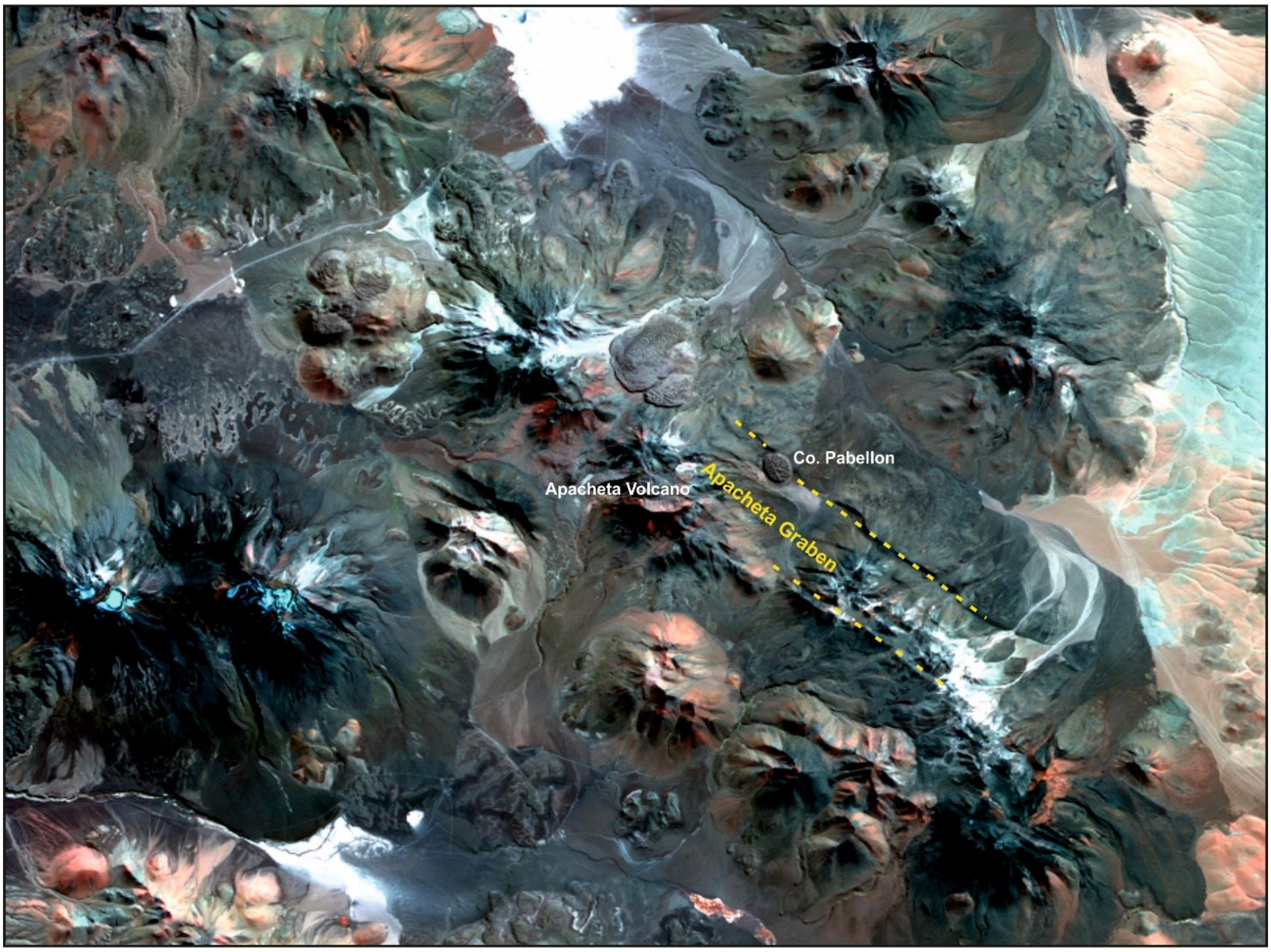

Figure 2: Satellite image with the location of the Apacheta graben (yellow dotted lines) and Cerro Pabellón dome.

2.2 Feasibility Stage: Deep Exploration

The deep exploration phase took place between 2009 and 2010. Four wells were drilled, three inside the Apacheta Graben (CP-1, CP-2, CP-3), and one outside it (CP-4), in order to check out the role of the graben itself in the development of the geothermal system. The location of these wells is shown in Figure 3. Data from volcanological evolution of the area indicate that the magmatism is not active anymore but is recent on both the borders of the graben (Rivera et al., 2007; Ahumada and Mercado, 2011; Salisbury et al., 2011; Piscaglia et al., 2012; Rivera et al., 2015; Sellés and Gardeweg, 2017; Rivera et al., 2020).

The three wells drilled inside the graben confirmed the presence of a 250-260 ºC water dominated geothermal reservoir, hosted in volcanic rocks (essentially tuffs and andesitic-dacitic lavas). A heavy thermal alteration (from supergene to propylitic) was also present. The thermal anomaly had his apex in the nearby of the first drilled well (CP-1), slightly deepening both to north (CP-2 well) and south (CP-3 well). The well CP-4, drilled outside the graben, showed the lowest temperatures of the group of four. The main permeable zones are located between 1,600 and 2,000 m. A 400-500 m thick clay cap covers the propylitic reservoir.

The static temperature profile of the well CP-1, given in Figure 4, clearly showed the presence of a high permeability convective geothermal system from 400 m up to the well bottom, also if in this well the main productive zone is located at 1760 m, with a reservoir temperature of around 260°C. The total flow rate of this well resulted 330 t/h at 7.5 bar wellhead pressure (WHP).

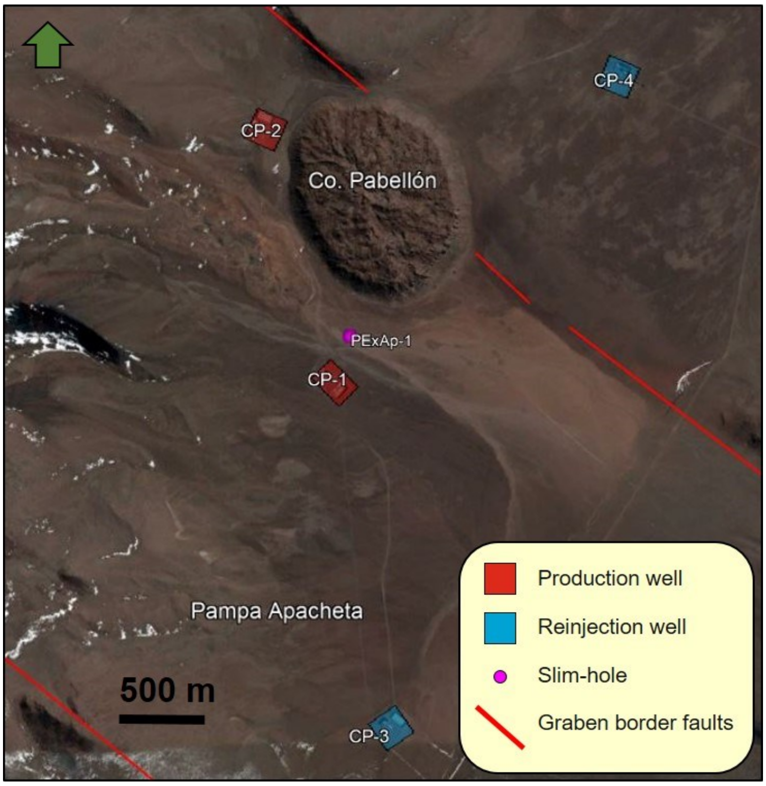

Figure 3: Location of slim-hole and deep exploration wells

Based on the good results of the deep exploration phase, between 2011 and 2014 a feasibility study for the development of a geothermal project in the Co Pabellón area was conducted. In the meantime, the environmental permits for the construction phase (RCA) were obtained. The project finally saw the green light at the end of 2014 and the construction activities began in July 2015. A total of nine additional production and reinjection wells were designed in order to reach different targets both inside (production) and outside (reinjection) the Apacheta Graben.

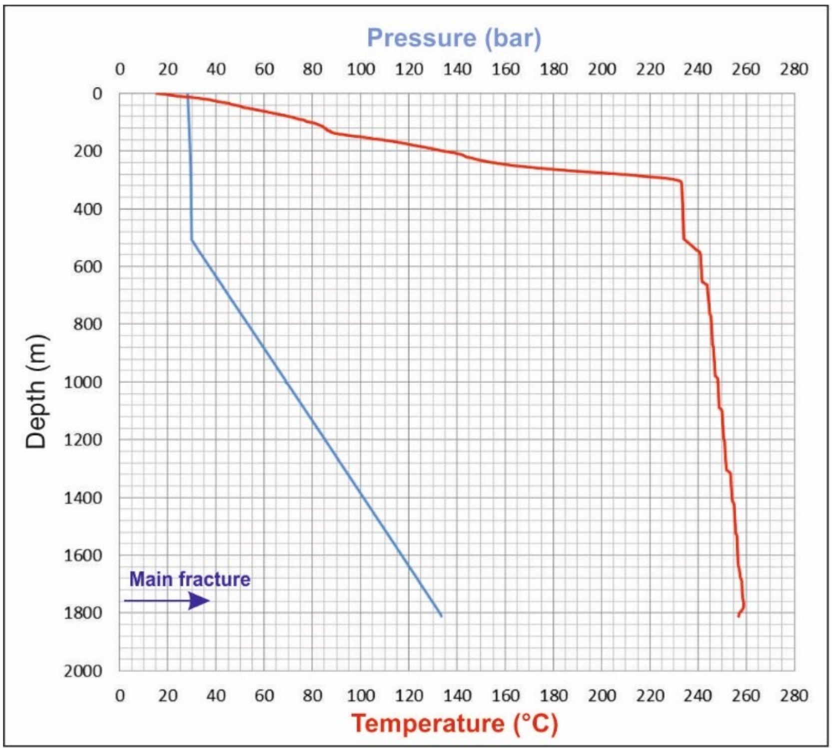

Figure 4: CP-1 well static temperature and pressure profile

2.3 Development Stage: drilling activity and resource characteristics

Following the Feasibility Stage, in 2015-2017, the nine scheduled new wells were drilled and one previous exploratory well was deepened (CP-3). The results of the drilled wells and of the CP-3 deepening resulted very positive, both for production and reinjection purposes. Among all the 13 wells drilled during the exploration and development phases, only one well (CP-2) is considered unusable because of the low production characteristics. At present six production and four reinjection wells are connected to the power plant.

The drilling activity was performed in really short time, even if conducted in very serious environmental conditions and using a single automatic drilling rig, but with a strong attention in reducing the moving from one pad to the next. Since working at high altitude considerably reduces the diesel generators capacity, they were modified in order to increase the power and reduce the fuel consumption and pollution. Moreover, the high altitude and the low temperature affect drilling activity reducing the worker performances: a winterizing drilling rig was necessary to avoid freezing of water and hydraulic lines and to allow people to work in acceptable conditions even with very low temperature and strong winds. In such extreme climatic condition, the automatic drilling rig permitted to operate without significant interruptions of drilling activity. Finally, every worker, even all the truck drivers arriving to the drilling site, were checked with specific medical examinations to be certified for high altitude activity.

The production zone was confirmed located inside the Apacheta Graben, on the west and south zones respect to Co Pabellón acid dome (Figure 1C). As already indicated by deep exploration, the development drillings confirmed the decision to locate the reinjection pole mainly on the northeast, in an area outside the main graben depression. In fact, due to the volcano-tectonic evolution of the Apacheta area (Rivera et al., 2007; Ahumada and Mercado, 2010; Rivera et al., 2015, Sellés and Gardeweg, 2017; Baccarin et al, 2020; Rivera et al., 2020), the stratigraphy, fracture distribution and well characteristics between the two zones are different, i.e. the geothermal system out of the graben is significantly deeper, although showing the same reservoir pressure.

The mean well depth is highly variable, ranging from 450 to 2,500 m for the production wells and around 2,500 – 3,000 m for the reinjection ones. The cap rock thickness is from 400 to 900 m in the production zone and from 1000 to 1500 m in the reinjection area and it is generally identified with the transition to the propylitic facies of hydrothermal alteration assemblages. The main productive layers are generally located at 1,500 – 2,000 m depth, also if CP-5 well, located in the central part of the graben, crossed a fractured layer at about 400 m with mainly steam production. The fractures are mostly located in dacitic tuffs but also some in lithic tuffs and andesitic lavas; in the area selected for reinjection (outside Apacheta Graben) fractures are at greater depth (up to 3,000 m) and with temperature values about 30-50 °C lower than in the production core. Beside this thermal difference, the static pressure values of the main fractures lie on the same altitude/pressure line for all the drilled wells, both inside and outside the Apacheta Graben, indicating that they all belong to the same geothermal aquifer.

From a production point of view, the eight productive wells are able to furnish more than 2000 t/h of fluid, with a steam title from 15 to 35%. Just CP-5 well represents an exception as it arrives to produce 90% steam. The performed injection tests indicate that the reinjection wells are capable to accept more than 2000 t/h of water.

2.4 Development Stage: design and construction of surface plants

The performed construction activities include:

- Power plant with 2x24 MW High Enthalpy Organic Ranking Cycle Units (HE-ORC);
- Gathering system to connect the production and reinjection wells to the power plant;
- A 220 kV Transmission line, 80 km length with two substations;
- A base camp for more than 700 people

The first 24 MW unit started the commissioning phase in March 2017 and three months later also the second 24 MW unit began to produce. A picture of the Cerro Pabellón plant is given in Figure 5.

Figure 5: View from south of the Co Pabellón geothermal area. In the foreground, the Co Pabellón power plant and the CP-6 drilling pad. In the background the CP-1 (on the left) and CP-5 (on the right) drilling pads and the Co. Pabellón Dome behind them.

2.4.1 Power plant

The Co Pabellón power plant is composed of two ORMAT Energy Converter units. Each unit includes two separate identical organic Rankine cycles, with a vaporizer, preheater and a recuperator in each cycle. The Motive Fluid (MF) is isopentane that is cycled in a closed circuit by the feed pumps through the recuperator, preheater and vaporizer in which it is heated and vaporized. The MF in vapor phase feed the turbine and then it is condensed in an Air-Cooled Condenser (ACC) back to liquid phase to the feed pumps.

A simplified scheme of one ORMAT Energy Converter unit is given in Figure 6.

The innovative choice of using binary technology with high-enthalpy geothermal fluids instead of traditional flash steam technology was due to the unique and extreme characteristics of the location, in terms of geographic altitude and climate conditions. At the same time, this allowed to reach the highest standards of environmental performance, assuring the total reinjection of the fluid to the geothermal reservoir.

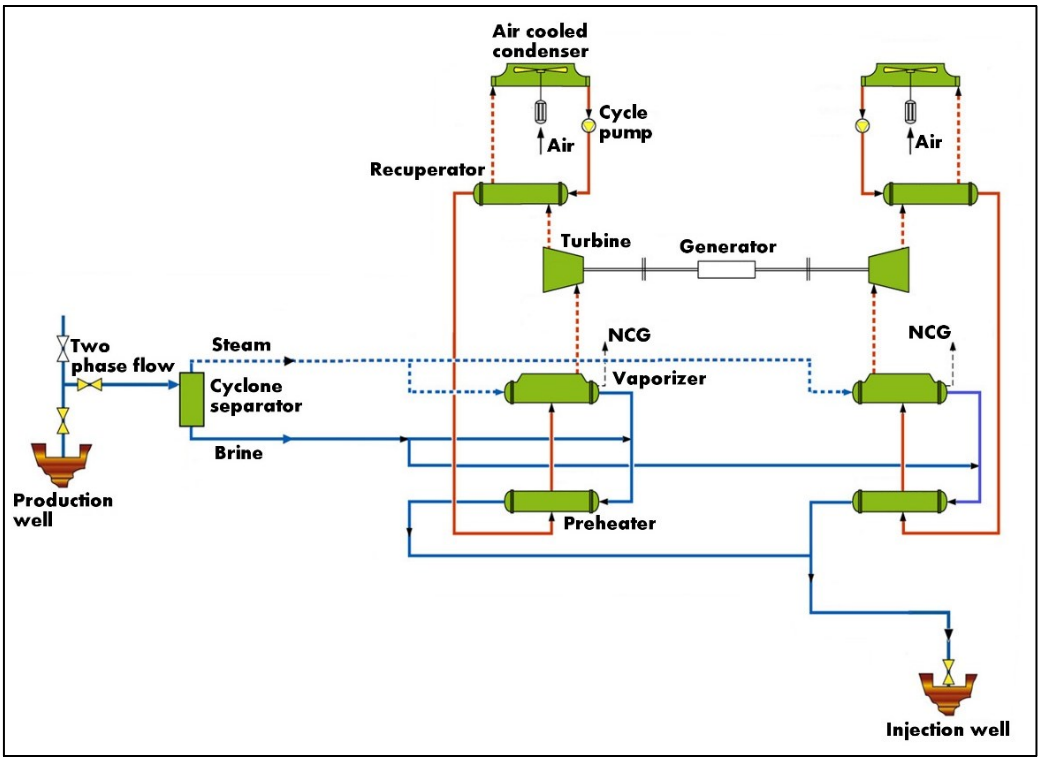

Figure 6: Simplified scheme of one ORMAT Energy Converter unit

2.4.2 Gathering system

According to the almost flat topographic characteristic of the area, and with the power plant location at an elevation a few meters lower than the three production pads (six production wells), the gathering system was designed to transfer the geothermal fluid in two-phase flow from the production wells to the separation area, located in correspondence of the power plant.

The steam is flowing through the vaporizer and the brine, mixed with the steam condensate, is flowing through the preheater. Brine and Condensate are then boosted by the injection pumps to the three reinjection wells located in two pads in the norther area. The well CP-3, located in the southern part of the graben, is also used for reinjection.

2.4.3 Transmission line

To connect the power plant to the main electrical transmission network an 80 km transmission line was built, 220 kV, single circuit, with a rated capacity of 110 MVA. The altitude of the path is between 4,500 and 3,000 m a.s.l., with maximum slope of 27%.

Two substation were also built, one in correspondence of the power plant and the other in correspondence of the interconnection with the main transmission line feeding the El Abra mining company, located at around 3,000 m altitude.

In Figure 1B the lay out of the transmission line is given.

2.4.4 Base camp

Because of the remote location, the high altitude, and the severe climate conditions of the project area, a camp for more than 700 people was built at 3,850 m elevation, 25 km from the plant. An innovative plant of energy production by solar PV and energy storage by lithium batteries and hydrogen was also installed there to produce electricity 24/7, free of CO_2 emission.

2.4.5 Design peculiarities

The peculiarities of the design for the Co Pabellón power plant were essentially linked to the low density of the air at 4,500 m a.s.l. and to the adverse climate conditions of the Atacama Altiplano desert. The climate is extremely dry, with an annual average temperature of about 2 °C and minimum values of around -25 °C.

The electrical design for all the systems in the whole project required particular attention due to the negative effect of the altitude. At 4,500 m a.s.l. the air density is about 40% less than at sea level which causes reduced heat transfer capability as well as worse dielectric properties. Most of the electrical design standards indicate that electrical components can operate safely at elevations between sea level and 1,000 m a.s.l.. The Co Pabellón project, being located well above the standards range of application, required custom design for all electrical equipment.

Cooling systems were specifically designed to take into account the reduced heat transfer rates resulting usually in bigger exchange surfaces and optimized geometries to favor the heat rejection. Worse dielectric properties required the introduction of an important derating design factor, increasing the size of the electrical equipment and in some case suggesting the use of gas insulated enclosures to ensure the electrical insulation of the components. All the installations, from the power plant to the substation and the transmission line, were affected by these considerations.

Engineers often expect carbon steel equipment to be, if not rated, at least suitable for service at temperatures as low as -29 °C. This is an often-assumed point below which many grades of carbon steel can undergo a transition from a ductile to a brittle material. For the reason above, all the process and structural piping was requested with a Charpy certification for 27 J at -20 °C.

3. SOCIAL AND ENVIRONMENTAL SUSTAINABILITY

3.1 Social sustainability

In the Project's area, there are six indigenous communities of Quechua and Atacameño origin: Ollagüe, Toconce, Conchi Viejo, Estación San Pedro, Cupo, and Taira that hold ancestral territorial rights. From the beginning of the project an extensive process of dialogue between GDN and the communities, with also the participation of representatives of Chilean Ministry of Energy, was carried out to explain the project and to elaborate programs aimed at the developments of social, patrimonial, cultural and economic aspects of the communities. In 2015, specific agreements were signed to provide annual contributions to the communities for a period of 10 years, which will be used for the implementation of projects proposed by the communities and relevant to the aspects above mentioned.

In addition to the economic contributions, others important initiatives were developed with the indigenous communities as follows:

- Small companies' community owned (SME): Six new SME, mostly managed by women, provided services to the Cerro Pabellón Camp in the areas of cleaning, transport, food (cold snacks), laundry, and management of the site's internal sales kiosk. This initiative has generated more than 40 new jobs, with an equivalent turnover of more than 1 MUSD in two years.
- Conservation of historical and anthropological patrimony: During all the period of construction, an important cultural supervision activity was carried out to protect indigenous patrimony, with personnel from the latter communities, which worked together the experts contracted by GDN for the environmental and archaeological monitoring, with criteria of cultural belonging, relating to the history of the local populations. All these initiatives also guarantee the creation of new professional skills, a human capital that in the future will be able to offer these services to the local market and in particular to the other industries present in the Region.
- Program for tourism development: A plan for the tourism development in all the Alto el Loa area was elaborated together with representatives of the communities, and is now in a phase of implementation.
- Rural electrification: The agreements signed with the communities include also a rural electrification program. The electrification of two communities (Ollague and Toconce) has been already completed, while the programs for the relevant communities are in progress.
  The first to benefit was the community of **Ollague** with its 120 homes. The village now counts with energy supply 24/7 through a hybrid plant. The hybrid off-grid project includes:
    - Solar PV: 205 kWp Thin film modules;
    - Storage: 752 kWh Sodium Nickel Chloride batteries;
    - Mini Wind turbine: 30 kW;
    - Backup Diesel: 250 kW.

  The availability of electricity 24/7 has brought significant improvements in the population's quality of life, with also the possibility of undertaking business initiatives.
  In addition, a "roof top" solar system with batteries now powers **Toconce**, another village of the Alto Loa. It supplies 24/7 energy to a village of 90 homes in a desert area of Chile with the following advantages:
    - Removing their access restriction to energy during nighttime (no supply from 1 to 8 AM);
    - Minimizing the consumption of fuel from existing diesel generator;
    - Testing advanced renewable technologies based on solar-battery system in a harsh environment, with strong temperature variations between day and night and extreme solar radiation in rarefied atmosphere.

3.2 Environmental sustainability

Since the beginning of the deep exploration phase (2009) and even more during the construction phase (2015-2018), the Co Pabellón Project was observed with great attention by the environmental authorities, being the first geothermal project in Chile (and South-

America). Several meetings and Q&A sessions with the authorities were required to solve some misleading, create a sort of “geothermal culture in the country”, and finally obtain the environmental permit for the construction (or RCA, 2012).

Because of the desert conditions and the strong interest of the mining companies in the utilization of the water resources for their industrial processes, the environmental authorities put a strong attention to hydrogeological aspects. Even if the geothermal fluid is reinjected back to the reservoir, the authorities obliged GDN to perform a strict monitoring program of both the shallow aquifers and the deep geothermal reservoir. A base line monitoring campaign was developed from the beginning of the construction phase in order to have a benchmark to compare with the data acquired during the operation period.

For a sustainable electricity generation in the campsite an innovative pilot plant CO_2 emission free, commercial size, composed of a PV plant and a Hydrogen Storage technology together with electrochemical batteries was installed. The energy produced 24/7 basis covers the energy needs of the wastewater purification plant and other utilities of the camp. This plant shows that it is possible to build renewable micro grids, capable of guaranteeing the permanent generation of clean and efficient energy. It has been an Enel Green Power initiative with the technological support of Electro Power Systems (EPS).

To reduce the camp ecological footprint, in addition to the above pilot plant, strong attention was put in reducing water consumption by using a treatment plant and in waste recycling. Moreover, the complete neutralization of the CO_2 footprint was achieved buying CO_2 credits in the international market. For these results, GDN received an award in 2017 from the Ministry of Environment.

4. CONCLUSION

The exploration of the Pampa Apacheta Geothermal System was initiated many years ago and, despite the difficulties due to the remote location, the altitude and the serious atmospheric conditions, the 48 MWe Co Pabellón plant, developed by GDN, is in operation from 2017.

The geothermal system is apparently controlled by a local graben (Graben de Apacheta o Pabelloncito), where volcanic fractured rocks hosts a geothermal reservoir with a maximum fluid temperature around 250 - 260 °C and a main permeable zone located at 1,500 - 2,200 m depth. Thirteen wells for production and reinjection purposes were drilled so far and only one of them, with low productivity, will not be used for the plant operation. The success ratio of the drilling resulted therefore over 90%.

Co Pabellón power plant is one of a few high enthalpy organic rankine cycle in the world and is one of the largest single-site binary plant in the world. Moreover, it is the first commercial geothermal power plant in South America and the highest worldwide (4,500 m a.s.l.). Connected to the binary power plant construction, another series of equally innovative and sustainable initiatives were developed, relevant to social and environmental sustainability in the surroundings, such as:

- Long term and constructive relationship with communities of Alto el Loa region, with economic support for programs aimed at the developments of social, patrimonial, cultural and economic aspects;
- Rural electrification and tourism development;
- A hydrogen-based hybrid pilot plant for 100% renewable 24/7 electricity supply to some utilities of the camp.

Co Pabellón will avoid the emission of more than 166,000 tons of CO_2 into the atmosphere per year and it will contribute to diversify Chile's energy mix and to mitigate the country's dependence on fuel imports. Considering that the production and the reinjection capabilities of the wells exceeds the power plant capacity, the construction of an additional 33 MWe gross unit, same binary cycle type, is scheduled to start in the second half of 2019.

REFERENCES

Aguilera, F., Tassi, F., Medina, E., Vaselli, O.: 2006. Geothermal Resource Exploration in Northern Chile: Constrains from Organic and Inorganic Gas Composition. Actas XI Congreso Geologico Chileno, 7-11 August 2006, Antofagasta, II Region, Chile, Simposio Geotermia, **2**, (2006).

Ahumada, S.R., and Mercado, J.L.: Evolución geológica y estructural del Complejo Volcánico Apacheta-Aguilucho (CVAA), Segunda Región, Chile. *Memoria de Título (Inédito)*, Universidad Católica del Norte, Dep. Ciencias Geológicas, Antofagasta (2010).

Baccarin, F., Volpi, G., Rivera, G., Giorgi, N., Arias, A., Giudetti, G., Cei, M., Cecioni, M., Rojas, L., and Ramirez, C.: Cerro Pabellón Geothermal Field (Chile): Geoscientific Feature and 3D Geothermal Model. *Proceedings,* World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, (2020).

Lahsen, A., Sepúlveda, F., Rojas, J., and Palacios, C.: Present status of geothermal exploration in Chile. *Proceedings*, World Geothermal Congress 2005, Antalya, Turkey, 24-25 April 2005 (2005).

Lahsen, A., Muñoz, N., and Parada, M.A.: Geothermal development in Chile. *Proceedings*, World Geothermal Congress 2010, Bali, Indonesia, 25-29 April, 2010 (2010).

Lahsen, A., Rojas J., Morata D. and Aravena D.: 2015 Geothermal Exploration in Chile: Country Update, *Proceedings*, World Geothermal Congress 2015, Melbourne, Australia, April 19 - 24, 2015 (2015)

Piscaglia, F.: The High Temperature Geothermal Field of the Apacheta-Aguilucho Volcanic Complex (Northern Chile): Geo-Petrographic Surface Exploration, Crustal Heat Sources and Cap-Rocks, *Plinius* **38** (2012), 148-153.

Renzulli, A., Menna, M., Tibaldi, A. and Flude, S.: New data of surface geology, petrology and Ar-Ar geochronology of the Altiplano-Puna Volcanic Complex (northern Chile) in the framework of future geothermal exploration. In: Congreso Geológico Chileno, Antofagasta, **11**, Actas 2 (2006): 307-310.

Rivera, G., Radic, J., Pincheira, W., Ramírez, C., and Bona, P.: Concesión Geotérmica "Apacheta" - Informe Geológico. Empresa Nacional de Geotermia S.A. (ENG), Internal report (unpublished), (2007).

Rivera, G., Morata, D., and Ramírez, C.F.: Evolución vulcanológica y tectónica del área del cordón volcánico Cerro del Azufre-Cerro de Inacaliri y su relación con el sistema geotérmico de Pampa Apacheta, II Región de Antofagasta, Chile. In: XIV Congreso Geológico Chileno, La Serena, *Actas* **14** (4) (2015).

Rivera, G., Morata, D., Ramirez, C. and Volpi, G.: Volcanic and tectonic evolution of Azufre – Inacaliri volcanic chain and Cerro Pabellón geothermal field (northern Chile). *Proceedings,* World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, (2020).

Salisbury, M.J., Jicha, B.R., de Silva, S.L., Singer, B.S., Jiménez, N.C., and Ort, M.H.: $^{40}Ar/^{39}Ar$ chronostratigraphy of Altiplano-Puna volcanic complex ignimbrites reveals the development of a major magmatic province. *Geological Society of America Bulletin*, **123** (5), (2011), 821-840.

Urzua, L., Powell, T., Cumming, W.B., and Dobson, P.: Apacheta, a new geothermal prospect in northern Chile. Geothermal Resources Council Annual Meeting, Reno, NV, *Actas,* **26**, (2002), 65-69.

Sellés, D.; and Gardeweg, M.: Geología del Área Ascotán – Cerro Inacaliri, Región de Antofagasta. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 190: 73 p., map scale 1:100.000, Santiago (2017).