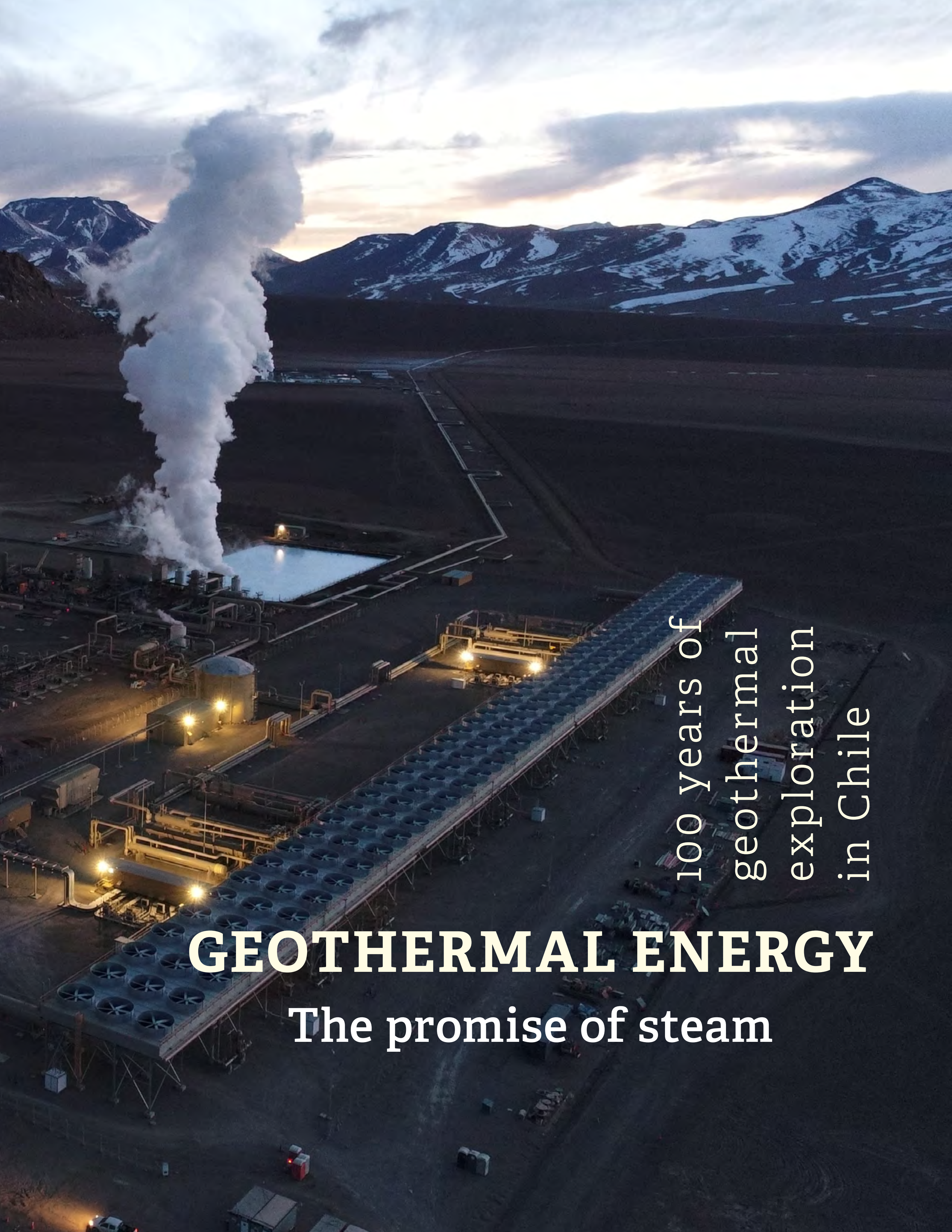


100 years of geothermal exploration in Chile

GEOTHERMAL ENERGY

The promise of steam

100 years of geothermal exploration in Chile

GEOTHERMAL ENERGY

The promise of steam

100 years of geothermal exploration in Chile

CREDITS

ISBN: 978-956-9130-60-1
Propiedad Intelectual: 2022-A-6031

CREDITS

Executive Director: Alberto Larraín Salas
Project coordination: Fernanda González Undurraga
Conception and writing: Claudio Betsalel Atías, Mauricio Electorat Müller
General editing: Fernanda González Undurraga, Gonzalo Salamanca Osorio and Pamela Silva Valenzuela
Art direction and design: Alejandra Lührs Berger, MUSEAL
Graphics: Karin Piwonka Bärthold
Translation of report by E. Tocchi: Mauricio Electorat Müller and Gonzalo Salamanca Osorio
English translation: Patricia Julia Geuther

Free distribution
ProCultura Foundation
Project under the Cultural Donation Law
First edition, Santiago, Chile, April 2022

ÍNDICE

Aerial view of the Cerro Pabellón geothermal power plant (Ollagüe, Chile). Enel (Chile).

The publication of the book " Geothermal energy, the promise of steam", in digital version, is an invitation to share a journey -started more than a century ago- in search of geothermal energy in Chile. It is aimed not only at those interested in earth sciences, who will certainly find unpublished background of the precursor research of this resource, but also aims to reach a wider audience, in classrooms and outside of them. Those who want to investigate from other perspectives this journey that has been a pioneering one and has shaped - in a leading way - the path of a new industry in South America. It is a story of many voices that end up building a proposal whose first sketch was made by a Tuscan engineer, Ettore Tocchi, who arrived at the port of Antofagasta in November 1921. He arrived confident in his knowledge of a new technology that was taking its first steps outside Italy, and he was in charge of implementing it in this country.

This is a book for all those who want to become familiar with the challenging and tenacious history of the search in the Atacama Desert for one of the energy sources that is still little known among renewable energies. Despite being one of the oldest and noblest if we consider its permanent availability and diversity of uses.

The journey of geothermal energy in this part of the world has been tricky and not without difficulties. These challenges, which started in the Tuscan town of Larderello, have been overcome by a team of countless professionals of all disciplines and nationalities. This story gathers the testimony of those lives. The first ones devoted to exploration, complemented with the professional and vital adventure of those who, as a corollary, fulfilled the mission entrusted to build a geothermal industry in Chile.

James Lee Stancampiano
Director of Argentina and
Chile Enel Green Power
and Thermal Generation

Fabrizio Barderi
CEO Enel Chile

When we talk about industrial heritage in Chile, it is necessary to understand that it is part of our identity, of the community and of our history.

Knowing its origin, its anecdotes, processes and challenges, in addition to its technical aspects, allows us to understand not only the product or service they provide to the country, but also to recognize its community, its professionals. And to value them as part of our biography and acknowledge the impact they have had on the economic and social development of the country.

On the 100th anniversary of the first geothermal energy explorations in Chile, this book celebrates and provides unprecedented background for the history of geothermal energy worldwide. It is a story that begins in 1920 with the journey of the visionary Ettore Tocchi aboard the steamship Orita and continues to this day.

Tocchi's expedition gave rise to one of the most innovative power plants in the country and around the world: it was the first in Latin America and the only one in the world to be built at that altitude.

By getting to know its history, its community and its latest achievements, we realize the relevance that electricity generation from geothermal energy had and has for Chile. Many people have contributed to its success following the path outlined by Tocchi. The commitment of all of them is reflected in the pages of this book, which highlights and values the emotional connection of those who told their stories, anecdotes and experiences for the elaboration of this material. These personal, intimate stories show us that the industrial heritage has a heart that beats strongly in all those who, in one way or another, have been part of its development.

I would like to thank Enel Chile, the National Library and the entire team in charge of this project, who in the midst of the pandemic managed to produce this publication and reconstruct, through a story full of humanity, the history and value of geothermal energy in Chile. We hope you enjoy it!

Alberto Larraín S.
Executive Director
ProCultura Foundation

Mother and children in Ollagüe. Enel (Chile).

GLOSSARY

Aquifer:

Geological formation that allows the storage and displacement or transmission of water through pores or cracks, providing significant quantities of water for exploitation in a relatively easy and economical manner.

Aeromagnetism:

Refers to the measurement of the Geomagnetic Field (GMF) with an airborne sensor. The study of the GMF can provide valuable information on the magnetic properties of rocks in a given region, properties which in turn are related to the nature of the rocks (type, mineralogical composition, etc.).

Hydrothermal alteration:

Physical and chemical changes affecting rocks where thermal fluids have circulated. These fluids, generally at high temperature and extreme pH, have the capacity to dissolve rocks and/or precipitate new minerals or natural elements. On the ground, they can be recognized as spots of variable extension with strong colorations of yellow, white, intense red or other tones that in some cases result in valuable mineral deposits.

Wetland:

Vegetation formation characteristic of high-altitude areas and that present permanent water saturation based on a network of running water courses, generating the favorable environment for the development of abundant fauna and vegetation adapted to high altitude climatic conditions.

Cementation:

Operation to cement the casing pipes during the construction of a well. Casing cementing is considered one of the most important operations in the drilling process. It is the necessary complement of casing to form the structure of a well, which gives continuity to the operations, and ensures the correct completion of the well and assures its duration and functionality over time.

Adventitious (or parasitic) center:

Pyroclastic and/or lava emission center located on the flank of a volcano characterized by having the same magma supply source as the volcano.

Pacific Ring of Fire:

Area along the shores of the Pacific Ocean, including the entire Chilean coast, which is characterized by concentrating some of the most important subduction zones around the world, causing intense seismic and volcanic activity. The great potential Chile has for the generation of geothermal energy and the exploitation of geothermal resources in general is explained by its privileged location within this global geological feature.

Volcanic complex:

A set of emission centers composed of various volcanic rocks (domes, lavas and/or pyroclastic deposits) characterized by persistent volcanic activity that is spatially, temporally and genetically related.

Geothermal exploration concession:

Procedure that entitles any Chilean natural person and any legal entity incorporated under the Chilean law to apply for a geothermal energy concession and to participate in a competitive bidding for the granting of such a concession.

Crust:

It is the outermost layer of the earth (20 to 70 km deep) that constitutes the tectonic plates. It is the upper part of the lithosphere that is separated from the mantle by the Mohorovic discontinuity and is divided into continental crust and oceanic crust.

Crater:

Depression, opening or cavity, usually circular, through which pyroclasts and/or lava are emitted during an eruption.

Dome:

Circular to subcircular volcanic structure formed by the extrusion of viscous lava accumulated over an emission center. They are commonly formed inside the main crater or on the flanks of large volcanic buildings. Their slopes are unstable and often generate rock collapses.

Non-Conventional Renewable Energy (NCRE):

In Chile they are defined as the energy sources that, in their processes of transformation and utilization into useful energy, are not consumed or exhausted on a human scale. These energy sources include wind, small hydroelectric (power plants up to 20 MW), biomass and biogas, geothermal, solar and tidal.

Enthalpy:

The amount of energy that a system can exchange with its surroundings. In geothermal energy, low and high enthalpy reservoirs are defined according to the fluid temperature (less than 30°C and greater than 150°C, respectively).

Electromagnetism:

It is a branch of physics that unifies electric and magnetic phenomena, and was first formulated in detail by James Clerk Maxwell (Maxwell's equations). It is one of the four "fundamental forces" of the universe (together with gravitational and "strong" and "weak" nuclear interactions).

Structural geological studies:

Analysis of the different deformations that affect rocks as a consequence of the tectonic stresses to which they are subjected, giving rise to faults and folds. In geothermal energy the geological-structural study is fundamental for the understanding of the circulation and trapping of fluids through the rocks.

Magnetotelluric studies:

A geophysical exploration method, from the family of electro-magnetic methods, which consists of the joint measurement of the earth's magnetic field (over a wide range of frequencies) and the electric field associated with "telluric currents" induced by that magnetic field. This allows determining the electrical conductivity of the subsoil (rocks at depth), which in turn varies depending on multiple factors, such as salinity, minerology and presence of fluids.

Eruption:

Emission of lava flows, gas and/or ejection of pyroclasts from a central source or from a fissure (or set of fissures). This can range from effusive to explosive, which depends mainly on the composition of the magma, the amount of gas and water steam present.

Geothermal exploration:

Survey and evaluation of an area in order to find a reservoir with high temperature fluids. It is divided into two stages: shallow and deep. The first includes geological, hydrogeological, geochemical (thermal manifestations) and geophysical studies; the second comprises deep wells (1000 to 2000 meters).

Surface exploration:

Survey and evaluation of surface and subsurface characteristics (through indirect methods) of an area to determine the feasibility of finding a geothermal system. For this, geological, geophysical and geochemical studies of thermal manifestations (thermal springs, geysers and fumaroles) are carried out.

Subsoil exploration:

Geophysical exploration methods (e.g., GMF) consisting of the measurement of a parameter or set of parameters that allow interpretation of lithological and structural variations at depth.

Geothermal exploitation:

Obtaining the geothermal resource, a high-temperature fluid, to be used for commercial purposes, such as electricity generation, heating of homes or agricultural facilities.

Fault:

Surface or plane of discontinuity in the rock, along which the cohesion of the material is lost, presenting a measurable displacement as a consequence of the application of a shear stress.

Fracture:

Surface or plane of discontinuity in the rock that manifests itself through cracks caused by the application of intense pressure. Unlike faults, in this case there is no measurable displacement along the fracture plane.

Thermal source (thermal manifestation):

Surface manifestation of fluids at temperatures higher than those expected for natural waters. There are different thermal manifestations such as hot springs, geysers, fumaroles and mud pots, among others. Generally, the chemical composition of these manifestations evidences characteristics of the fluids in the geothermal reservoir and, from them, the temperature of the fluids deep down can be estimated.

Fumarole:

Emissions of high-temperature gases and vapors that emerge through fractures from the earth's surface. Usually associated with volcanic and/or geothermal activity.

Geyser:

Thermal manifestation in the form of a spring that sends jets of boiling water and steam abruptly and periodically into the air.

Geology:

Science that studies the Earth, the materials it is made of (rocks and minerals), the structure and spatial arrangement of these materials, and the processes (internal and surface) that affect them over time. The latter leads to the study of the evolution or geological history of a given area of study. This area of study can range from a small area of a few meters or square kilometers, to a region or district of large dimensions, including studies on a planetary scale.

Geochronology:

A field that deals with the determination of the absolute age of rocks, fossils and sediments, using different methodologies for each of these materials. These methodologies are varied, and include for example chemical techniques based on the radioactivity of certain chemical isotopes (radiometric dating) or luminescence techniques, magnetostratigraphy, etc.

Geophysics:

Ciencia que estudia la Tierra desde el punto de vista de la física y su Science that studies the earth from the point of view of physics and its subject matter includes all those phenomena related to its internal structure, physical conditions and evolutionary history of the Earth. For its investigation it uses quantitative physical methods such as seismic reflection and refraction, and a series of methods based on the measurement of gravity; electromagnetic, magnetic or electric fields and radioactive phenomena. In some cases, these methods take advantage of natural conditions or phenomena (gravity, terrestrial magnetism, tides, earthquakes, etc.) and in others they are man-made (electric fields and seismic phenomena).

Geochemistry:

A branch of geoscience that uses tools and principles of chemistry to explain the mechanisms involved in geological processes which occur in the formation of rocks and fluids. In geothermal exploration, geochemistry is used for the characterization and interpretation of processes involved in the formation of rocks, waters and gases.

Geothermal (geothermal energy):

It comes from the Greek words "geo" (earth), and "therme" (heat). Therefore, geothermal energy refers to a branch of geosciences focused on the study of the thermal conditions of a given location, the source of heat and the surface manifestations (e.g., fumaroles, geysers or hot springs) that can occur where temperature and the rate of temperature rise in depth (geothermal gradient) is higher than under normal conditions. Geothermal energy refers to both the thermal energy available from thermally anomalous areas of the earth's surface, as well as the electrical energy that can be generated in geothermal plants from the hot fluids present in most geothermal systems.

Hydrology:

Branch of geoscience that studies the water resource, its occurrence, circulation, and distribution on and below the earth's surface.

Lava:

Term applied to magma when it emerges to the surface during a non-explosive eruption from an emission center and flows by gravity. It refers to hot material (up to 1,2500C) that forms relatively thick lava flows.

Baseline:

The concept refers to the description of the current situation, on the date of the study, without influence of new anthropic interventions. In other words, it is the snapshot of the prevailing environmental situation, bearing in mind all environmental variables, at the time the study is carried out.

Magma:

Molten rock at high temperature (700 - 1250°C), formed by a mixture of liquid, gas and crystal that is generated in the mantle and/or inside the earth's crust. When it emerges to the surface it gives rise to volcanic processes.

Mantle:

One of the three concentric layers that make up the Earth as a result of differences in density between the layers. It is a function of variations in composition, temperature and pressure. The mantle comprises about 83% of the Earth's volume and lies between the Earth's core and crust.

Environment:

Set of physical, chemical, biological and social components capable of causing direct or indirect effects, in the short or long term, on living beings and human activities.

Geothermal model:

Conceptual scheme that integrates geological, geophysical and geochemical studies carried out in an area to determine the possible existence of a geothermal system at depth. If it exists, it also proposes a configuration of the latter indicating a heat source, a reservoir with its incoming and outgoing flows of liquid or vapor and, ideally, its interactions with the surface hydrology. This model is improved even in the advanced stages of operation.

Earth's inner core:

This refers to the innermost part of the Earth and corresponds to a solid sphere with a radius of 1,216 km located at the center of the Earth. It is made of an alloy of iron and nickel and its density is estimated at approximately 14 g/cm3. The depth of its upper boundary (separating it from the outer core) is approximately 5,155 km below the surface.

Earth's outer core:

Refers to the liquid portion of the Earth's sphere, located between the base of the mantle and the roof of the inner core, located approximately 2,885 km below the surface and with a thickness of about 2,270 km. The main evidence for proposing that its state is liquid is based on the fact that seismic S-waves (shear waves) do not propagate through this part of the Earth's interior.

Petrography:

Branch of geology that deals with the study of the observable and measurable characteristics of rocks and their constituent minerals, i.e., their descriptive elements. Among the observable or visible (qualitative) characteristics are color, luster, shape, structure, fabric, flavor, odor and magnetic response. Measurable (quantitative) characteristics include mainly size and rock hardness (on the Mohs scale).

Stone:

Popular name assigned to rocks, especially in the field of construction. It refers to a solid formed by a set of minerals; depending on their origin they can be classified into igneous, sedimentary or metamorphic rocks.

Drilling platform:

Area defined in the drilling of a well that has the purpose of marking the delimitation of the operations sector.

Tectonic plates:

Rigid blocks of the lithosphere that have movement relative to each other without internal deformation occurring on the Earth's asthenosphere. This movement can be convergent (subduction or collision), divergent (mid-ocean ridges) and transcurrent.

Dry steam geothermal plant:

A geothermal power plant that uses only steam to drive the turbine, meaning that only steam rises through the boreholes. Once the steam is used, it is converted into water to be sent, through a reinjection well, back to the reservoir. Reservoirs of this type are rare.

Flash steam geothermal plant:

Plant built from geothermal reservoirs with temperatures of 170°C or higher. From the well, the hot water pressure leads through pipes to the "separator", where pressure is reduced. After the steam drives the turbines, it is condensed back to water and returned through a reinjection well to the geothermal reservoir, to be reheated and reused. Most geothermal power plants in the world are of this type.

Binary-cycle geothermal plant:

Many geothermal reservoirs contain hot water, but not enough to produce steam and drive turbines. In these cases, the reservoir water is used to heat a second liquid whose boiling point is lower than that of water (such as alcohol), which, when heated, expands and makes the turbine move. As this is a closed loop, the secondary liquid is kept in the heat exchanger and the geothermal fluid is returned to the reservoir. This type of technology has residential and urban applications so it has expanded its use around the world.

Energy potential:

Measurement of the amount of energy that can be produced from a natural resource. To calculate it, it is necessary to consider the particular characteristics of each project in all its stages and the environmental impact it generates. In the case of non-conventional renewable energy (NCRE), the natural resource from which the energy is extracted receives reduced or moderate intervention and is not permanently altered. In the case of a geothermal system, the potential will be measured in megawatts (MW), whether thermal (in heat units) or transformed into its electrical equivalent (as a contribution to an electrical grid).

Well:

Drilling generally vertical carried out on the Earth's surface for the purpose of searching for and exploiting minerals, groundwater or petroleum, among others. In the case of geothermal energy, wells commonly reach depths of more than 1000 meters.

Gradient well:

Drilling with exploratory character in a specific point of the earth to measure the variation (gradient) of temperature as the depth increases, with the purpose of finding a geothermal system.

Renewable resource:

An energy resource that can be used continuously without being overexploited, since it regenerates itself within a given time span. Examples of renewable resources include small hydroelectric power plants as well as wind and geothermal energy.

Geothermal reservoir:

A subsurface zone (generally deeper than 1,000 m) composed of a sequence of hot rocks with a certain degree of porosity and fracturing that make them permeable and saturated with fluids (water and gas) at high temperature. The water and steam coming from these reservoirs are the geothermal resource for electricity generation, among other uses.

Rock:

Material composed of one or more minerals, as a product of geological processes occurring in the rock cycle. There are three main groups: (1) igneous, produced by cooling and magmatic consolidation inside the Earth or external volcanic processes; (2) sedimentary, generated from the erosion and transport of pre-existing rocks, and the subsequent lithification of the fragments (sediments); and (3) metamorphic, also produced from pre-existing rocks, when these are subject to drastic changes in pressure and temperature.

Igneous rock:

Rock resulting from the cooling and consolidation of magma. They can be volcanic or plutonic, depending on whether they consolidate on the surface or in the interior of the earth's crust, respectively.

Salar or salt flat:

Surface lake whose sediments are dominated by salts (chlorides, sulfates, nitrates, borates, etc.). Salts are accumulated by strong evaporation, which in the long term is always greater than the inflow of water into the basin. It is the result of a long process in which salts accumulate because they do not drain outwards (to the oceans through rivers), i.e., due to the hydrologically closed nature of the lake (endorheic), a process generally linked to the presence of an arid climate with high evaporation rates.

SERNAGEOMIN:

Acronym for Servicio Nacional de Geología y Minería (National Geology and Mining Service). Chilean public agency, under the Ministry of Mining. In the mining field, it is in charge of regulating and promoting the activity in the country, as well as advising the State regarding mining property and registering the activity, preparing national mining statistics. In the geological (and geophysical) field, its main mission is to contribute to the geological/geophysical knowledge of the national territory, which can be used scientifically, by the government (for example in territorial planning), or by private companies linked to industrial activities that depend on existing geological information (mining, geothermal, hydrocarbons, etc.).

Seismology:

Branch of geophysics that deals with the study of earthquakes and, in general, the study of the transmission of seismic waves generated both in the interior and on the surface of the earth. Among its main objectives are the propagation of seismic waves (which provides valuable information on the environment they pass through), the origin of earthquakes and seismic risk (prevention of possible damage, construction standards, etc.).

Drilling:

Term used as a synonym for drilling in mining, petroleum, geothermal and geotechnics, which refers to the action using mechanical means (drilling machine) that aims to build a well. To achieve this objective, all the destroyed material inside the hole must be extracted with the use of compressed air or water. In the case of exploration drilling, they can be: 1) diamond (when drilling a rock core is extracted) or 2) reverse circulation (the rock is absolutely destroyed and crushed rock is extracted).

Subduction:

Process of convergence of tectonic plates that have a displacement in the same direction but in the opposite orientation. Thus, the denser and heavier plate sinks under the less dense and lighter one. In subduction environments, much of the seismic activity and continental volcanoes are concentrated.

Earthquake:

Sudden ground motion (shaking) associated with the release of elastic deformation energy in the form of seismic waves. The greatest accumulation of energy (as progressive deformation of rocks) occurs in areas of convergence of tectonic plates (subduction environment). There are also earthquakes (or tremors) associated with volcanic activity although these are, in general, of lesser magnitude than those of tectonic origin.

Vapor:

Gaseous state that fluids acquire due to the action of heat. Water vapor is a gas that results from evaporation or boiling of liquid water or sublimation of ice.

Volcano (stratovolcano or composite volcano):

Edificio volcánico mayor formado por una alternancia de lavas y A major volcanic edifice formed by an alternation of lavas and pyroclastic deposits, built by successive eruptions from a main emission center.

Volcanology:

Branch of geosciences that deals with the study of volcanoes and the understanding of related causes, phenomena and products.

Geyser San Federico, in Larderello (Tuscany, Italy).
Fabio Sartori Collection.

PART ONE

HUMANITY AND THE EARTH

From Tuscany to Antofagasta

The steamship Orita, the largest of the Pacific Steam Navigation Company's ocean liners (9250 tons), arrived on November 2, 1921 at the port of Antofagasta on its route from Liverpool to South America. On board, probably in one of its one hundred and sixty-nine first class cabins, was Ettore Tocchi. An electrical engineer, as described in El Mercurio newspaper, and former director of the Larderello Power Station, in Tuscany, near Volterra. Engineer Tocchi had been able to familiarize himself with Spanish for slightly more than a month. If we count the trip from northern Italy to Liverpool, or La Rochelle, or Lisbon to catch the ship that would bring him to the Chilean desert. He himself told this to the journalist of El Mercurio de Antofagasta, in an interview published the day after his arrival: "I knew little Spanish, but I practiced it frequently in the long month that I was sailing". Imagine the port of Antofagasta in 1921. First of all, there was no real wharf. At least not one where the true floating citadel that was the Orita, capable of carrying more than a thousand passengers, with a crew of one hundred and seventy-two people, could dock. That's why Engineer Tocchi boarded one of the innumerable boats that went to pick up passengers and cargo to bring them to the mainland.

Bay of Antofagasta, 1920. Collection of the National History Museum, Chile.

Pacific Steam Navigation Company steamship Orita, on which Tocchi made his transatlantic crossing to the port of Antofagasta in 1921. Postcard of the time.

There, on the wooden dock that led out to sea, someone was undoubtedly waiting for him. Most likely one of the members of the Preliminary Community of El Tatio, perhaps several of them. One thing we do know is that he was taken to the Gran Hotel Londres. "The only first-class establishment in Antofagasta" -as the advertisements in the newspapers of the time announced-, on the corner of Prat and Latorre Street. We also know that he stayed in apartment number eight. He probably gave the interview in the lobby of the hotel; or maybe in apartment eight (as the advertisement promised "luxurious apartments, with personal in-house service").

And what is the interview about?

The illusion of a splendorous future

The first striking thing is not what Tocchi has to say -which is relevant indeed as we shall see-, but what the journalist has to say. For the simple reason that he is offering us probably the only physical description -at least in Spanish and in the written press. Almost a brief biography of the pioneer of geothermal energy in Chile:

"We observed him. He is very similar to the old Spanish noblemen: tall, with a well-shaped body, wide forehead, serene face, light-colored eyes barely covered by a pair of fine glasses. The oval of his face finishes softly in a white beard on his chin, which gives the man a venerable and strong appearance that instills respect.

However, from his opening sentences, from the moment you hear the first characteristic inflections of his language, his personality slowly captivates you and inspires your complete trust.

As a full-blooded Italian, every word is accompanied by action. His eyes, through the lenses, come alive, transmitting to the listener what they want to say. His hands draw deep shafts in the air or design powerful jets of water ejected from "geysers" in Iceland or New Zealand or Johnstone, in the United States...

There is no doubt that we are in front of a character who knows how to say what he wants to be understood, with the combined powers of word and action".

The Gran Hotel Londres (left) on Calle Prat, where Tocchi stayed at in Antofagasta. Postcard of the time. Collection of the National Library of Chile.

Plaza Colón square in Antofagasta, ca. 1920.
Collection of the National Library of Chile.

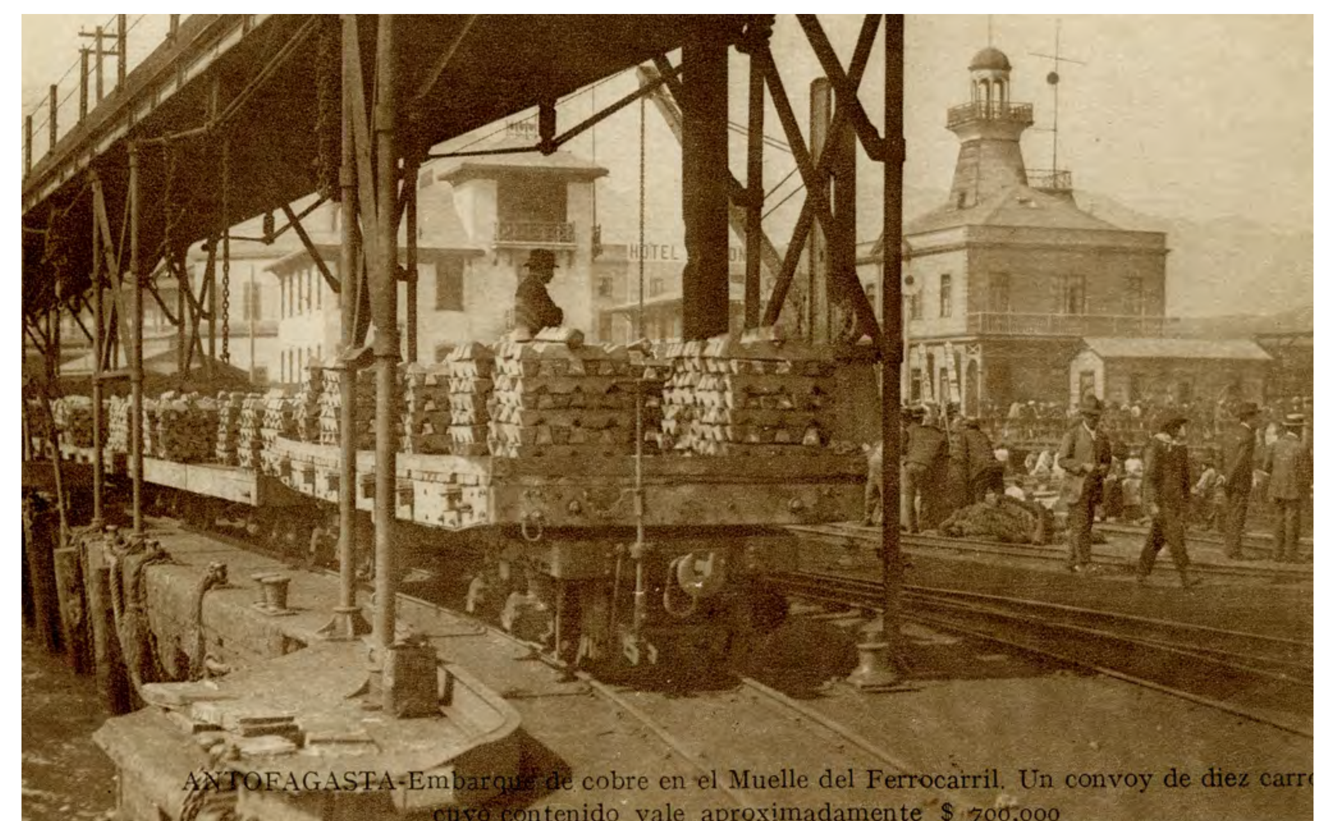
Seaside esplanade and railway quay at the port of Antofagasta in the first decades of the 20th century. Collection of the National Library of Chile.

The combined power of word and action… The journalist is absolutely right, although far beyond -the peculiar form of manifestation of men and women of Italy, this combination between word and action will be precisely what will characterize Ettore Tocchi's stay. Although one could also write the "adventure" and even the "epos" - of Ettore Tocchi in Chile. But let us answer once and for all the main question: why is the Italian engineer coming to Chile? The answer is given in the interview itself:

"Without a big fuss, discreetly but firmly, some time ago one of so many companies that have been appearing to the public eye in recent years was founded in Antofagasta. Like most of them, it had no other goal than taking advantage of the natural resources provided by Mother Nature to our soil.

But we must make a significant difference between the others and the one we are interested in. The Preliminary Community of El Tatio differs substantially from the others not only how it is organized but also in terms of its focus, which is the use of "soffiones" as driving force. Coming from the Tatio volcano, located in the foothills of the mountain range in the interior of San Pedro de Atacama. The comprehensive studies of this Community required the support of science in the form of an expert who would come to say the last word.

Shipment of copper in Antofagasta, ca. 1920. Postcard of the time. Collection of the National Library of Chile.



Ettore Tocchi and Marie Curie in front of the Palais de Larderel (1918). Geothermal Museum of Larderello (Italy).

And the expert, a renowned electrical engineer, "signore" Ettore Tocchi, is already here. He will be able to say whether it is possible or not to harness the huge forces contained in the core of the earth, whose manifestations reach the surface in the form of steam".

Asked about the possibility of using the steam stored underground to generate electricity in the region, Tocchi says:

"From the studies I have made, based on the data sent to me while I was in Italy, I can almost assure you that these "soffiones" are very similar, if not identical, to those in Larderello. If we manage to establish the identity, power and extension of the currents that produce the force of these steams, I can assure that this will generate great wealth. The resulting power will be sufficient to produce light and ensure the operation of all the machines of all the saltpeter mines and industries, the railroads, the metallurgical furnaces and factories in general".

The journalist finishes off the interview by transforming the reasonable optimism of the Italian engineer into a dithyramb about the magnificent future that awaits the region and the country. It is good to keep this in mind because it is undoubtedly the expression of a perception shared in those years: a blind faith in the future, which is perhaps also - and perhaps above all - a way of disregarding the many signs that in 1921 indicated that, on the contrary, the decline of the saltpeter industry had begun and would not stop.

"Therefore, it is inevitable to believe that this region of Chile is predestined to live a splendid future, because of its layers of marble rocks, its vast fields that are just waiting for the seed to produce a thriving agriculture, the certainty of the existence of large oil deposits, the chain of hills full of rock salt in the vicinity of the Augusta Victoria line, on the border with Argentina, without taking into account the far-reaching caliche territory, the gold and copper mines that are already being exploited, everything, everything, makes us believe in a prosperous future."

In an interview published by the ABC newspaper of Antofagasta on November 20, 1921, Ettore Tocchi declares:

"There is a potential for the business, but I will not know its value, or the amount of energy that could be obtained until the studies are completed."

The idea of supplying cheap energy to the entire Atacama mining industry and related industries (railroads, metallurgical furnaces) is not an invention harbored in the imagination of Ettore Tocchi, but a yearning of the industrialists of northern Chile. In particular, of the capitalists behind the saltpeter industry. And in this exploration of the possibilities of steam - especially the one that emerges from the geysers of El Tatio - the Italians settled in Atacama played a significant role. In fact, the creation of the Preliminary Community of El Tatio is, to a large extent, an Italian initiative.

The Preliminary Community of El Tatio

In 1917 the Italian Giovanni Severina arrives in Antofagasta. He comes as a representative of the Franco Tosi Legnano company, which sells machinery for the saltpeter industry. Not long after, Tosi Legnano indicates to its representative in Chile the company´s interest for the geysers of El Tatio and asks him to visit the place. But he does not provide him with the necessary resources to arrange an expedition. We are in 1917 and El Tatio is not so easy to reach. Furthermore, it is about organizing a scientific expedition that could determine, based on in situ studies and exploration, the possibilities of installing the first geothermal power plant in the country.

Giovanni Severina then partners with three traders from Antofagasta surnamed Capillo, Ivanovic and Vázquez and creates the Preliminary Community of El Tatio. The Community issues shares to raise funds and contacts the engineer Plinio Bringhenti in Milan. Bringhenti decides to decline the offer to come to Chile, but recommends his colleague Ettore Tocchi, who has just left the management of the Larderello geothermal power plant.

This is how engineer Tocchi arrives at the Gran Hotel Londres in Antofagasta on November 2, 1921.

Saltpeter, a vanishing dream

Let's talk a little about the historical context of that year 1921 in the Atacama Desert. The first thing to bear in mind is that towards the end of the 19th century and during the first decade of the 20th century, a saltpeter boom occurred in northern Chile, especially in the Province of Antofagasta. Originally it belonged to Bolivia (it was called the Department of the Litoral) and was incorporated into the national territory after the War of the Pacific (1879-1884), in which Chile fought against the joined forces of Peru and Bolivia. After the incorporation of this enormous territory to Chile, the saltpeter industry experienced a rapid development. Thanks, among other things, to the construction of a vast network of railroads that connected the forty-five "saltpeter offices" in the interior with the ports. For instance, in 1900 the railroad between Antofagasta and Coloso was inaugurated. And in 1902, the one linking the latter port with the town of Yungay. Coloso then became an important saltpeter port. In 1907, for example, more than 300 ships had docked in its bay. It had a tennis court, soccer field, cinema. The road between Coloso and Antofagasta was the busiest road in the province, with more than 100 motor vehicles per day, according to statistics of the time. The same occurred in the office of Pampa Unión, with over fifteen thousand inhabitants, a local police station and three newspapers. And the same applies to the port of Taltal, which had eleven thousand five hundred inhabitants in 1907 and more than fifty stores, including eleven tailor shops, as well as a cinema, three English-language newspapers and consular representation from Spain, France, Germany, England, Sweden, Italy, Argentina and Peru.

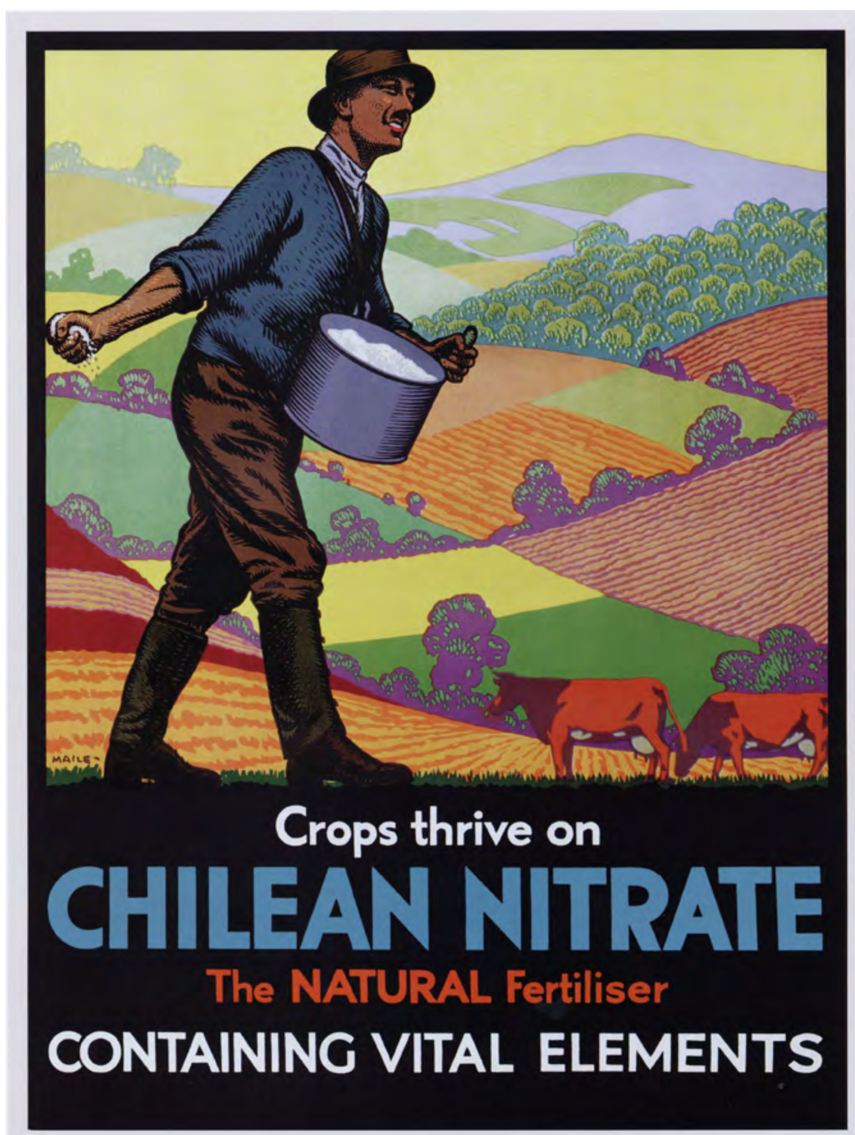
Geyser in El Tatio geothermal field. Marcela Mella.

Workers inside saltpeter mines, ca. 1900. Collection of the National History Museum (Chile).

But in 1921, at least a couple of events occurred that would shatter the dream of that "splendorous future" mentioned by the Antofagasta journalist. The great disaster of the First World War, to begin with, was going to have a direct impact on the saltpeter industry. During the war, this mineral was essential, but once the war was over, European countries needed much less saltpeter than in previous years. Towards the end of the first decade of the century, the warehouses of the Norte Grande offices and those of the industries of the consuming countries were full of saltpeter. Consequently, there was a plummeting in demand. But also, because a misfortune never comes alone -especially when it has not been possible, nor wanted, to take advantage of the strong accumulation of capital generated by saltpeter for the diversification of the national industry-, during the war the German chemist Fritz Haber developed synthetic saltpeter. This development took place after Carl Bosch, also a chemist, had developed the process of synthesizing ammonia from hydrogen and nitrogen under high pressure between 1908 and 1913. This was a hard blow to the national saltpeter industry, which was forced to drastically reduce its production. By the 1920s, of the forty-five saltpeter offices in the

Antofagasta region, thirty-five had stopped working, two were working at half capacity, another two at an even slower rate and only six were still operating at full capacity. In 1916, Chile exported three million metric tons of saltpeter. In 1919 that figure drops to a little less than one million, according to "El fin del ciclo de la expansión del salitre: la inflexión de 1919 como crisis estructural", by Sergio González, Renato Calderón and Pablo Artaza. As expected, this prompted a mass exodus of workers from the offices to the ports and, from there, down to the south of the country, with its resulting wave of misery and social and political instability. But this misery was already occurring at the peak of the industry's boom, because the owners of the saltpeter mines -mainly English and Chilean capital- put limits on mineral production, assigning quotas to each office, in order to generate shortages and increase the demand and price in international markets. This fraudulent practice of collusion or cartel, known at the time as "saltpeter arrangements", certainly led to increased profits for the owners of the capital, with dramatic results for the workers,

Poster advertising Chilean nitrate in Great Britain and Ireland (1900). Collection of the National Library of Chile.



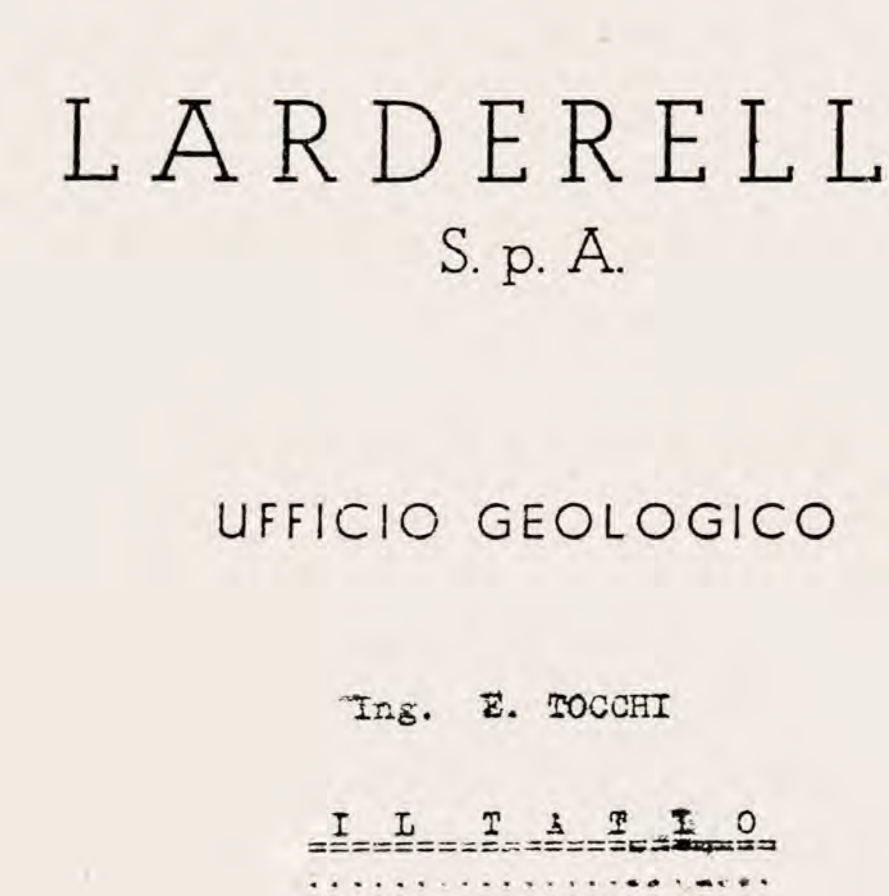
Large primary crusher operator. María Elena Office, ca. 1930.

who were left without their jobs overnight. "Between 1884 and 1913," Juan Floreal Recabarren writes, *"five were organized, with catastrophic results: 1884, 1891, 1896, 1901 and 1909."* The Antofagasta newspaper El Industrial mentions, in its January 9, 1896 edition, a report from the Saltpeter Delegation to the Ministry of Finance that reads: *"Separation of employment in the offices has left a large number of jobless workers in the pampa (plain). A number that I estimate at three thousand, representing around six thousand people who have nothing to live on."*

That was the Chile with a "prosperous future" that Ettore Tocchi was arriving to.

The Tocchi Report

Little is known about Ettore Tocchi's stay in Chile and the conditions of his time at El Tatio. Juan Floreal Recabarren, in his *"Episodios de la vida regional"*, states that to support the engineer's expedition, the Preliminary Community funded the construction of a road from San Pedro station (on the railroad that linked Antofagasta with Bolivia) to Linzor, a two-hour drive from El Tatio. He also reports that a Ford automobile was purchased to transport the measuring instruments and a house was built at El Tatio. Twelve mining claims were bought to assure the exploration activities. Finally, he says that the businessmen involved in the adventure, Luis Lacalle, Nemesio Vásquez, Antonio Luksic, Alfredo Cousiño and Aliro Parga, invested more than four hundred thousand pesos, a considerable sum for the time.



LARDERELLO

S. p. A.

UFFICIO GEOLOGICO

Ing. E. TOCCHI

IL TATIO

Cover page of Ettore Tocchi's report on El Tatio geothermal field. Geothermal Museum of Larderello.

In its edition dated on Friday, December 16, 1921, *El Mercurio* de Antofagasta reports a General Shareholders Meeting of the Preliminary Community of El Tatio:

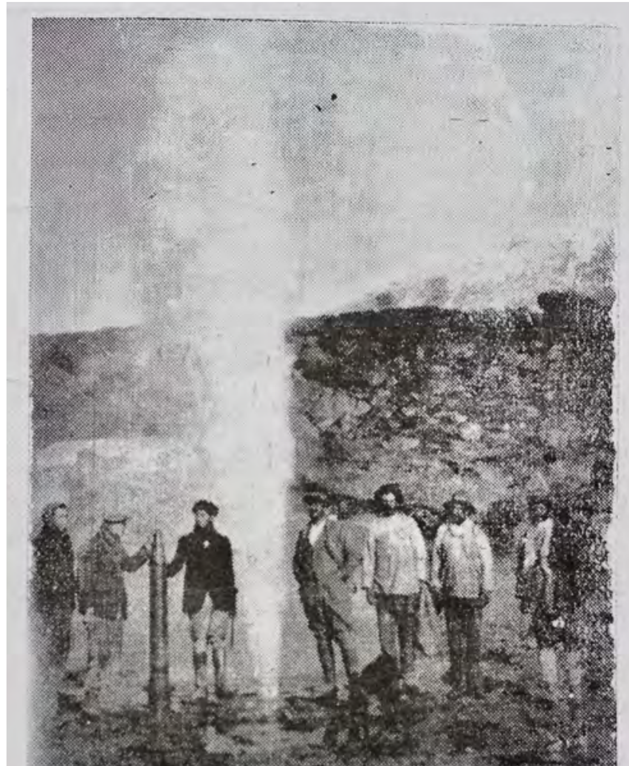
"A few days ago, the shareholders of this Community gathered in a General Meeting, under the leadership of its Chairman, Mr. José J. Granada and its Secretary, Mr. Nemesio Vásquez Cisternas.

The Secretary read the minutes of the Board of Directors' meeting held on the past November 24th including a report or presentation by the engineer, Mr. Tocchi, on his first exploration and verification trip to the Community's land as well as the Board of Directors agreements for the continuation of the studies proposed by the engineer, the collection of the second installment and the approval of the transfers for the released shares.

Mr. Tocchi was offered the floor, and he made a brief and similar presentation on the results of his trip, adding some data requested by shareholder Mr. Alfredo Cousiño.

At present, they are waiting for the arrival of specific machines that were shipped from Italy and on their way already. In addition, drilling machines and specialized technicians will be brought in."

Tocchi and his assistants installing a "steam measuring apparatus" at the geyser 18 de septiembre. El Tatio, 1922. "Album of Tarapacá and Antofagasta" (1924). Private Collection of Cesare Coronata Zunino.



El soffione "18 de Septiembre" antes de la colocación del medidor de vapor

El soffione "18 de Septiembre" con el aparato medidor de vapor colocado

In brief, Ettore Tocchi made a first visit to El Tatio that would have taken place between November 3 and 23, 1921, since he arrived on the 2nd of that month in Antofagasta and on the 24th he attended the Shareholders' Meeting of the principal company.

It is reasonable to think that Ettore Tocchi returned to El Tatio in mid-December 1921, with the mission of studying the power of the geysers and determine the feasibility to create the first geothermal power plant in the country.

There is only one document that provides us more information about Tocchi's work in the altiplano (high plain), but it is of utmost importance. It is the report written by the engineer himself, giving an account of his mission. He wrote it in Castiglioncello, in January 1923. And in it he says that he left El Tatio on September 23, 1922. His stay in the Chilean pampa would have lasted about ten months. Who accompanied him? In his writing he refers on several occasions to native inhabitants, whose company must have been important and not only to obtain information about crucial elements of the Altiplanic culture. We know that the driller who arrived later from Italy was called Antonio Cavialini. Was Cavialini his partner in those hard-working days, over four thousand meters above sea level, and in the cold nights of the Altiplano? What other technicians from Italy accompanied him?

The report, entitled *Il Tatio*, carrying the letterhead "Larderello S.p.A - Ufficio Geologico", consists of more than thirty pages and is divided into seven sections, in addition to the introduction: Geographical position, Access routes, Topography and geology, Climate, Steam study, Exploration work and Estimation of available energy.

Shareholder's title of the Preliminary Community of El Tatio. Private Collection of Cesare Coronata Zunino.


Nº 135

Por 16 ACCIONES

Comunidad Preliminar del Tatio

Constituida por escritura del 30 de Junio 1921, ante el Notario don Belarmino Urzúa T. y modificado por escritura de 23 de Junio 1924.

CAPITAL: Setecientos mil pesos. Dividido en 9,600 acciones de $ 72.90 c/u., totalmente pagado

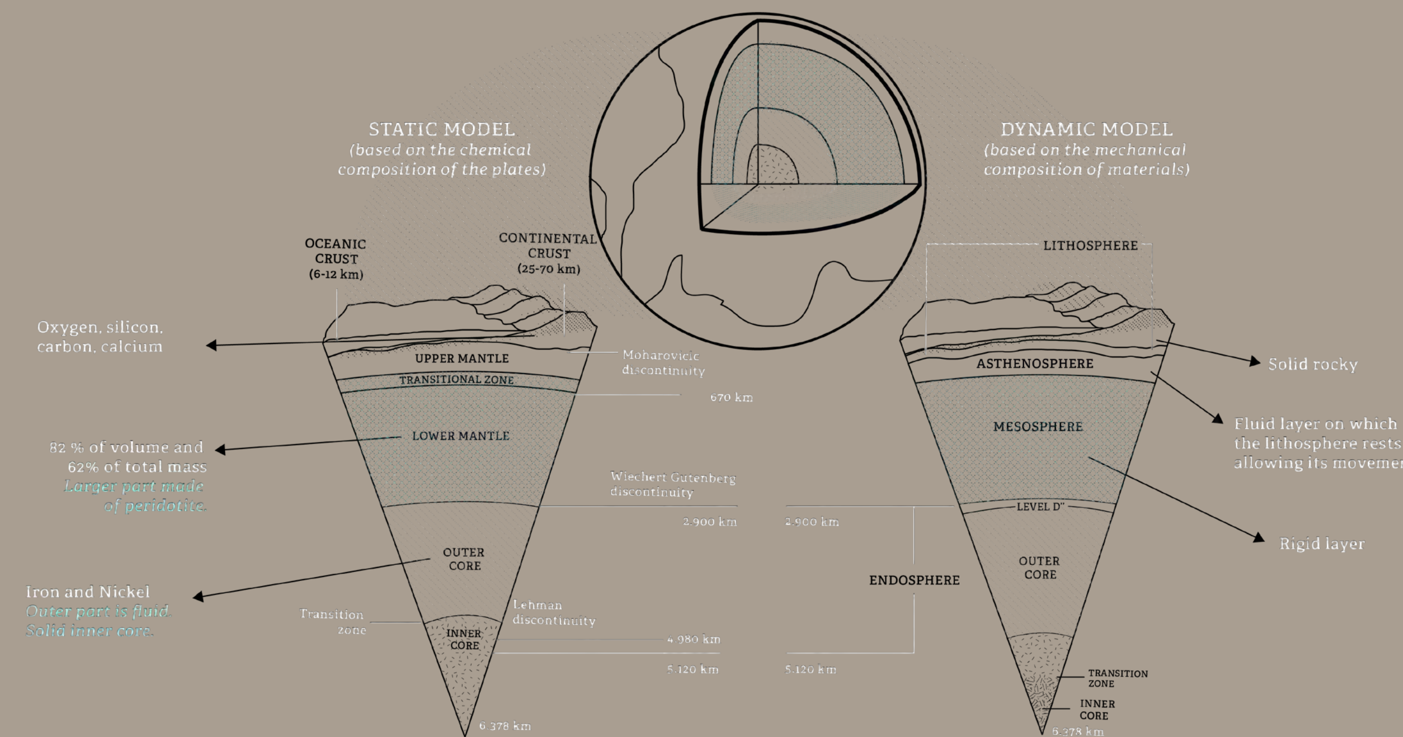
Certificamos que el Sr. Tito Coronata está inscrito a fojas 172 bajo el número del Rejistro de Accionistas de la Comunidad Preliminar del Tatio, como dueño de diez y seis acciones de la Comunidad.

Antofagasta, 30 de Septiembre de 1924

Presidente.

Secretario.

EARTH STRUCTURE: TWO MODELS STATIC MODEL



Since the time of Ettore Tocchi's memorable expedition to the heights of El Tatio geotermal field, the representation of the Earth's structure has evolved enormously. Today, it is alternatively described by the chemical composition of its layers (static model) or by the mechanical properties of its materials (dynamic model).

According to the first and most classical model, the structure of the Earth is composed of crust, upper mantle, lower mantle, outer core and inner core. The second model defines the lithosphere, asthenosphere, mesospheric mantle (ormesosphere), outer core and inner core components.

Top: Ettore Tocchi's camp at El Tatio ca. 1922. Enel Historical Archive (Italy). Bottom: Ruins of the same camp today. Marcela Mella.

It is strange that, to date, Ettore Tocchi's Report has not been highlighted and published as one of the most important scientific texts in the history of science in Chile. Although written in and by an Italian, we could dare say that it is one of the most complete studies on the possibilities to generate electricity from steam in the Andes Mountains of northern Chile. In any case, Ettore Tocchi is the first in his time to approach in detail - with a literary, refined style, which makes it very pleasant to read - the description of the then called Puna de Atacama, from different points of view: Geographical, geological, hydrological, geochemical, mineralogical, climatic and, of course, in making an evaluation of the economic and even political possibilities of geothermal energy in the north of Chile.

As the Tocchi Report is the cornerstone of the development of geothermal energy in the country, it seemed inevitable to highlight it in this book. In this way, readers will be able to refer, for the first time, to the document that opens the way to geothermal energy in Chile. And although it is impossible to give an account here of the complexity of the engineer's analysis, let us look at some of its essential aspects. On the mineral wealth of the region, for example, he writes:

"The Puna de Atacama ... which today may be deemed to lack any feasible means of communication, hosts a vast and scarcely known mineral wealth. The exceptionally pure and abundant rock salt covers the dry bed of an ancient sea (the Salar de Atacama). Borax, sodium carbonate, gypsum, sulfur, copper in its pure state, silver and perhaps oil and oil shales.... Without any irrigation system because of the very scarce surface water courses, the soil has become infertile in very vast extensions. But it does not cease to be very fertile as soon as it can be irrigated, as demonstrated without exception by the few spots where fortunate geological circumstances allow the waters, which must flow abundantly underground, to surface. These spots are very rich in pastures and fruits of all kinds and enjoy a delightful climate, resulting from a combination of opposite effects between the low latitude (23-24 degrees Celsius) and the remarkable altitude, constantly above 2000 meters."

And in reference to the possibilities of a widely available source of energy for all the productive activities of the region, he adds:

"Abundant driving force made available to farming and mining activities, in addition to the connection with the coast assured by railroads, would make an amazing transformation of the conditions of this rich territory yet to be valorized. But unfortunately, it is precisely that driving force, together with the too scarce water that will always be difficult to supply, unless one has the courage to conveniently use other energies, such as the geothermal one, among others."

Regarding the benefits for the saltpeter industry, his diagnosis is clear:

"Pampa Salitrera establishments burn at least 300,000 tons of oil per year, which is already expensive at the time of its arrival. To this oil, we must add the remarkably high costs and rates of rail transport."

Let´s remember that we are in 1921. Tocchi´s proposal, if it works, would have been an extremely "marvelous transformation", a true revolution, the possibility of a real industrial - and, therefore, capitalist - upgrade, which did not actually occur in Chile. Now, Tocchi himself realizes the limitations and obstacles to carry out such a big project, such as the attitude of Chilean capitalists, incapable of capturing the profound impact of that "marvelous transformation" if it were to take place:

"In contrast to this promising panorama of the wealth yet to be exploited of this true, gorgeous display of nature, we have the indifference of Chilean capitalists towards the affairs of the North (even

Old map of the El Tatio geothermal concession.
Enel Historical Archive (Italy)

today) other than the saltpeter-related business. In addition to the lack of roads (1 km barely for every 40 km), together with the complete absence of both water and the driving force."

This is a direct criticism to businessmen of the time who were only interested in short-term profits. Visionary, Tocchi, because he points to a problem that will weigh down the country's development for many decades to come. And he says this despite the fact that domestic capitalists brought him to carry out his study. Did Tocchi see further - and even much further - than his associates?

In any case, he concludes his introduction by insisting on the potential of geothermal energy and its capacity to transform the region's economy:

"I believe that this quick review will allow to justify the hope that the exploration work that I happily initiated in El Tatio will confirm the feasibility of turning the construction of a powerful geothermal power plant into a reality, whose energy -distributed to the users of mining, the offices of the Pampa Salitrera and the distant City- will contribute to the valorization of the great and not always known resources and natural wealth of the region of Antofagasta."

And the engineer closes his report with a much more precise estimate:

"Having occurred to me, on other occasions, of having to translate into figures, for business people's use, my impressions about El Tatio. I spoke of the possibility of installing there a 50,000kw power plant. Based on the aspects mentioned in this writing, I still consider that such a power could be perfectly achievable, provided that the continuation of the so well initiated drilling confirms the feasibility of obtaining steam under the desired conditions of temperature and chemical composition."

Ettore Tocchi observes geothermal activity at El Tatio (ca. 1922). Enel Historical Archive (Italy)

Enough!... And then what?

In spite of the possibilities stated by Ettore Tocchi's work and detailed by him with a discreet hope in his Report. In 1925, when the crisis of the saltpeter industry was already an irreversible reality, everything collapsed. That year, engineer Domingo Monaguillo declared before the Preliminary Community of El Tatio Board of Directors: : *"Drilling has been suspended at a depth of 150 meters, instead of the 100 meters planned. To continue, it is necessary to invest six hundred and forty thousand pesos more".* This was equivalent to sixteen thousand pounds sterling of that year. Juan Floreal Recabarren, quoting a reporter of the time, writes: *"Businessmen did the math and, like the dealer at the gambling table, yelled: Enough!"*

The 1929 crisis will end up burying the hopes of developing geothermal energy in Chile and of geothermal energy contributing in turn to the country's development, as Ettore Tocchi clearly saw.

We had to wait for the 1960s for the promise of steam to find its way back into national energy projects. And we will have to wait for the 2000s for this "powerful geothermal power plant" to become a reality.

Today Cerro Pabellón injects 81mw into Chile's Central Interconnected System.

If Ettore Tocchi were here, he would deserve a toast in his name. But since he is not, we dedicate at least the following pages to him.

GLOBAL MAP OF TECTONIC PLATES

Source: USGS

Ancient Roman baths of Aquis Querquennis in the town of Bande (Galicia, Spain). Its thermal waters have a natural geothermal origin.

HEAT, WATER AND STEAM

Let's go back. Much further back. And imagine the deep fear that volcanic eruptions, earthquakes and other violent and huge manifestations of geothermal phenomena or those associated with geothermal energy must have provoked in the first human populations. It is a fear and respect that, incorporated and elaborated much later in complex cosmogonies and religious cults, have always been present in mankind throughout its history.

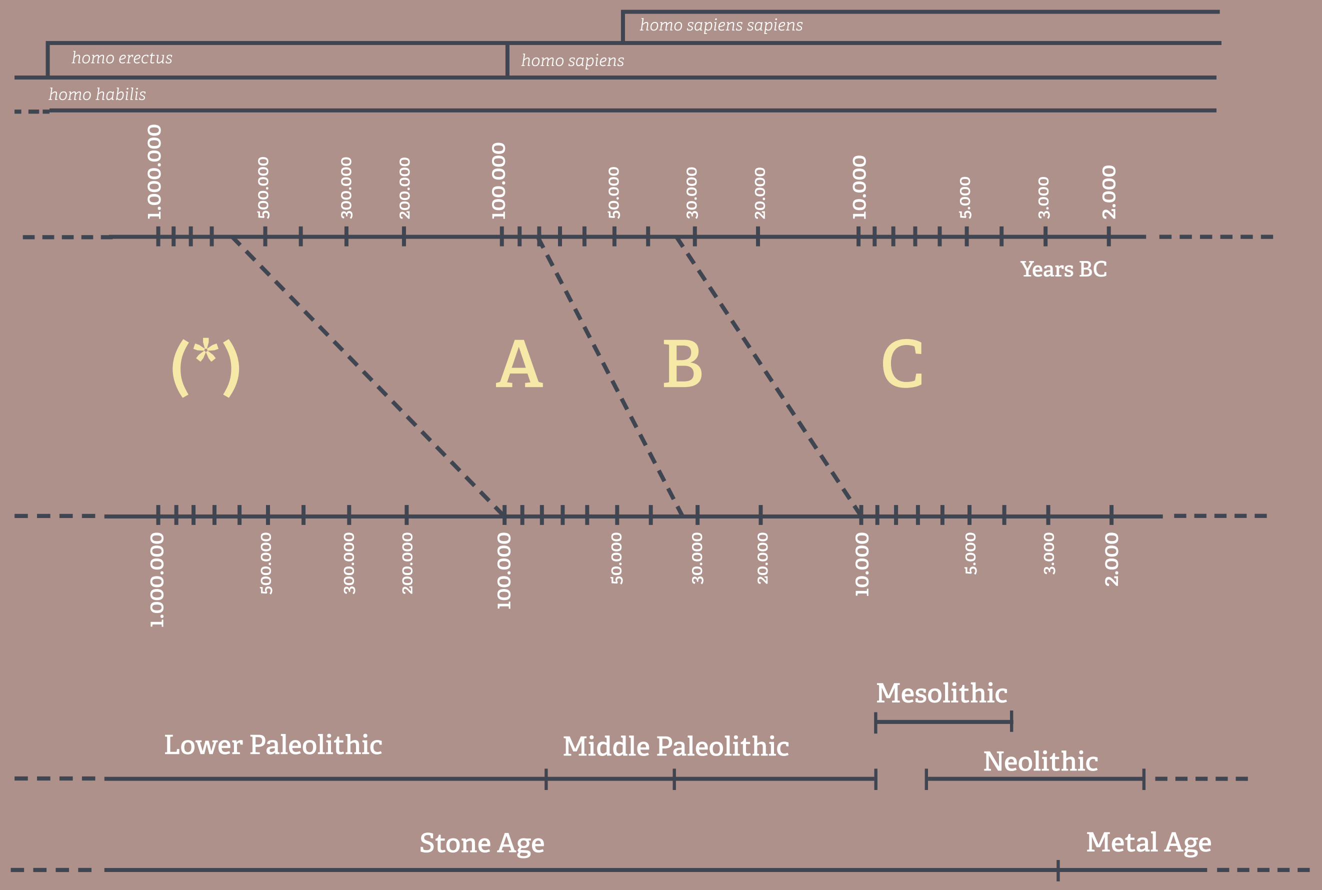
Sacred hells

Yes, the world beneath the surface harbored hells inhabited by powerful, fickle and irascible entities. But at the same time, and as human societies developed their capacities and expanded their presence in various continents, the mysterious and sacred heat of the earth also began to generously provide thermal springs, the cooking of food in boiling water or in contact with hot stones. And, some thousands of years before the end of prehistory, the first hygienic and therapeutic uses (mud therapy, disinfection and curing of wounds and toning of the skin) documented by ancient oral histories and legends. Geothermal energy thus became one of the first energy sources used by mankind.

The systematic use of natural heat from the depths of the earth coincides with the emergence of the first stable human settlements, many of which practice agriculture that uses rich soils near volcanic areas. Gradually, a convivial relationship is established,

Prehistoric populations probably developed religious ties to natural manifestations associated with the "heat of the Earth". In the image, Parinacota volcano (Putre, Chile). Sernageomin.

PREHISTORY: A LONG ROAD



(*): First contacts with geotermal phenomena

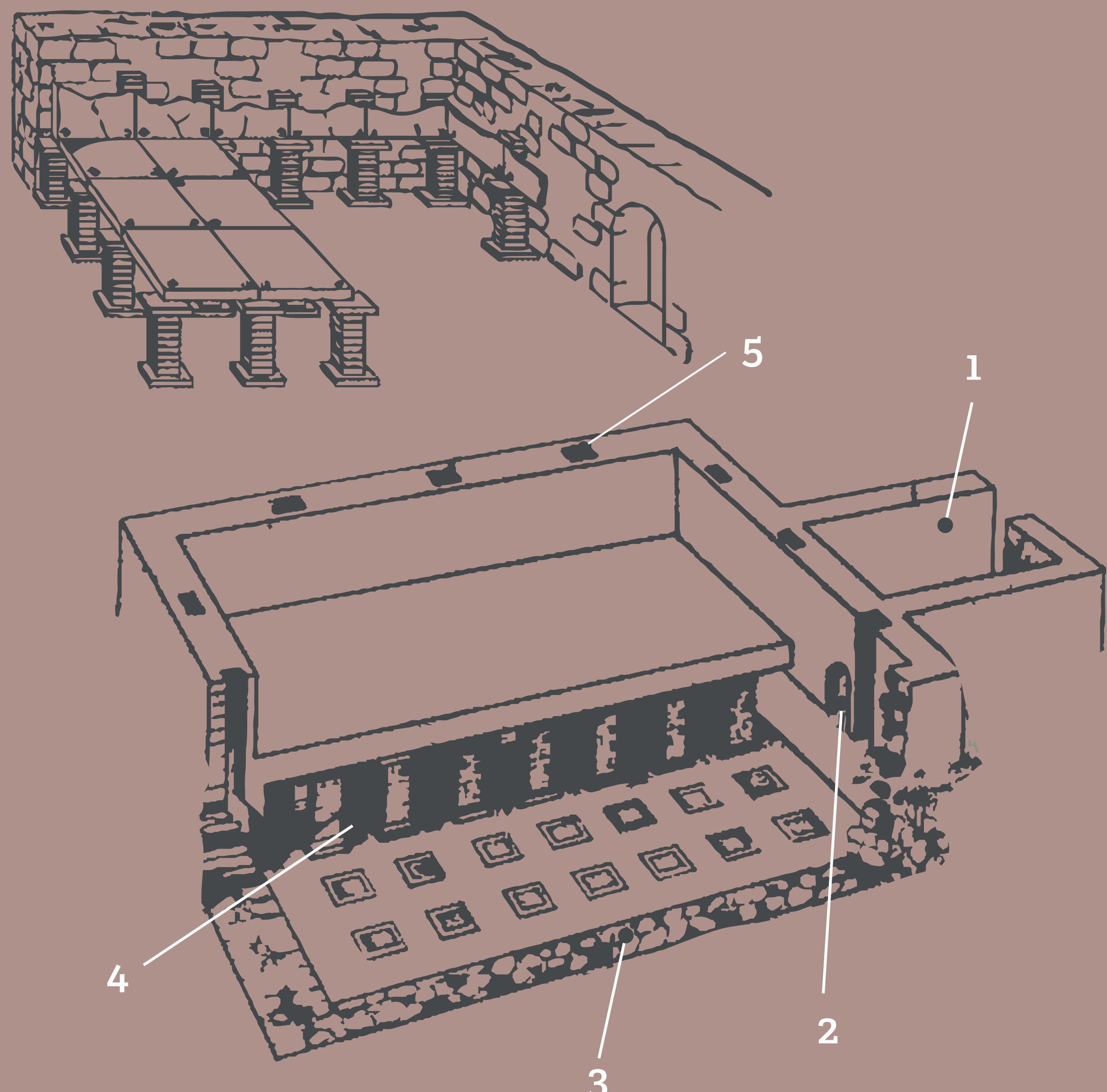
: Bathing in natural hot springs and early use of volcanic rocks

B: Cooking food in very hot water

C: First therapeutic applications (mud therapy, wound drying, skin healing and toning) and elaborate use of volcanic stones (obsidian and other igneous rocks).

Source: "Our Geothermal Legacy: A Historic Overview", Mario César Suárez A. and Raffaele Cataldi. World Geothermal Congress, Melbourne, 2015.

ROMAN HYPOCAUST



The hypocaust floor heating system was invented in Greece and perfected in the 1st century BC by the Roman architect Caius Sergius Orata. It was mainly used in termal baths.

1- Heating room (powered by a natural geotermal source or by boilers)
2- Opening in the wall to allow the passage of steam from the heating room to the baths
3- Subsoil
4- Hypocausts
5- Honeycombed channels that allow the hot air to heat walls and adjacent rooms

Source: "Our Geothermal Legacy: A Historic Overview", Mario César Suárez A. and Raffaele Cataldi. World Geothermal Congress, Melbourne, 2015.

always involving sacredness, between the communities and a specific environment. In this relationship, geothermal activity, such as volcanoes, hot springs, fumaroles and various hydrothermal deposits of kaolinite, sulfur, iron oxide, borax, among others are those that prevail.

In Çatal Hüyük - considered the first Neolithic "city", located in the south of the Anatolian peninsula (Turkey) -, which at its peak covered 13 hectares, a large mural painting depicting the eruption of the Hasan Dag volcano some 8,200 years ago has been discovered. Imagine the great shock that this violent geothermal event, which took place about 140 kilometers from the prehistoric city, caused in the population of the entire region. To the point of creating a detailed artistic representation that would make it last in time and memory.

Thermal balneology

At the beginning of Antiquity, the cooking of food with geothermal heat, the thermal baths and the cure of skin affections with thermo-mineral muds were widespread practices throughout the Mediterranean region. And of course, among the Etruscans. They arrived, during the XII century B.C., to what is today the region of Tuscany in Italy. The Etruscans - great navigators and traders- developed the first known industry of products based on geothermal resources, and developed an intense social life and a culture of exercising around the natural thermal baths. Given the magnitude of geothermal phenomena in the region, where the famous Devil's Valley is located, it is no coincidence that Tuscany itself witnessed, three thousand years later, the inception of modern geothermal technology.

The Etruscan bathing culture played a pivotal role in the Roman development of thermal balneology and recreational thermal baths. Although thermal baths had been built in Lipari (Sicily) as early as 1,600 B.C., they flourished in all the territories under Roman control from the 1st century B.C. to the 4th century A.D., with more than 2,000 baths. About a thousand of them were located in the city of Rome itself and were extremely popular among all social classes.

Roman public baths fulfilled multiple functions. They all offered balneotherapy (baths, saunas, mud therapy); body aesthetics (massages, shaving, hairstyling, depilation, skin care and toning); wrestling, bodybuilding, workouts; restaurants (some more formal and others fast food); information centers; public and private meetings (political, business, cultural, etc.), social events and entertainment.

Roman thermal baths in Bath (Somerset, England). Diego Delso.

In addition to offering all these services, the natural thermal baths (with geothermal springs) were also centers for rituals, venues for athletic games and other sporting events, venues for popular festivities, and spaces for regional and local markets.

Beyond Rome

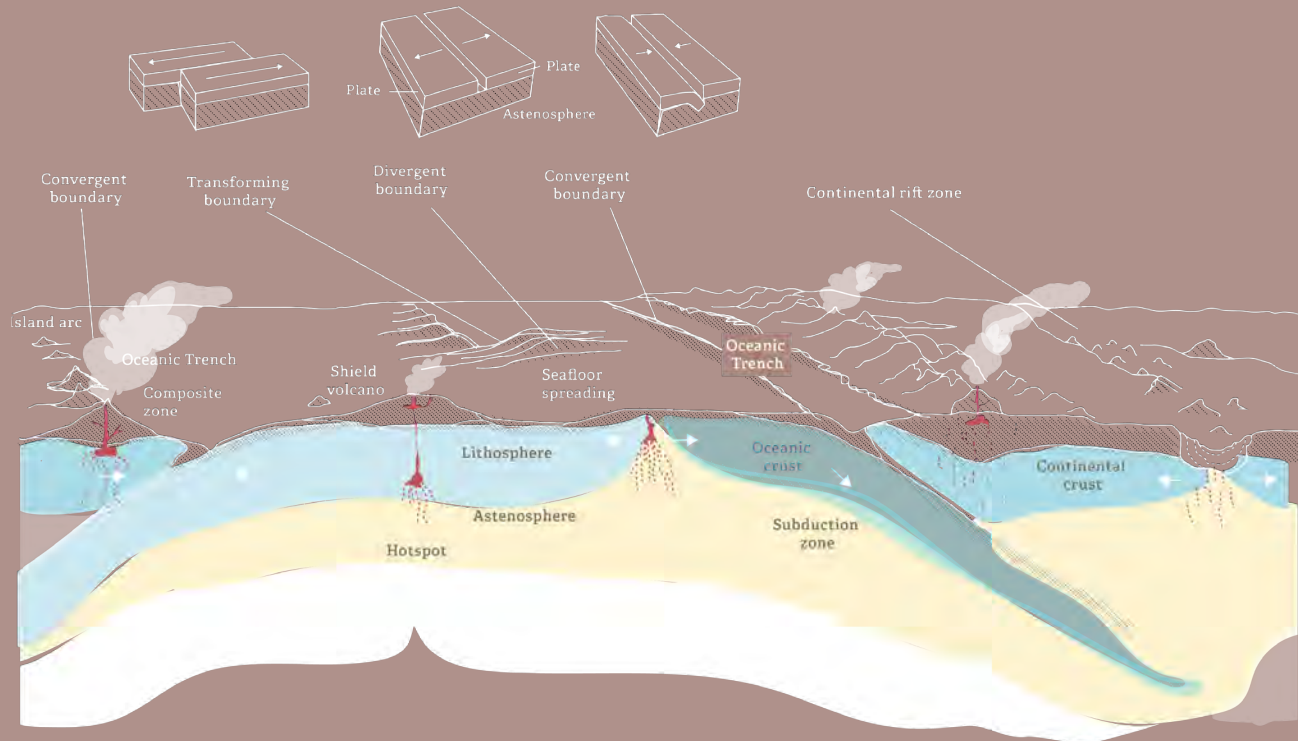
But although it reached an unprecedented expansion with the Romans, the use of thermal waters for therapeutic purposes in the Mediterranean region dates back, as already mentioned, to the Neolithic. The healing properties of thermo-mineral waters were already known in Asia Minor, southern Europe and North Africa by Sumerians, Babylonians, Assyrians, Phoenicians, Hittites, Cretans, Mycenaeans, Illyrians, Macedonians, Egyptians, Numidians, Sicans, Etruscans and Venetians.

During the peak period of thermal baths in the eastern Mediterranean and Anatolia, there were more than 300. The most popular were in Epidaurus, Edipsos and Pergamum (ancient Aeolida, in Asia Minor).

The Talmud - which collects Jewish laws, traditions and stories in both the civil and religious spheres, and which was written between the 3rd and 5th centuries by scholars from Babylonia and ancient Israel - recommends the use of the hot springs "for sufferers from skin diseases, leprosy, ailments of the urinary, and digestive tracts, rheumatism, arthritis and nervous diseases."

The Talmud recommends thermal baths for various ailments. The painting shows a copy of a page of the Talmud of Sephardic origin. Rebeca García Merino. Sephardic Museum. Ministry of Culture and Sport, Spain.

WHAT IS PLATE TECTONICS?



USGS

Plate tectonics or global tectonics - from the Greek *τεκτονικός*, tektonicós, "builder" - is a unifying theory that explains various geological events. Based on a model of the Earth in which the lithosphere (cooler, rigid outer part of the planet) is divided into several fragmented moving pieces unequal in extent and thickness, called plates.

The lithosphere sits on top of the warmer asthenosphere, which is probably made of materials that can deform. It is estimated that some kind of heat transfer, originating in the core and mantle, sets the tectonic plates in motion.

In the 1920s, the Irish researcher John Joly concluded that, due to the inefficient thermal conductivity of the crust, the radioactive heat generated in the Earth accumulates under the crust and melts the mantle, causing termal convection (convection is one of the three forms of heat transfer). From this proposal, the theory of mantle convection was later structured and applied in the 1930s to continental drift. Subsequently, it was proposed that convection could also occur in the solid mantle.

Tectonic plates move passively in response to convection currents. There are distinct zones with updrafts and others with downdrafts. It would be the weight of the sunken mass that would drag the rest of the plate behind it.

The plate tectonic theory also explains the formation of mountain ranges (orogenesis). It also provides a satisfactory explanation for the fact that earthquakes and volcanoes are concentrated in certain regions of the planet (such as the Pacific Ring of Fire), or for the location of large submarine trenches along islands and continents, and not in the center of the ocean.

Temazcal excavated in the ruins of the ancient Mayan town Joya de Cerén (El Salvador), buried under lava by a volcanic eruption in 600 AD. © Mariordo (Mario Roberto Duran Ortiz).

Traditionally, Turks have made thermal baths an integral part of their community life. Based partly on Roman tradition, the baths provide not only spaces for social interaction and entertainment, but also thermo-mineral solutions for curing rheumatic and sciatic pains, gynecological, kidney and mental problems.

America, Asia and Oceania

Equally important in their respective cultures, Finnish saunas as well as Japanese and Arab baths have different origins from those of the Mediterranean area. In Japan, the existence of thermal baths has been traced back to 11,000 years B.C., although their therapeutic use for chronic diseases has only been documented since 1734.

In pre-Columbian America, various Mesoamerican and North American locations practiced the so-called Temazcal (from the Nahuatl *temazcalli*, "house where one sweats"), a ritual and therapeutic steam bath (detoxification by sweating) obtained by sprinkling glowing volcanic stones with cold water. In Mayan language it was called *zumpul-ché* and in Mixtec, *ñihi*.

The use of thermal water among the Chinese dates back some 3,000 years. Uses such as boiling food, washing clothes, treating skin diseases and recreational activities that included tea, rice wines and liquors, were common especially in present-day Taiwan and Tibet.

In New Zealand, the Maoris used geothermal energy in areas as diverse as agriculture, cooking, bathing, heating and therapy. They have traditionally worshipped the heat of the earth, which they believe is protected by divine guardians.

Geothermal district heating 2 thousand years ago

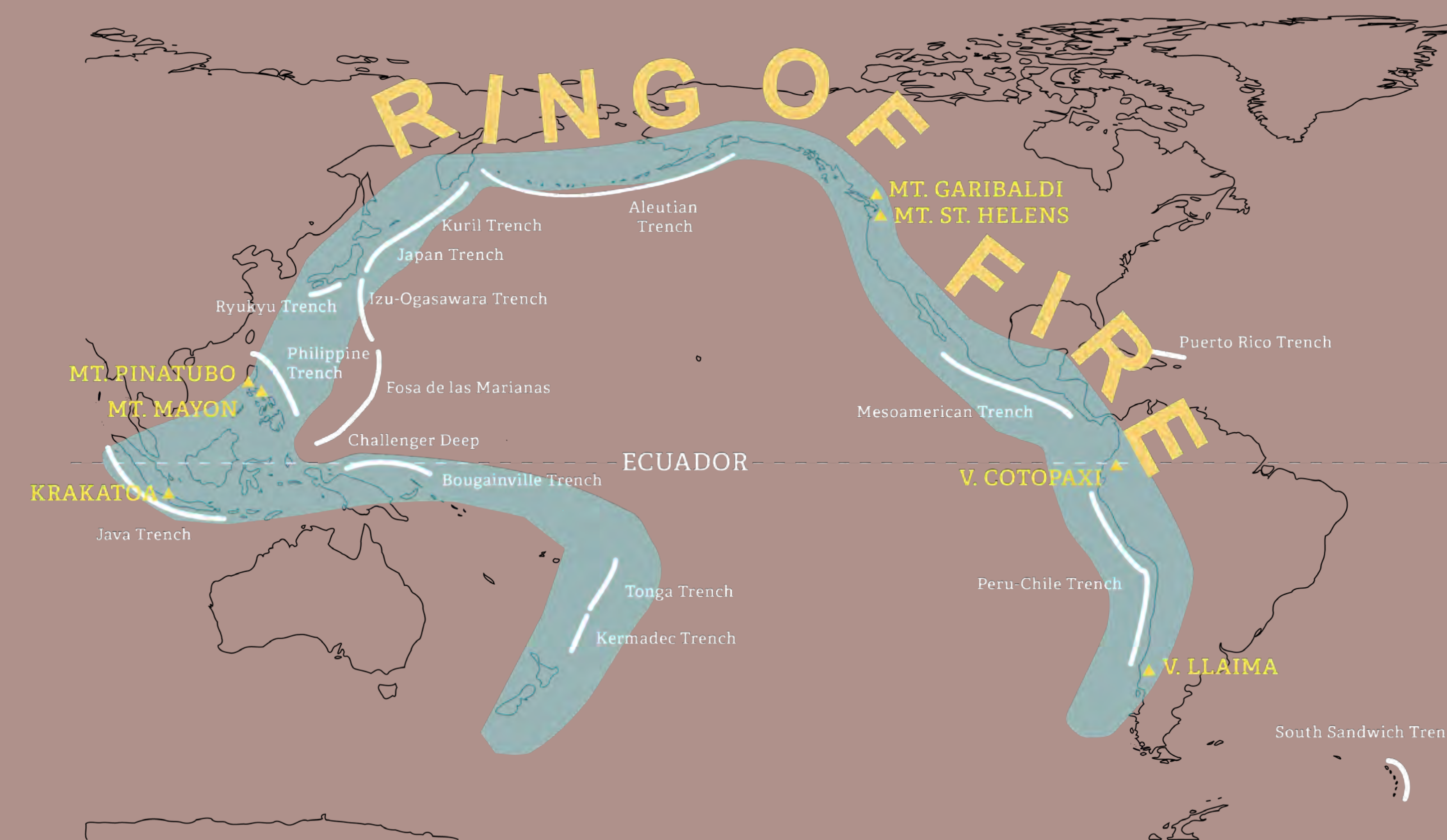
We cannot close the subject of social life and technological developments associated with geothermal energy in pre-modern times without briefly mentioning some remarkable facts regarding heat supply.

In Ephesus, located in present-day western Turkey and a major trade center of the Mediterranean in ancient times, pipes that allowed geothermal heating of a large number of buildings in the city's neighborhoods more than 2,000 years ago have been found. A similar technology was discovered in another culture that had no contact with classical Greece: a geothermal district heating system at Paquimé (Casas Grandes) in northern Mexico, in operation during the first half of the 11th century.

In the southern French town of Chaudes-Aigues (Aguas Calientes), a complex urban geothermal district heating system was in operation as early as 1334. A century earlier, the Viking settlers that came to Iceland developed pipelines for heating by transporting geothermal flows. Also in Iceland, in 1753, a successful experiment was carried out to produce salt from seawater by vaporization using geothermal heat.

Aztec Temazcal represented in the Codex Magliabecchiano (16th century, Mexico). Loubat Collection.

THE PACIFIC RING OF FIRE



USGS

The Pacific Ring of Fire, also called the Rim of Fire or the Circum-Pacific Belt, is located on the coasts of the Pacific Ocean and concentrates some of the most important subduction zones (the process of sinking of one tectonic plate under another) in the world, which generates intense seismic and volcanic activity.

It extends over 40,000 km and is shaped like a horse shoe. It incorporates 452 volcanoes (more than 75 % of the world's active and inactive volcanoes), and most of the so-called supervolcanoes. About 90 % of the world's earthquakes occur in this area (and 80 % of the world's most intense earthquakes).

The Ring of Fire is generated by plate tectonics. The Eastern section of the Ring is the result of the subduction of the Nazca plate and the Cocos plate under the South American plate, which moves westward. The Cocos plate is subducted below the Caribbean plate in Central America. A part of the Pacific plate, along with the small Juan de Fuca plate, sink under the North American plate. Along the northern part of the belt, the northwestward-moving Pacific plate is being subducted beneath the Aleutian Islands arc. Further west, the Pacific plate is subducted along the arcs of the Kamchatka Peninsula in the south beyond Japan. The southern part is more complex, with a series of small tectonic plates in collision with the Pacific plate, from the Mariana Islands, Philippines, Bougainville, Tonga and New Zealand. Indonesia lies on the Ring of Fire along the adjacent northeastern islands, including New Guinea, and the Alpine-Himalayan belt along southern and western Sumatra, Java, Bali, Flores and Timor.

The Licancabur volcano seen from the Chajnantor plain, with ice formations in the foreground. Volcanoes and mountains play an important spiritual role among the Atacameños. B. Tafreshi.

Desert vegetation in the Quebrada del Zaquete sector. Marcela Mella.

Geothermal energy and divinities

Even today, the Atacamenian or Likan-Antai communities (northern Chile, northwestern Argentina and southwestern Bolivia) honor and maintain a deep and daily relationship with Pachamama, the spirit of the earth. And it is no coincidence that, at least in Chile, all rituals and offerings to the spirit of the earth are oriented towards the east and the Andean highlands, where the sun rises amidst a constellation of mountains and volcanoes that have a life of their own. Life - in the broadest sense of the word - comes from those sacred heights, where many altarshave been built, that have been there since pre-Columbian times. Volcanoes *(apu)* and mountains *(mallku)* have an outstanding divine entity in the Atacamenian cosmic view. Some are more important for the communities as a whole (for example, the Licancabur volcano, "mountain of the people" or "of the country", located on the Chilean-Bolivian border) and others are relevant mainly for specific communities. Key seasonal tasks such as the "cleaning of irrigation canals" are invoked by sacredness and are not carried out without the huaqui, "payment" or "permission" to the earth, through which a balance is cyclically restored by returning to the pachamama what the people have taken from her.

The relationship of the Atacamenians -communities that still maintain their traditions in the Andean Altiplano - with geothermal phenomena is sacred, but distant, unlike the coexistence established with the earth´s heat in other latitudes. In fact, the Atacamenian centers of rituals have been located on the summits since ancient times, distant from the towns and villages.

In other parts of the world, a similar sacredness is observed in the relationship between human communities and geothermal phenomena. For the Maori, volcanoes, hot springs and fumaroles are *Wahi Tapu*, a term used to describe the sacred. A perception of geothermal phenomena very similar to that of the Sioux, who called them *Wakan Tanka* (Great Mystery).

The heat or fire of the earth was - and still is - a gift from the gods for the benefit of humans in multiple cultures throughout the world. At the same time, the beings or entities that inhabit the underground worlds are so immensely powerful and unpredictable that there is no room for anything but a reverent attitude towards them. As Mexican researcher M. C. Suárez points out, "in many places and in different epochs, geothermal energy had a preponderantly religious interpretation and a dual ethical relationship: constructive / destructive, beneficial / harmful, good / evil, helpful / malicious."

Terracotta head of Huehueteotl, the "old god", as the ancient divinity of fire in Mesoamerica used to be known. Sean Pathasema.

Ancient cults

In Neolithic Italy, religious cults and funerary rituals linked to geothermal manifestations already existed, many of which took place in caves with hypogeal waters. Big vases have been found in Sicily in natural tunnels with sulfurous steam at about 39°C.

The ancient Greeks expressed gratitude for the curative properties of their thermal waters erecting temples near the thermal springs to Asclepius, deity of medicine and son of Apollo and the mortal Coronis. Thermal waters were sacred, a generous gift of the gods of Olympus.

Romans built altars to their gods and goddesses at the hot springs. At the altar to the goddess Minerva at the hot springs in Bath (present-day southwest England), archaeologists found about 130 lead stone plaques on which people had written various petitions to the goddess.

Huehuetéotl, god of fire and the most ancient divinity of Mesoamerica, was directly related to volcanoes and the earth. His representation as an old man suggests the antiquity of geothermal phenomena. A "point of view" radically different from that of the ancient Japanese populations, for whom the fire god Kagutsuchi was a young god - son of the central divinities Izanami and Izanagi - who inhabited the volcanoes and whose fury was expressed in their eruptions.

On the island of Bali (Indonesia), immemorial beliefs originated in the Neolithic period merged with later Hindu and Buddhist influences around the sacred mountain concept. In an ordered universe stretching from the heavens and volcanic peaks, home of divine spirits who may or may not favor the human beings, down to the plunging depth of the sea, home for threatening harmful forces, all that is holy is associated with height. In this respect, it is clear why one of the most sacred places in every Buddhist temple of Bali is a shrine of offerings dedicated to the volcano *Gunung Agung*.

GunungAgung volcano in Bali. David Leiter.

THE PLACE WHERE HELL WAS

In the foreground, sulfur and boric acid encrustations. Larderello geothermal field. Fabio Sartori Collection (Italy).

The smoking waters versan the veins
for the vapor that the earth has in the belly,
that from the abyss pulls them upo

Versan le vene le fummifere acque
per li vapor che la terra ha nel ventre
che d'abisso li tira suso in alto

The landscape described by the great Florentine poet Dante Alighieri in Book VI of the Rhymes exists in reality. And perhaps the author of the Divine Comedy visited it once. Or most probably he heard about it. It is not so far from Florence, just over 60 kilometers southwest of Tuscany. It is the so-called Devil's Valley, permanently wrapped in a ghostly mist from a multitude of fumaroles, jets of steam and boiling pots with pestilent emanations of boric acid, ammonia and carbon dioxide.

Still untouched for much of the Middle Ages, this threshold of the underworld must have seemed to Dante's contemporaries a vivid image of the flaming and much-feared inferno, to which sinful souls were taken to suffer eternal punishment. Centuries would pass before the valley witnessed nothing less than the emergence of modern geothermal technology in the world, which of course would still seem somewhat diabolical to more than a few observers at the beginning of the 20th century. But let's not get ahead of ourselves.

Decline, fall and revival

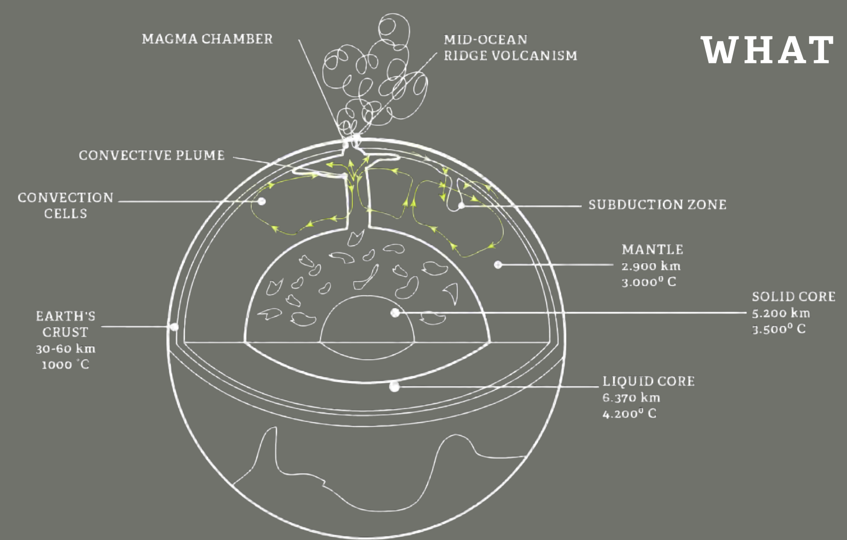
After the fall of the Western Empire in the 5th century, the Etruscan and Roman industry of geothermal by-products and therapeutic treatments - in addition to politics, business and entertainment - based on thermal baths had declined and eventually disappeared. Balneotherapy and the use of certain hydrothermal minerals gradually revived from the late Middle Ages onwards, in Tuscany and other geothermal areas of the Italian peninsula. However, these practices did not reach the scale and socio-economic impact they had in ancient Rome, being limited to the local level.

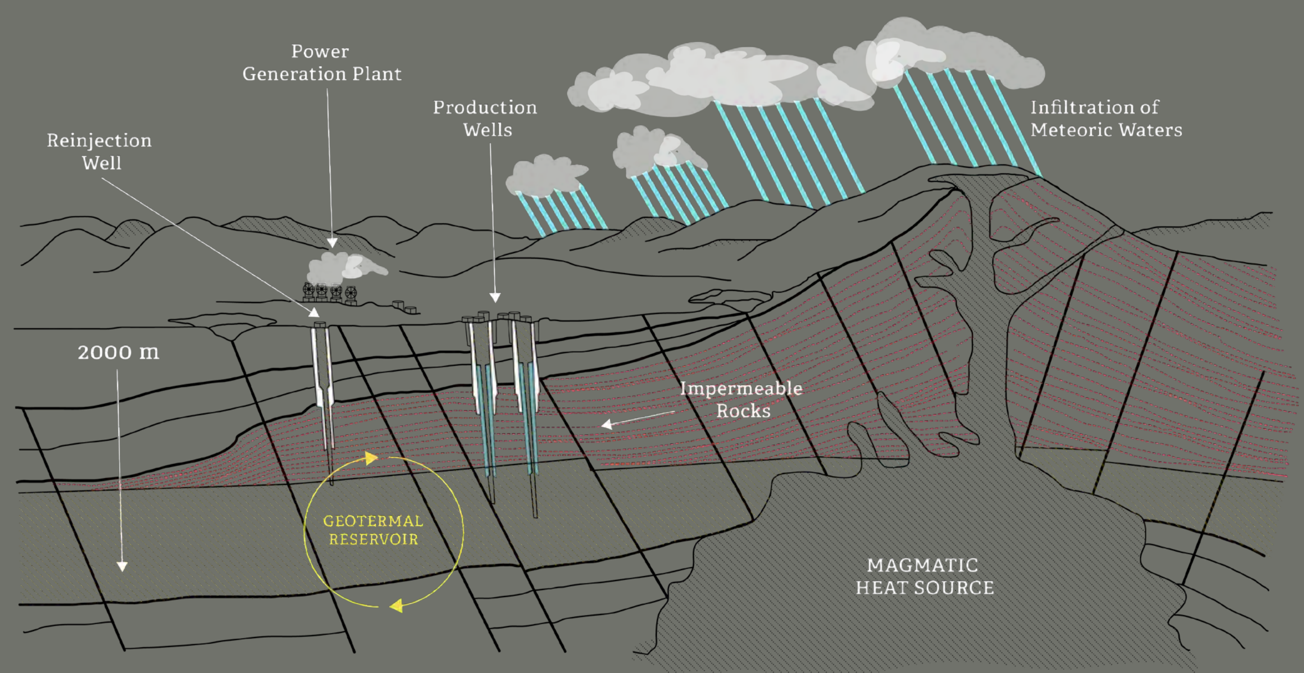
Except for Tuscany, from the late 15th century onwards. The war for the control of the geothermal area of the Devil's Valley between the municipalities of Volterra and Florence - a conflict known as the *Guerra delle Allumiere* - ended in 1472 with the victory of the latter, which resulted in the Medici family gaining control of the area.

Therefore, the extraction of hydrothermal minerals in the area became a monopoly of the Republic of Florence, which was assigned to the Florentine Wool Corporation. The city's textile industry was greatly favored by access to boric compounds and other minerals that previously it had to import, becoming one of the most important in Europe. However, its intensive extraction for more

MAP OF THE TOWN OF LARDERELLO COMMUNE OF POMARANCE, TUSCANY

WHAT IS GEOTHERMAL ENERGY?





The word geothermal comes from the Greek *geo* ("earth") and *therme* ("heat"). Simply put, it is the heat of the Earth. This internal heat of the planet comes both from the core and from the decay of radioactive isotopes (U235, U238, Th232 and K40), and is the result of the formation of the Earth just over 4.5 billion years ago.

In economic or industrial terms, geothermal energy is the heat accumulated in underground rocks (geotermal system) at industrially-profitable depths, and which can be transformed into electrical energy through a geotermal plant. To be considered a resource, a large amount of thermal energy with temperatures between 150 ˚C and 300 ˚C must be stored in permeable rock relatively close to the surface (between 1 and 3 kilometers deep). Geothermal resources are renewable and are available only in certain places on the planet, in the form of geotermal systems. There are four main elements of a geotermal system: heat source, reservoir, geothermal fluid and seal layer. The geothermal fluid is key, as it allows the development of this energy transformation process, being extracted by production wells and returned to the reservoir with the help of reinjection wells.

than two centuries ended up depleting the surface mineral reserves in the area. From the second half of the 18th century onwards, the activity declined considerably.

It was not until the second decade of the 19th century that the so-called "boraciferous region" of Tuscany regained productive vitality, due to a new and flourishing borate industry, developed by the French engineer and entrepreneur François Jacques Larderel.

A new chemical industry

The development of the new borate industry in Tuscany was preceded by the discovery in 1777 of boric acid in the geothermal manifestations of Monterotondo Marittimo (south of Volterra) by the German chemist Hubert Franz Hoefer. Two years later, the Italian scientist Paolo Mascagni confirmed the finding at Castelnuovo Val di Cecina (north of the first location and very close to present-day Larderello), using a different technique.

Francesco de Larderel. Enel Historical Archive (Italy).

The discovery was key, since boric acid - also known as Homberg's sedative salt - was widely used by pharmacists at the time, especially for the treatment of eye diseases. Its unexpected availability in Tuscan hydrothermal deposits drastically reduced the costs of the product, since previously a borate (compound) known as tincal, from which boric acid was extracted, had to be imported from Persia, India and even China.

Business opportunities were evident, and as early as 1812 the first company was established to extract boric acid from the *lagoni* (pods of muddy, bubbling water rich in hydrothermal minerals) in today´s Larderello. A second company opened between 1815 and 1816. High temperatures required to process the brines were obtained by burning wood from nearby forests. In just 10 months, 36 tons of boric acid were shipped at very attractive prices to the French market, eager for the new Tuscan product.

Vertigo of innovation

It was not until 1818 that a third producer of boric acid settled in the area, and ended up making history. Chemin, Prat, La Motte & Larderel was formed by four French partners exiled in Livorno. François Larderel was appointed technical director of the undertaking. And very soon he introduced a first technological breakthrough: the creation of artificial *lagoni* in areas rich in dried hydrothermal incrustations.

Over the next 10 years, about 50 tons of boric acid was sold annually in European markets. But in 1827 a foretold crisis occurred: the area had been deforested by the intensive use of firewood, burned to generate the heat required by the production process. It seemed to be a dead end. The company was liquidated by the

First Geothermal Power Plant.
In the town of Larderello, Italy.
Enel Historical Archive (Italy).

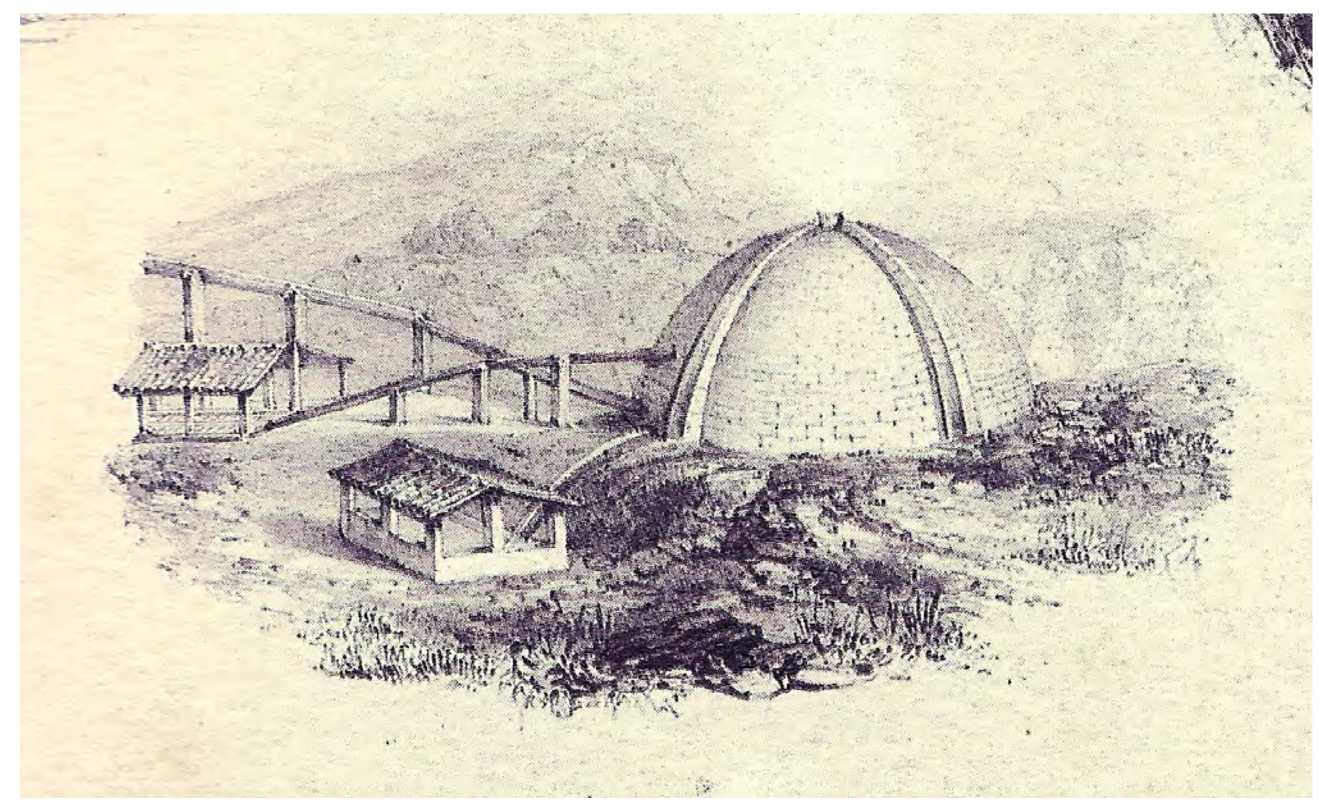
purchase of all the remaining shares by Larderel, who seemed to be up to something.

And so it was. That same year, their second technological innovation - of greater importance than the first one- was the covered *lagone*. It consisted of a hemispherical brick structure that was built over each *lagone*. The structure made it possible to separate steam from water, which underwent an initial process of concentration of its saline content. The heat of the steam formed in the intermediate and upper part of the dome, at a temperature of about 100°C, was used to evaporate and dry the brines, thus eliminating the need to burn wood.

Between 1828 and 1829, Larderel implemented the cascading *lagoni*. The *lagoni* located in the same line along the slope were connected by small open ducts to channel the boric water by gravity. The water overflowing from the *lagone* located at a lower altitude was conveyed to settling tanks and then to drying tanks. These latter were heated by steam transported by a pipe from the middle and upper part of the nearest covered *lagone*.

Between 1832 and 1834, wells of between 6 and 8 meters were dug in the immediate vicinity of the natural *lagoni* in order to increase the production of borate water.

Covered (vaulted-roof) "lagone" system for collecting steam from surface manifestations (an engraving of 1850). Top left: pipe conveying boric brine to the lower part of the system. Middle: another pipe extracting steam that has been separated in the intermediate part of the system. Bottom: a third pipe conveying the concentrated boric brine to vaporization tanks. Enel Historical Archive (Italy).



Hadrian's boiler

Between 1840 and 1845 a fourth technological advance was perfected, the *caldaia adriana* (Hadrian's boiler), named after its inventor, Hadrian, one of Larderel's sons. It consisted of a series of brick ducts lined with lead sheeting, in which the borate brine was circulating against the flow of steam injected into the space under the base of the aforementioned brick ducts.

Due to these technological advances, and in only 21 years (from 1829 to 1850), the production of boric acid increased from 125 to 1,000 tons per year. The economic impact of Larderel's activity in the region was so significant that the Grand Duke Leopold II of Tuscany appointed him Count of Montecerboli (after the name of the town where the company of Larderel and his partners were originally based in 1818) and renamed the town where the boric acid production by the French immigrant and new Tuscan aristocrat was based as Larderello in 1846.

Between 1842 and 1900 the production of borate compounds obtained from new wells drilled at increasing depths (25 to 30 meters in 1842 to between 250 and 300 meters in 1900) increased significantly.

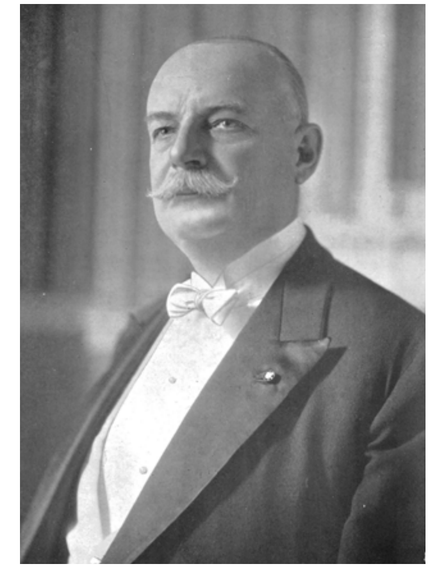
In the first half of the 20th century, chemical production became more diverse. In addition to boric acid, sodium perborate, ammonium carbonate and talcum powder were produced, among other products in high demand by the pharmaceutical industry.

An engraving of 1850 of the boric acid industry at Larderello. Steam flowing from the brick domes (called "lagonicoperti") is collected and conveyed to the "Hadrian's boiler" (center). Enel Historical Archive (Italy).

Boric acid production plant at Larderello, ca. 1915. Geothermal Museum of Larderello (Italy).

The first mobile geochemical laboratory for sampling and analysis of geothermal gases and fluids. The laboratory was mounted on a horse-drawn carriage. Larderello area, 1904. Geothermal Museum of Larderello (Italy).

The geothermoelectric industry begins



Piero Ginori Conti. Geothermal Museum of Larderello (Italy).

Prince Piero Ginori Conti was appointed general manager of Società Larderello in 1903, a few years after marrying Adriana, the eldest daughter of Count Florestano de Larderel, grandson in turn of Count Francesco (as François Larderel became known after being granted his nobility title). The leadership of the Florentine aristocrat - who had to acquire technical and scientific training along the way - proved to be key, as he not only modernized the production processes of the family chemical industry, but also quickly saw possibilities for technological innovation in other areas of geothermal energy use.

As soon as he assumed his new role, Ginori Conti carried out mechanical energy production tests using state-of-the-art pumps driven by geothermal steam, in order to stimulate wells and pump boric brine to the chemical processing facilities. As early as 1903, laboratory experiments began to determine the feasibility of using well fluids to produce boric acid and simultaneously generate electricity. In the early months of 1904, the world's first mobile geochemical laboratory was set up in a horse-drawn carriage for sampling and rapid chemical analysis of fluids, gases and mineral sediments.

A history-making experiment

On July 4, 1904, Ginori Conti conducts a successful experiment, producing electrical energy from geothermal fluids. He used an indirect cycle process with steam, obtained with a heat exchanger (a device that allows the exchange of heat between two fluids separated by a high temperature conductive wall, which prevents the two fluids from coming into contact). As a result, the geothermal steam (impure and containing various chemical substances that could become encrusted or aggressive to certain metals at the time) was reheating fresh water until it evaporated.

Purified steam - obtained from the original fluid in a well near Larderello - activated a piston motor connected to a 10-kW dynamo. In turn, the dynamo was connected to 5 light bulbs of a few watts of power. It was at that moment that the light came on.... For the first time in history, and thanks to the genius of Piero Ginori Conti and the previous advances of François Larderel, geothermoelectric energy had been generated.

In 1905, the first prototype engine powered by geothermal energy, with pistons manufactured by the Cail company, was installed. The engine was driven by steam (also obtained with a heat exchanger) and was connected to a 20kW dynamo. As a result, the prince's palace and some other houses were illuminated with a geothermal energy source for the next 10 years.

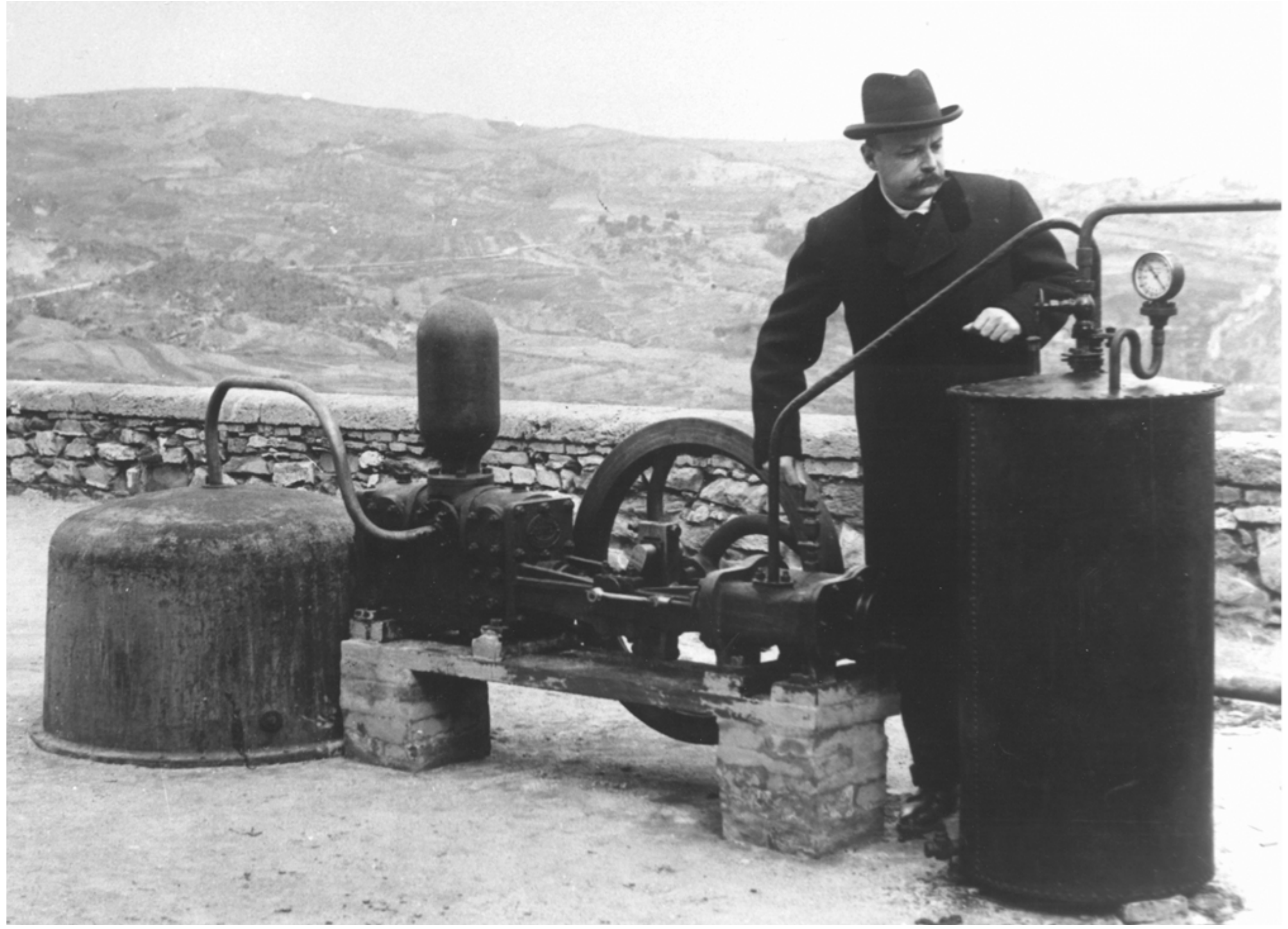
In 1908 an engine powered by geothermal energy manufactured by the Neville Company, similar to the previous one, was installed for the operation of chemical plants in Larderello and its surroundings.

The first geothermal power plant

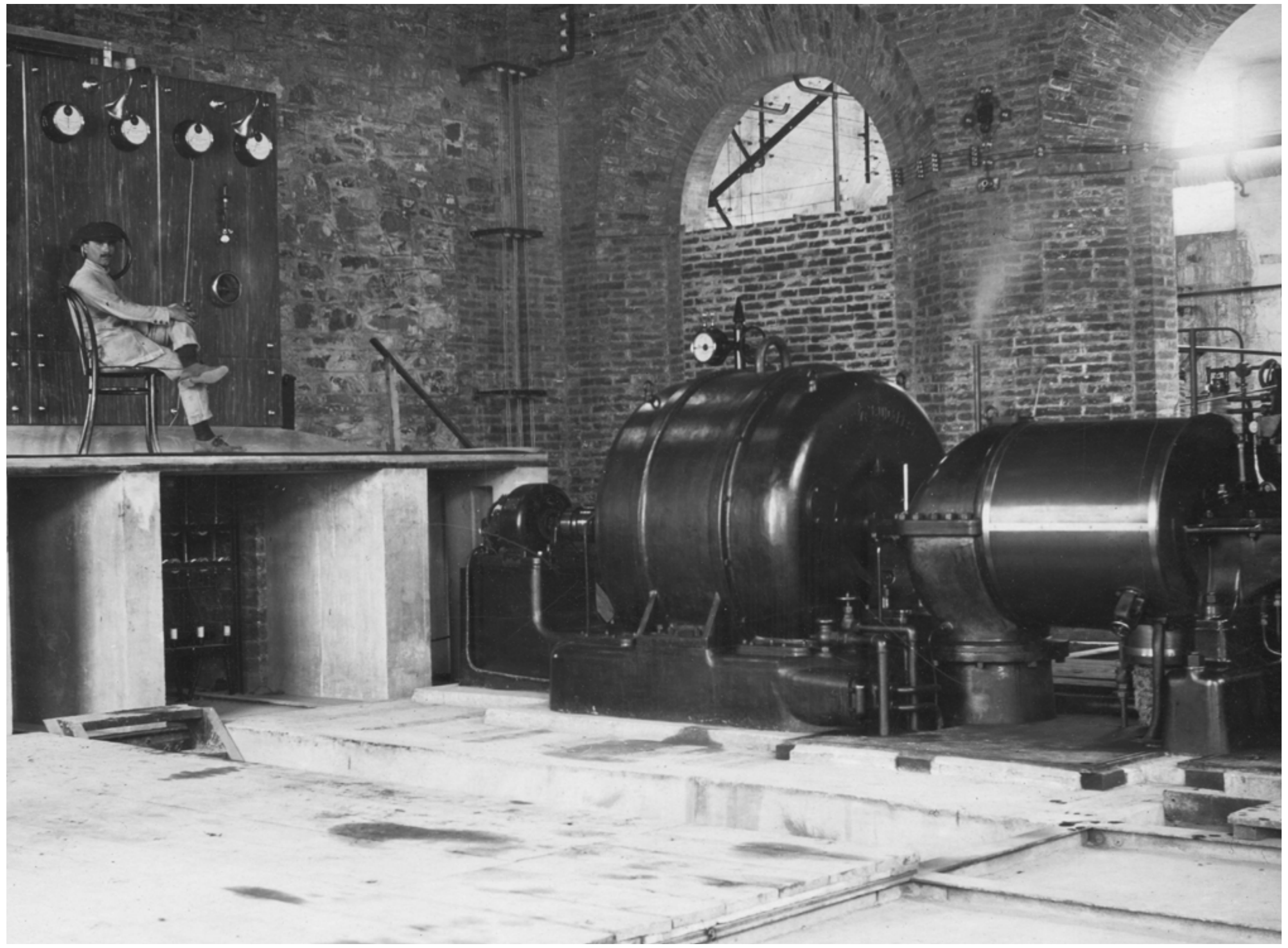
But only in 1913 the world's first geothermoelectric plant, called Larderello 1, came into operation. It consisted of a 250kW turbine generator manufactured by Società Franco Tosi, which was still powered by steam (indirect cycle). It is interesting to point out that this is the same company that sent Giovanni Severina to Chile and asked him to organize an expedition to El Tatio. Through Severina, Franco Tosi Legnano is at the origin of the Preliminary Community of El Tatio.

But let us return to our subject matter. Inaugurated in 1913, the plant generated electricity for all the chemical plants in the borate region. Between 1914 and 1916 it integrated the residential areas of Pomarance, Saline di Volterra and Volterra using the world's first power line supplied by geothermoelectric energy, which -with a length of 25 kilometers- connected the above-mentioned towns with Larderello 1.

Technological leap. In 1904, Piero GinoriConti produces for the first time electricity based on geothermal energy. Enel Historical Archive (Italy).



First geothermal well drilling in Larderello. Matto well (1906). Geothermal Museum of Larderello (Italy).



The first geothermal power plant in the world, inaugurated in Larderello in 1913. Larderello 1 had a capacity of 250kW. Geothermal Museum of Larderello (Italy).

In 1916 the first generating unit of Larderello 1 was dismantled and replaced by two turbine generators manufactured by Società Franco Tosi, each (turbine plus alternator) of 3.5MW. They still operate with indirect cycle. The capacity of these units was high, comparable to the largest thermal and hydroelectric units of that time.

With the development of new material technologies, the turbines of geothermal power plants will end up being activated directly by "natural" steam from the geothermal fluid coming from the wells, obeying the thermodynamic process called "direct cycle". This is what Piero Ginori Conti attempted to achieve in 1923, when he installed an experimental 23kW direct cycle generation unit at Serrazzano (southwest of Larderello). The unit operates smoothly for two years, after which it is reinstalled in the technical school of Larderello and used to train personnel.

Larderello 2 plant destroyed by German troops during their retreat from Italy at the end of World War II. June 1944. Geothermal Museum of Larderello (Italy).

Unstoppable growth

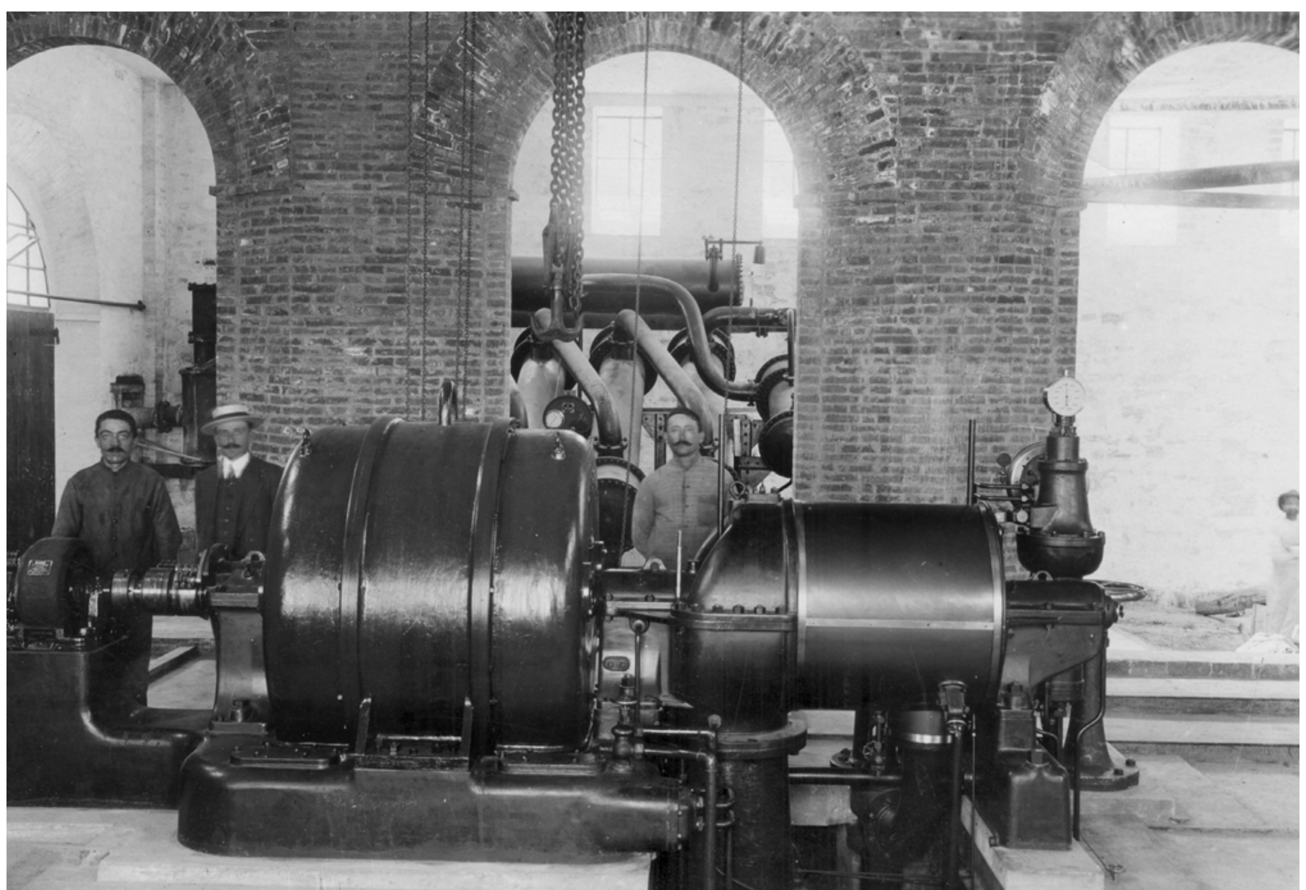
Between 1926 and 1927 two new direct cycle units are installed in Castelnuovo Val di Cecina, one of 600kw and the other of 800kw. And in 1930 a 3.5MW direct cycle unit was installed at Larderello 1 plant. By December 1930, the total capacity of geothermal power generation in the boraciferous region was 11.9MW (7MW of indirect cycle units and 4.9MW of direct cycle units with atmospheric exhaust).

The installed capacity did not stop growing in thesubsequent years. Between 1935 and 1939, Larderello 2, the first large-scale geothermal power plant, came into operation. It consisted of six indirect cycle units of 10MW each.

Despite the depletion of the boric acid contained in the geothermal fluid of the wells, the production of this and other chemical components was still very profitable.

Already during the Second World War, between 1940 and 1943, four indirect cycle units of 10MW each were installed in Castelnuovo Val di Cecina, similar to those of Larderello 2. In Serrazzano, two direct cycle units of 3.5MW and 5MW. And at Sasso Pisano, south of Larderello, a 3.5MW direct cycle unit.

Turboalternator of the first geothermal power plant. Geothermal Museum of Larderello (Italy).



Facade of the Geothermal Museum in Larderello. Geothermal Museum of Larderello (Italy).

Total (or near-total) destruction

At the end of 1943, the installed geothermal power capacity at Larderello totaled 129.3MW (107MW of indirect cycle units and 16.9MW of direct cycle units with atmospheric exhaust).

Disaster struck between the spring and summer of 1944. Before retreating in the face of advancing Allied armies, German troops destroy all the geothermal power plants and chemical plants in the boraciferous region. Nothing is left standing. Except for one small miracle: under the rubble, the 23-kW direct-cycle pilot generating unit is intact. It is the unit that once operated in Serrazzano and that from 1925 had served the trainees of Società Larderello technical school.

Thanks to the electricity provided by this small unit and the great sacrifices and reconstruction efforts of local communities, in the autumn of 1944 began a new stage in the development of what is now one of the largest geothermal power production centers around the world.

LARDERELLO GEOTHERMAL ENERGY DURING THE WORLD CONFLICT (1939 - 1951)

By Giorgio Simone

The year 1939 is crucial for Società Boracifera Larderello (Larderello Boraciferous Society) and for geothermal energy. In addition to achieving a remarkable success with the start-up of Larderello 2 power plant, the first one with an installed power of a good 69 MW, the Company experienced the loss of its founder. On December 3, in Florence, Prince Piero Ginori Conte died at the age of seventy-four. And a few days later, on December 9, enforcing the dispositions stated in Royal Decree 318, published on February 20, 1939, which rules the prospection and development of mineral deposits of gas vapor usable for the production of electrical energy, the "Larderello Società Anonima per lo sfruttamento delle forze endogene" (Larderello Limited Liability Company for the exploitation of endogenic forces) is founded. Seventy per cent of the shares are in the hands of the Chilean State Railways, while the other portion corresponds to the Italian Real Estate Institute. The Ginori Conte family retains a small minority interest.

The new Limited Liability company had, on December 31, 1940, a workforce of 1653 employees, of which 1335 were based in Larderello and 318 in the other boraciferous factories in the area. The infrastructure of the geothermoelectric sector includes five power plants, with an installed power of 72.5 MW, the average flow rate of the fluid to the plants is 1000 t/h. The number of wells drilled in 1904 is 203, of which 100 are operative. The length of the active steam pipelines reaches 20 km. Obviously; they have come a long way from the fifteen wells that existed in 1818.

While Europe was devastated by the war, between 1942 and 1944, the geothermal power plants of Castelnuovo, with four turbo-alternators of 10,000 kW each, and Sasso Pisano, with a unit of 3,350 kW, started operation in the boraciferous region. The installed geothermal power of "Larderello SA" reaches 126.8 MW, of which 16.8 MW are free download.

After the Sicily landing in July 1943 and the advance northwards along the peninsula, on April 22, 1944 the Anglo-Americans started the strafing and bombing of the Larderello plants, which continued until June 26. On June 10, SS and Nazi-Fascist squads sweep the Castelnuovo region and on June 14 they carry out one of the most tragic retaliations to which the liberation of Italy gave rise: 77 miners captured in the Niccioleta mine, together with four partisans, are massacred in the vicinity of the Castelnuovo Geothermal Power Station.

Factories are closed and production is suspended. Larderello SA is on its knees. From June 27 to 29, before retreating, the German sappers destroy all the turbines and productive wells by mining them. On June 29, the American soldiers of the Fifth Army liberated Castelnuovo, Larderello, Pomarance and advanced towards Volterra.

Among the liberation forces advancing through Italy is also the Second New Zealand Division. Some of its engineers, from the beginning of the Italian campaign in July 1943, had an objective, already programmed before their departure from Wellington. Their goal was to carry out an inspection of the geothermal power plants at Larderello to try and collect as much information and technological knowledge as possible in order to build plants of the same type in the geothermal field of Rotorua, in New Zealand. In October 1944, when the geothermal installations are already in the Allied hands, the delegation of New Zealand Army engineers arrives at Larderello. However, they could only observe the total destruction of the plants by the Germans and took a series of photographs, still in the archives today, which unequivocally demonstrated the damage inflicted on each of the turbine shaft bearings. Damage too precise to have been caused by aerial bombardment.

The post-war period also began with changes for geothermal energy. On February 28, 1945, the Limited Liability company was transformed into a joint stock company, and the Chilean State Railways acquired the shares of Larderello SA, definitively excluding the representatives of the Ginori Conti and Larderel families.

Between March 1945 and April 1948, all the turbo-alternator sets of Castelnuovo and Larderello power stations were reactivated and the supply of electrical energy to feed the electric traction equipment of the State Railways was resumed. The installed power slightly exceeds the one existing before the war, 138,500 kW versus 135,800 kW.

Thanks to the extraordinary progress in drilling equipment, associated with the use of the "rotary" system, Larderello built well 82, known as "the great fumarole", with a capacity of 300,000 kg/h of steam, and well 85, in the area of Valle Secolo, with a slightly lower capacity of 295,000 kg/h. These two wells allowed Larderello to become the largest geothermal power plant in the world. On May 1, 1951, work was completed on the Larderello 3 power plant, with an installed capacity of 120,000 kW.

82-83 Steam escaping from a cooling tower in a geothermal power plant in Larderello. Geothermal Museum of Larderello (Italy).

PART TWO

FROM LARDERELLO TO THE WORLD

THE POSTWAR:
LETHARGY IN CHILE AND GLOBAL EXPANSION

While Italy was paving the way for the commercial exploitation of geothermal energy, inaugurating the first geothermal power plant in 1913 to achieve the installed capacity of 129.3 MW just 30 years later, what was happening in the rest of the world?

Nothing comparable to Larderello's rapid development, at least initially. In 1918, New Zealand - a future geothermal power - already showed interest in replicating the Italian experience in its territory. Japan drilled its first geothermal wells in Beppu in 1919. And in 1921, the United States drilled at The Geysers, 116km north of San Francisco, installing a 20 kWe experimental plant that was in operation from 1925 to 1958.

Top 3

That same year, 1921, geothermal studies and drilling began in Chile, led by Ettore Tocchi. "When Tocchi drilled the first well to measure temperature (he called it "soffione 18 de septiembre", as reported in the local press of that time), at that moment Chile became the third or fourth country in the world to drill a geothermal well," says geologist Diego Morata, director of the Geothermal Center of Excellence for the Andes and an academic at the Universidad de Chile.

"First Italy, next Japan, and then the United States and Chile at the same time. The wells had a depth of 50 meters. Today they would be called a gradient well. Chile ranked third in geothermal exploration around the world, together with the United States. Let´s put it this way... If the country had realized what it had, today Chile would be a geothermal power," concludes Morata, quite disappointed.

Japan drilled its first geothermal wells in 1919 at Beppu. In the picture, Umi-Jigoku natural hot springs, near the same locality on the southern island of Kyushu. ID 71506890 © Molinscat| Dreamstime.com

But although the adventure of the Preliminary Community of El Tatio ends abruptly in 1925, there were still important efforts to promote Ettore Tocchi's studies and proposal and to develop the geothermal industry in Chile. One of them took place in 1948. In its September issue of that year, the Mining Bulletin of the National Mining Society published the technical reports by the Italian engineers Plinio Bringhenti (yes, the same one that had been initially approached by the Antofagasta entrepreneurs in 1917) and Marcello de Leva. The reports on the production and distribution of electrical energy from the "endogenous" or "thermo-volcanic" forces of El Tatio. Such production could become, according to Carlos Lanas, the civil engineer of the Universidad de Chile who presented both reports in the publication, "the starting point of a thriving industrial development of northern Chile".

A new try

In his "Report on El Tatio geothermal area", Bringhenti relies primarily on the results of geological investigations and drilling carried out by Ettore Tocchi almost 30 years earlier, but he updates to the post-war time his proposal for geothermoelectric energy production both in financial and technological terms.

"Among the different geothermal areas that I know - he writes - Italian and foreign (New Zealand, Alaska and Sonoma County in the United States, etc.), that of El Tatio presents the closest original analogies with the *soffioni* of Tuscany." And the geological similarities between the two regions also include the area of steam composition: "The condensation water analyses that I have received from Engineer Tocchi, have shown me the identity of composition of the two steams, because in both, the same chemical components are present, boric acid and ammonia, and in the same percentages. What is even more characteristic, you can find a particular substance, organic, of ithiolytic type, also present in Larderello."

The early industrialization of geothermal power generation in Tuscany never degraded the environment. The image shows a grasshopper peeping out over sulfur and boric acid incrustations, next to thermal springs in Larderello. Fabio Sartori Collection (Italy).

Bringhenti's "memorandum" - as he prefers to call it –addresses a brief history of the development of the Italian geothermal industry in order to establish obvious parallels with the potential of El Tatio, dealing concisely but precisely with the issues of steam availability in the aforementioned Chilean geothermal area, drilling, type of geothermal power plant recommended and obtainable power.

The " magic" energy figure

The numbers speak for themselves: the cost of installing a "power plant with endogenous forces" in El Tatio in 1948 amounted to a maximum of 1,300 Chilean pesos per kW, which was very advantageous versus a minimum cost of 10,000 pesos per kW installed for a hydroelectric plant. To produce 300,000 kW - the "magic" figure of energy that central Chile urgently required at that time - with hydro power, an investment of 3 billion pesos was needed, a cost that drastically dropped to 390 million pesos in the case of geothermal energy.

Even adding the additional cost of transmitting this electrical energy for about 1,700 kilometers from El Tatio to the south of the country by "busbars" - here the calculations of the engineer Marcello de Leva played an important role - the total investment did not exceed 1,200 million pesos at the time. Much less than half the investment required for a hydroelectric power plant with the same installed capacity. Even the additional drillings needed in El Tatio did not total more than 30 million Chilean pesos.

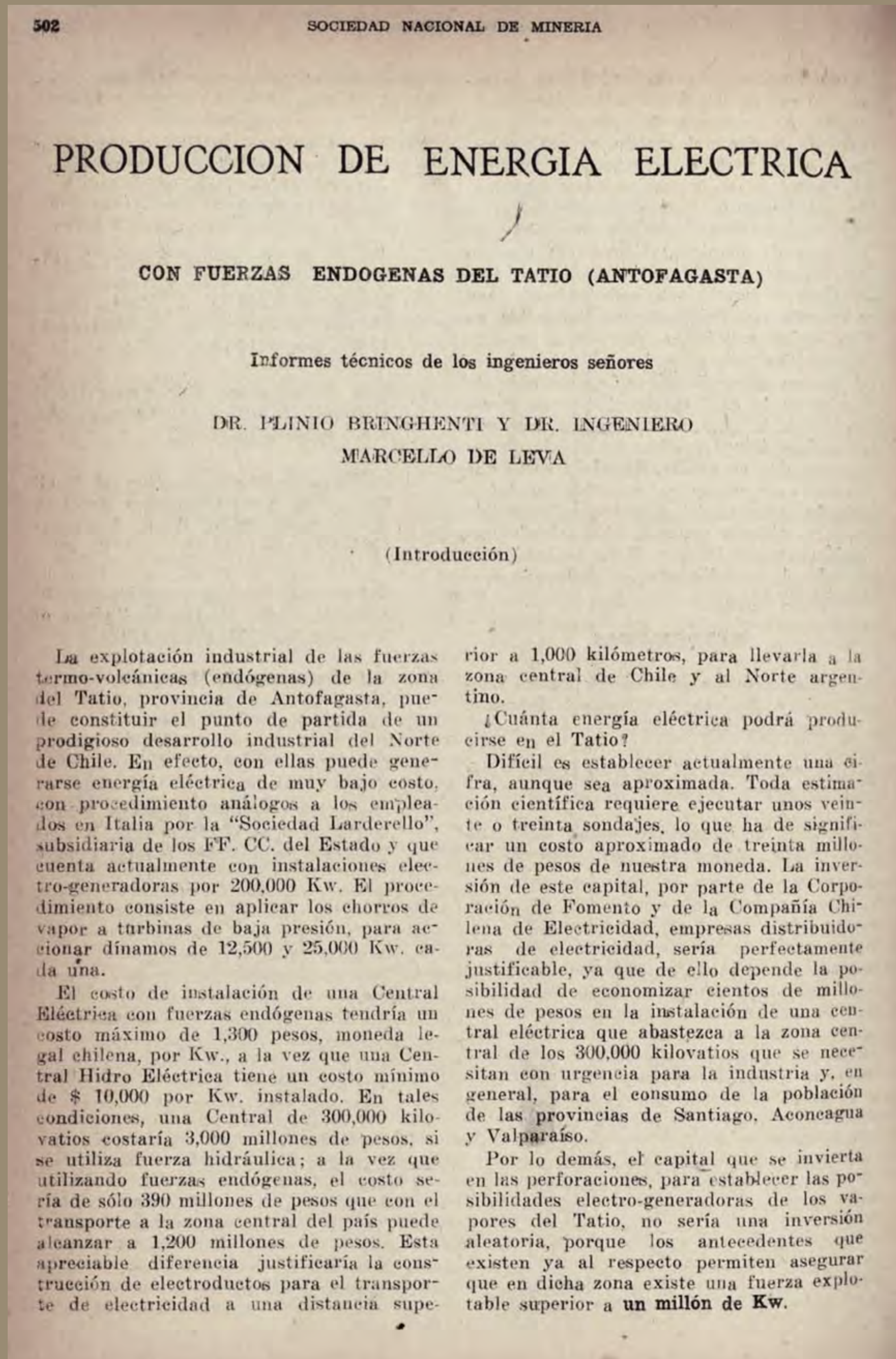
Plinio Bringhenti concludes his letter by pointing out that *"... the availability of electric energy has always created the industrial development of a country (...) On ending this short memorandum, I can only reconfirm my strong and deepest conviction (that) there is a huge quantity of steam in El Tatio and that from there a huge quantity of electrical energy can be obtained at lower cost than from any other procedure. Those who understand this and take advantage of it are fortunate."*

With such a clearly outlined road map, one would have expected an enthusiastic reaction from the Chilean economic development agency and the national electricity company. Or in general, by the relevant decision-makers of the time. However, no one in Chile took up the challenge. Nobody "understood" nor "took advantage".

It is not easy to understand that almost three decades after Tocchi's heroic efforts in El Tatio, Bringhenti and De Leva wrote their reports on their own initiative. Who in Chile, besides the engineer Lanas, asked them or somehow encouraged them to do so? More than 70 years later, it is almost impossible to know this for sure. But be that as it may, with the null impact of the initiative, another historic opportunity for the development of the country's energy matrix vanished.

There would be yet another episode in 1960, when –upon request of

Ahumada street in Santiago, Chile, 1940. Collection of the National History Museum (Chile).



502 SOCIEDAD NACIONAL DE MINERIA

PRODUCCION DE ENERGIA ELECTRICA

CON FUERZAS ENDOGENAS DEL TATIO (ANTOFAGASTA)

Informes técnicos de los ingenieros señores

DR. PLINIO BRINGHENTI Y DR. INGENIERO MARCELLO DE LEVA

(Introducción)

La explotación industrial de las fuerzas termo-volcánicas (endógenas) de la zona del Tatio, provincia de Antofagasta, puede constituir el punto de partida de un prodigioso desarrollo industrial del Norte de Chile. En efecto, con ellas puede generarse energía eléctrica de muy bajo costo, con procedimiento análogos a los empleados en Italia por la "Sociedad Larderello", subsidiaria de los FF. CC. del Estado y que cuenta actualmente con instalaciones electro-generadoras por 200,000 Kw. El procedimiento consiste en aplicar los chorros de vapor a turbinas de baja presión, para accionar dínamos de 12,500 y 25,000 Kw. cada una.

El costo de instalación de una Central Eléctrica con fuerzas endógenas tendría un costo máximo de 1,300 pesos, moneda legal chilena, por Kw., a la vez que una Central Hidro Eléctrica tiene un costo mínimo de $ 10,000 por Kw. instalado. En tales condiciones, una Central de 300,000 kilovatios costaría 3,000 millones de pesos, si se utiliza fuerza hidráulica; a la vez que utilizando fuerzas endógenas, el costo sería de sólo 390 millones de pesos que con el transporte a la zona central del país puede alcanzar a 1,200 millones de pesos. Esta apreciable diferencia justificaría la construcción de electroductos para el transporte de electricidad a una distancia superior a 1,000 kilómetros, para llevarla a la zona central de Chile y al Norte argentino.

¿Cuánta energía eléctrica podrá producirse en el Tatio?

Difícil es establecer actualmente una cifra, aunque sea aproximada. Toda estimación científica requiere ejecutar unos veinte o treinta sondajes, lo que ha de significar un costo aproximado de treinta millones de pesos de nuestra moneda. La inversión de este capital, por parte de la Corporación de Fomento y de la Compañía Chilena de Electricidad, empresas distribuidoras de electricidad, sería perfectamente justificable, ya que de ello depende la posibilidad de economizar cientos de millones de pesos en la instalación de una central eléctrica que abastezca a la zona central de los 300,000 kilovatios que se necesitan con urgencia para la industria y, en general, para el consumo de la población de las provincias de Santiago, Aconcagua y Valparaíso.

Por lo demás, el capital que se invierta en las perforaciones, para establecer las posibilidades electro-generadoras de los vapores del Tatio, no sería una inversión aleatoria, porque los antecedentes que existen ya al respecto permiten asegurar que en dicha zona existe una fuerza explotable superior a **un millón de Kw.**

First page of Bringhenti and De Leva's report on Tatio's geothermoelectric potential, published in September 1948 by the Boletin Minero or Mining Bulletin.

Wairakei geothermal power plant, New Zealand.

the Chilean mining company Santa Fe - the engineer Remo Contini traveled to Chile, representing the Geothermal Energy Consultancy (CEG), based in Rome and the scientific and technical support of Larderello. Contini is developing geological and geophysical surveys and studies in El Tatio and, to the southeast, in the Laco sector. Highlighting in particular the favorable conditions of El Tatio for the development of a geothermoelectric project, the CEG issues a detailed report to the Santa Fe mining company and recommends going ahead. But for whatever reason - high risk and costs, disregarding the chaos caused in the country by the devastating earthquake on May 22, the strongest ever recorded on earth - it appeared that the time for geothermal technology in the country had not come yet. It all came to nothing, closing thus a brilliant and pioneering chapter in the history of geothermal energy in Chile, led by the Italians, the biggest developers of geothermal industry at the time.

Those who did take advantage

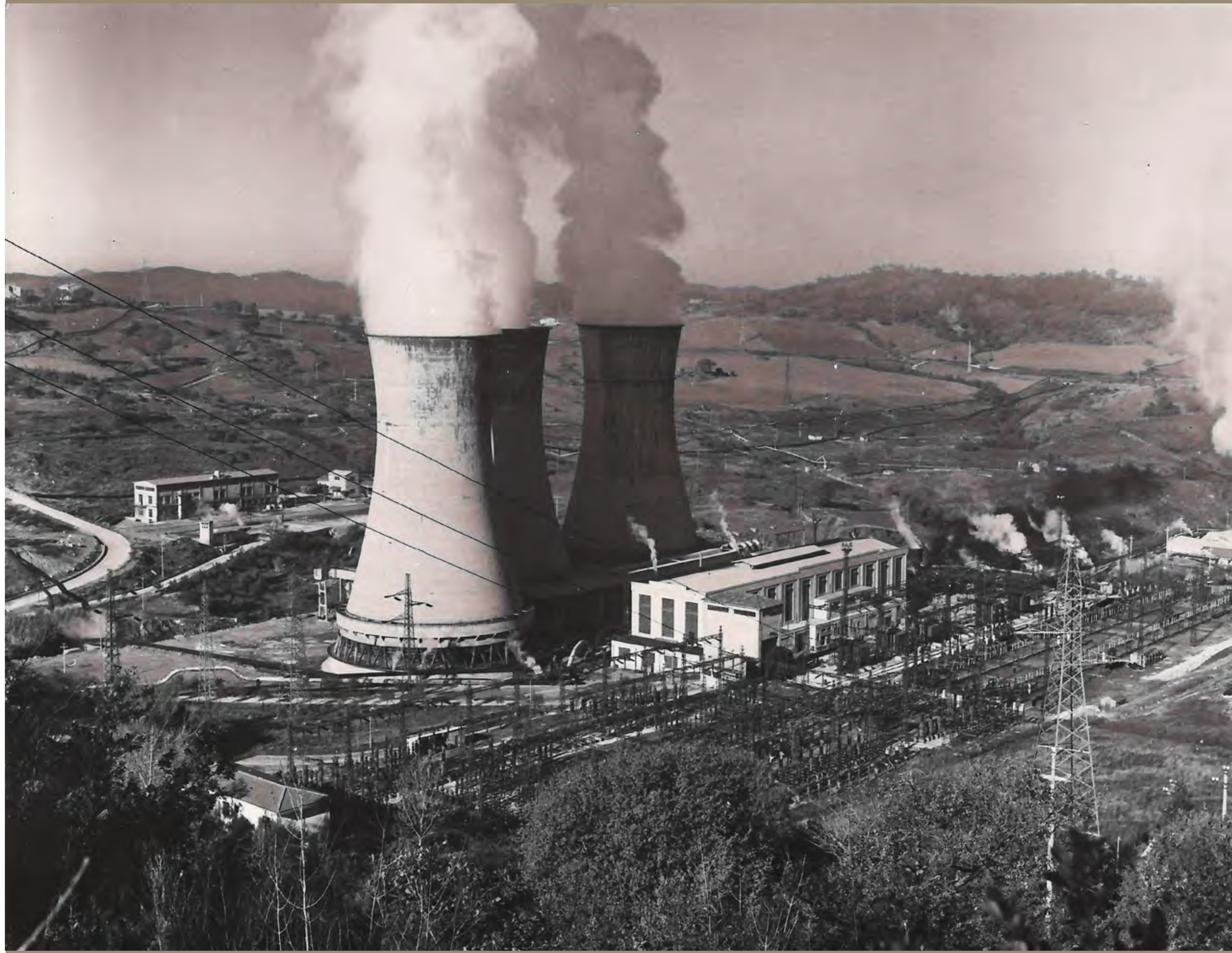
In contrast to business stagnation in Chile, other countries with geothermal potential had begun to take an interest in the new technology. And since the late 1950s, the use of geothermal resources for electricity generation definitely crossed Italy's borders.

Over four years, between 1954 and 1958, the first geothermal power plants were built and started operating in New Zealand, in the towns of Kawerau and Wairakei. In 1959, a small experimental plant began operating in Pathé, in the State of Mexico. And in 1960, Pacific Gas and Electric began operating its first commercial geothermal power plant at The Geysers (California), which is now home to the world's largest geothermal industrial complex. That same year, 1960, Larderello achieved an annual electrical power production of 2 billion kWh, with an installed capacity of nearly 300 MW.

The Mexican and American plants - called "dry steam" plants- used directly the steam from underground sources, since no liquid was drawn from the geothermal wells along with the steam. This is a simple but unusual technology, as geothermal reservoirs capable of directly supplying steam on a commercial scale are rare around the world. The New Zealand case was different, as its plants were the first to use "flash" technology, which consists of separating the steam from the liquid mixture (water plus "wet steam" coming out of the reservoir's producing wells). The steam - isolated by pressure cyclone separators - is used to drive the turbo -generators. Once condensed, it is put back into underground deposits along with the liquid (which is directly re-injected into the subsurface from the cyclone separators). The total process fluid is then returned to the reservoir for reuse.

The growth of globally installed geothermal power capacity was very gradual until the early 1970s. The turning point came with the first world oil crisis in 1973, when many countries began to explore the possibilities of alternative energy resources to hydrocarbons, until then massively predominant.

Interior of a cooling tower at Larderello. Its dimensions can be better appreciated by looking at the human figure at the bottom. Fabio Sartori Collection (Italy).



Larderello 3 power plant, ca. 1970. Geothermal Museum of Larderello (Italy).

Sonoma Geothermal Power Plant at The Geysers (USA). Stepheng3.

Interior of the Larderello 3 power plant (ca. 1970). Geothermal Museum of Larderello (Italy).

An attractive option

Geothermal energy became at that time an extremely attractive energy production alternative, especially in countries with geological features associated with high-temperature resources, namely those countries with territories located on the margins of tectonic plates and with recent volcanic activity.

What was this attractiveness based on? Firstly, it is an autonomous resource, completely unaffected by the ups and downs of foreign trade. Also, the ratio (quotient) between the actual energy generated by a geothermal power plant in a certain period of time (usually annual) and the energy generated if the plant had operated at full load in the same period of time, a ratio technically known as plant capacity factor, is one of the highest among all available power generation technologies. Thirdly, and related to the above mentioned, a geothermal power plant has little or null generation intermittency, providing a relatively constant flow of energy, which makes it extremely efficient from the entire electricity generation system point of view (base- load generation). Finally, it is a technology with low environmental impact.

Therefore, it is not surprising, that several countries that had local access to high-temperature geothermal resources gradually decided to join the global club of geothermal power generation, especially, following the energy crisis that hit the world in 1973.

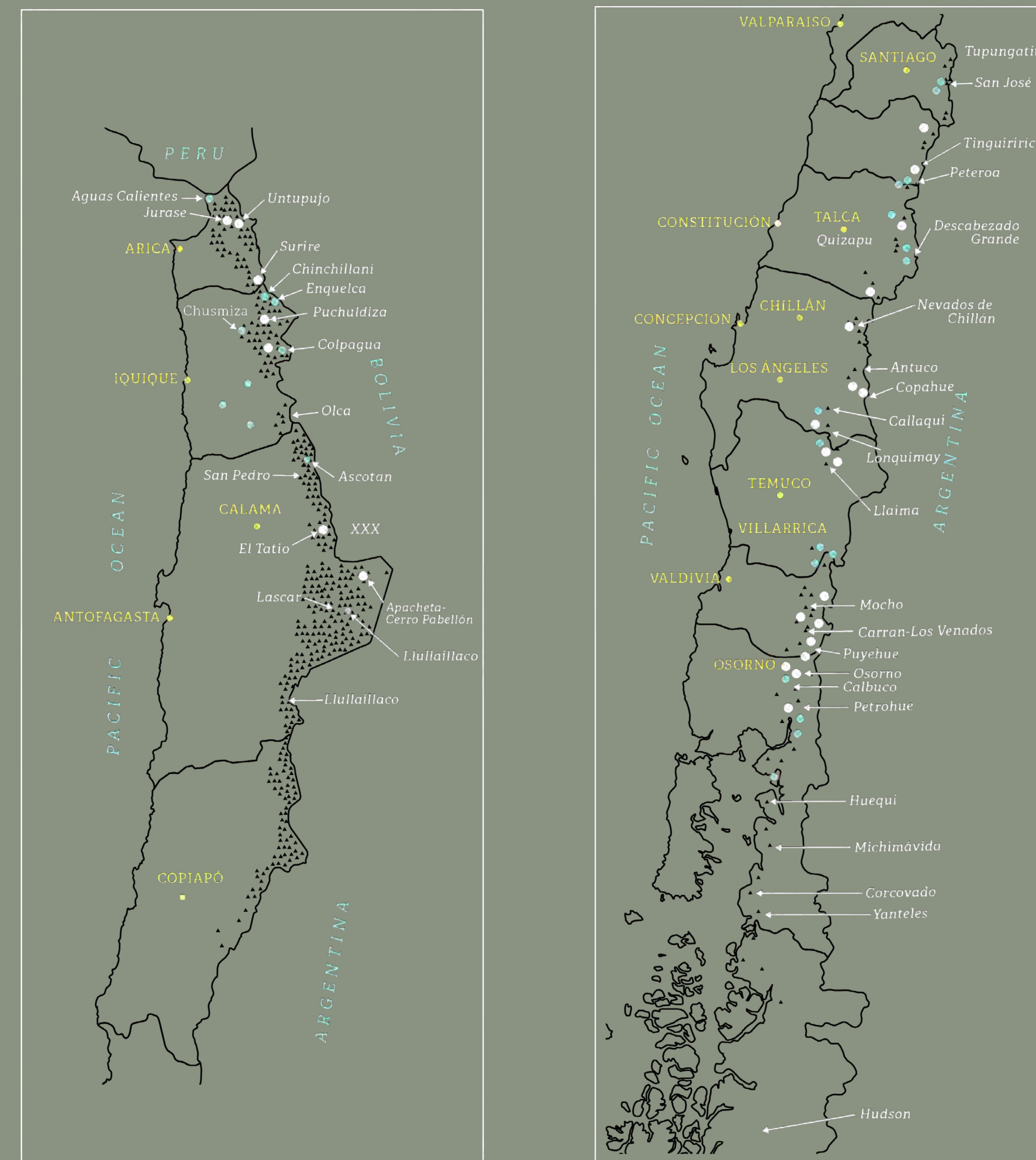
An eagle flies over a geyser in the Atacama Desert. © KseniyaRagozina.

THE REVIVAL OF AN OLD DREAM

In Chile, the work of Ettore Tocchi, promoted by the Preliminary Society of El Tatio, which gave so much to hope for, has led, however, to a silence that lasted for almost five decades. It is as if that promise of a splendorous future, which the journalist of El Mercurio de Antofagasta sees when he interviews the Italian engineer the day after his arrival in the country, evaporated like one of the usual illusions of the desert. It all came to nothing. As Nicanor Parra would say: total zero. A poet, a historian, a philosopher could perhaps see in this abandonment one more manifestation of something like the "national character": Chile is a country, you could say, in which usually the fabulous projects full of future crumble one fine day and pass into oblivion. Was that not, after all, what happened with the magnificent wealth generated by the saltpeter industry? And before that with that of the guano? Not to mention the political projects. To sum up, since the end of the drilling conducted by Tocchi in El Tatio in 1922, geothermal energy and its range

Generator room of Endesa's Pullinque hydroelectric power plant (1962). Collection of the National Library of Chile.

GEOTHERMAL ZONES IN CHILE



▲ With their names, active volcanoes ● 30°C - 60°C ○ > 60°C of possibilities entered into a prolonged oblivion that lasted until 1968, or almost fifty years. While the countries mentioned in the previous chapter developed an important geothermal industry, in Chile hydroelectricity and other forms of energy linked to fossil fuels were favored.

The return of geothermal energy

But everything changes: in 1968 the Chilean government signed an agreement with the United Nations Development Program, which marked the awakening of that long lethargy. Under the alliance between Chile and the UNDP, Corfo (Corporación de Fomento de la Producción) created a Committee for the Development of Geothermal Energy. The promoter of geothermal energy in this new context is the Chilean state-owned oil company, Enap. Ljubomir Tomasevic was one of the company's geologists who participated from the very beginning in the reactivation of exploration and drilling in the El Tatio area. Here is his account of the experience:

"Enap was appointed as the operator of geothermal development in Chile. Then fifteen of us were appointed in Punta Arenas in 1969, all from the drilling department. We traveled on July 20 of that year. I remember because we stopped in Santiago the day the Americans stepped on the Moon and we saw that at the Gran Palace Hotel, on Huérfanos Street, where we were staying. The next day we left for Calama. We acclimatized to the altitude there, because we came from Magallanes, we were Chumangos, used to living by the sea and the wind. After four days in Calama, we went up to San Pedro. We stayed there one day and then we went up to El Tatio. Four of the group had to return to Magallanes because they could not stand the altitude. The rest of us had some problems typical of altitude sickness, but we survived. So we stayed there. That's how the history of contemporary geothermal energy in Chile began."

The exploration led by Enap, in the framework of the agreement between Chile and UNDP, took place in the Salar de Surire, but mainly in El Tatio and Puchuldiza. In Puchuldiza, five exploratory wells were constructed between 1974 and 1977, with poor results. A sixth well, financed by the Japanese government, showed higher temperatures but did not confirm the existence of an exploitable resource.

From that moment on, El Tatio is where the main efforts are concentrated. Between 1969 and 1971, six small diameter wells were drilled (650 to 750 m depth). Then, between 1973 and 1974, seven production wells were drilled (from 870 to 1820 m depth). These wells confirmed the existence of a high temperature geothermal resource. Engineer Tomasevic experienced this process first hand:

*Sediments and geothermal brine in El Tatio.
Marcela Mella.*

"At Enap, we developed geothermal energy between 1969 and 1974, with contributions from the United Nations. In 1974, we finished our exploration. We finished the first stage, which were the first six wells. That allowed us to conclude that the deposit was good. Then we went on to the second stage, we built the production wells, from well 7 to well number 13, all wells with good diameter, all producers. The investment was 25 million dollars. This is no small investment. We made a good investment and the field was developed. Then came all the reports, one from the group of professionals from Chile, which included the Universidad de Chile, the people from Enap and Corfo. In addition, the UNDP drafted its own report, with its experts, who were all New Zealanders. In the end, an Italian company made a last report, later, in 1980, to verify and check the previous reports. They verified that El Tatio is a great deposit".

But then the military coup took place.

We were working when the military coup took place," Tomasevic recalls. The day we managed to enter Enap, I don't remember exactly what day it was, whether it was September 15, 14 or 20, the manager told me: look, here are the keys to the truck, you have money, you have everything, you go and continue with all the work you can do. And I go north. By land. I arrive at El Tatio and we continue working. We were about 158 people in total, all the people from civil construction, drilling, production, geology. Because we had all the groups up there. At that time we did not work from the office. Projects were developed in the field. You had geologists, administrators, you had all the offices in El Tatio. They are still there, people will wonder why there were so many offices. It was because everything was handled in the field, not in the capital. It has always been done that way in Magallanes. This is how we were trained and mentally inculcated. Everything is done in the field, not in the city. So, we continued working. We had our camp in a valley, one day we went out very early in the morning, we looked around: it was full of machine guns, we were surrounded by soldiers. But they quickly realized that we were working. That happened because we were handling explosives. We had everything up there. In a warehouse with everything declared, with their respective permits. When they remembered that we were up there with that amount of explosives, they went up quickly. But nothing happened. We had them there for two or three months, they played hunting donkeys around, but nothing more. We kept on working."

In El Tatio the good results led to a feasibility study, considering the installation of a geothermoelectric plant capable of producing between 15 and 17 MWe. In 1978, a call for bids was issued to hire a consulting firm, but the project was not carried out.

But everything changes and changes again. In 1982, the Committee for the Development of Geothermal Energy was closed. The activity was left in the hands of the national universities and Sernageomin, which published a National Register of Thermal and Mineral Waters in 1997 and 1999.

In the early nineties, after the reinstatement of democracy, interest in geothermal energy once again gained strength in Chilean political and institutional sectors. In December 1991, the government sends to Congress a bill to regulate the exploration and exploitation of geothermal resources, while Enap resumes exploration tasks together with several foreign companies. In 1993, Enap and the French CFG carried out a survey of areas with geothermal potential in the central zone of the country, choosing the Nevados de Chillán area for more advanced studies. These culminated in 1995 with the drilling of a shallow well (274 meters deep) and found steam at 198°C. The well is shut down the following year for safety reasons and the Enap-CFG project does not proceed. In the second half of the decade, Enap resumes geothermal exploration activities in partnership with the US giant Unocal. But something essential is missing to go further: a regulatory framework that stimulates activity in the sector and provides security and incentives for private initiatives.

By drilling a shallow well in 1995, ENAP and the French company CFG found subway steam at 198°C in the Nevados de Chillán area. Marcelo Vildosola Garrigo.

THE RETURN OF ITALY

Construction works at Cerro Pabellón geothermal power plant. Enel (Chile).

Finally, and after decades of hesitations and setbacks, in 2004 a radical change took place in the previously interrupted history of geothermal power generation in Chile. In April of that year, the Regulations for the Geothermal Energy Concessions Law were officially published. They provided a regulatory framework making possible and encouraging public-private investment in a newly emerging renewable energy sector.

A specific legislation for geothermal energy

Law 19.567 on Geothermal Concessions had been in the pipeline since 1991. It took more than eight years for it to become law in January 2000. But only in April 2004, with the publication of the aforementioned Regulations, the indispensable legal framework for an effective implementation and management of the geothermal sector became a reality. To date, Chile is the only South American country, together with Peru, that has specific legislation related to geothermal energy.

Along with Law 19.567, a decree came into force defining the "probable sources" of geothermal energy. Based on an extensive and thorough study by the National Geology and Mining Service (Sernageomin), a total of 120 sites distributed throughout the country were established. According to the Geothermal Energy Concessions Law, the exploration and potential exploitation of such sites or areas of "probable sources" requires a concession granted by a competitive bidding process.

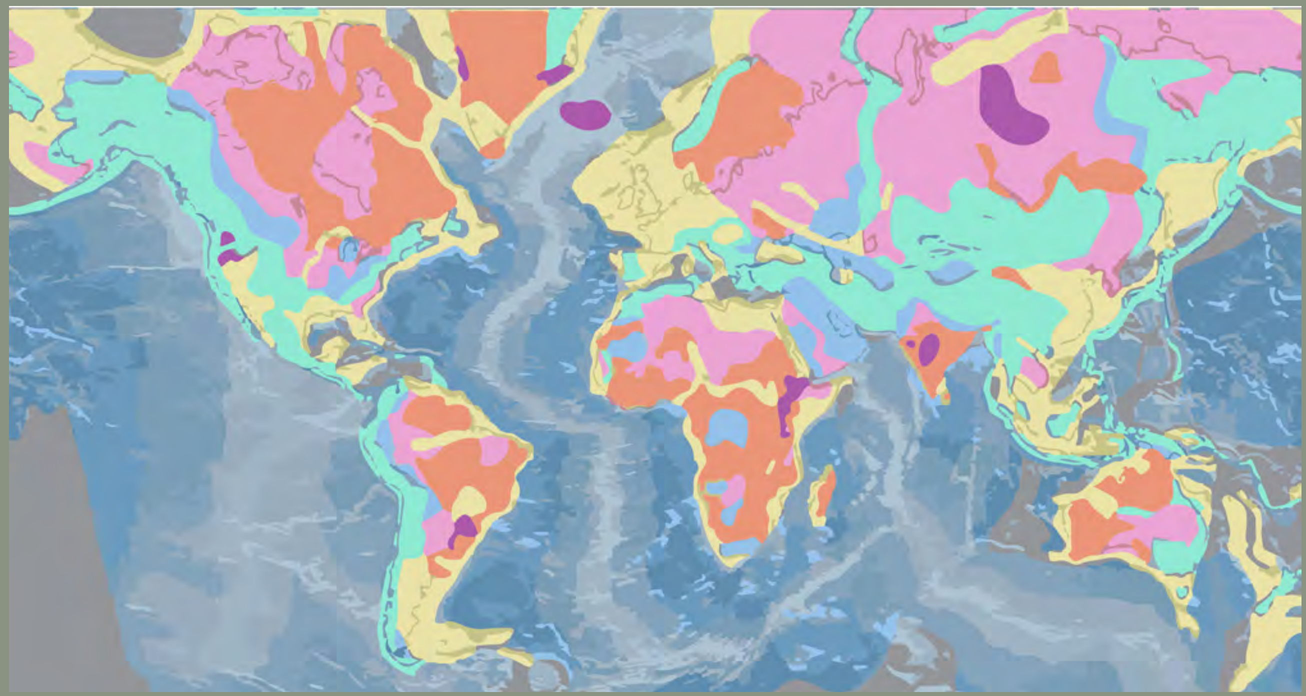
Although the Regulations have undergone several modifications to overcome legal and administrative weaknesses or shortcomings evidenced in subsequent years, their enactment in 2004 was a paramount milestone. And the results were instant. Several Chilean and foreign companies in the energy sector became interested in the concessions. They participated in bidding processes and began exploring in different areas of the country, generating a dynamism that -except for a few opportunities- the national geothermal sector had not seen before. Would this be the time to succeed? Would there be geothermal power generation in Chile for the first time in its history?

After the approval of the new legislation, the state-owned National Petroleum Company (ENAP) was in a position to offer attractive partnerships to the private sector. Thanks to its extensive geothermal exploration portfolio and its broad knowledge and good management of relations with political decision-makers. In this favorable context, the interest of Enel, an international giant in the energy sector, was raised.

Accident with consequences

"Sometimes the strategy of big companies is created by accident," recalls Valerio Cecchi, then president of Enel Green Power - the Italian giant's renewable energy branch - for Latin America. The

WHAT IS GEOSCIENCE?



Source: USGS

Geoscience or Earth science includes natural science disciplines that study the structure, morphology, evolution and dynamics of our planet. Its main exponent is geology (from the Greek γῆ geo, meaning "earth," and λογία or logos, implying "study"), which investigates the internal and external composition and structure of the Earth, as well as the processes by which it has evolved over geologic time to the present day.

Geoscience is also part of the planetary sciences through astrogeology or planetary geology, which studies the planets of the solar system.

Geoscience is of fundamental importance for its application in areas such as mining, hydrocarbons, hydrogeology, geothermal energy, geoheritage and in the study of natural disasters such as landslides, earthquakes, tsunamis and volcanic eruptions. It plays an important role in geotechnics and civil engineering as well.

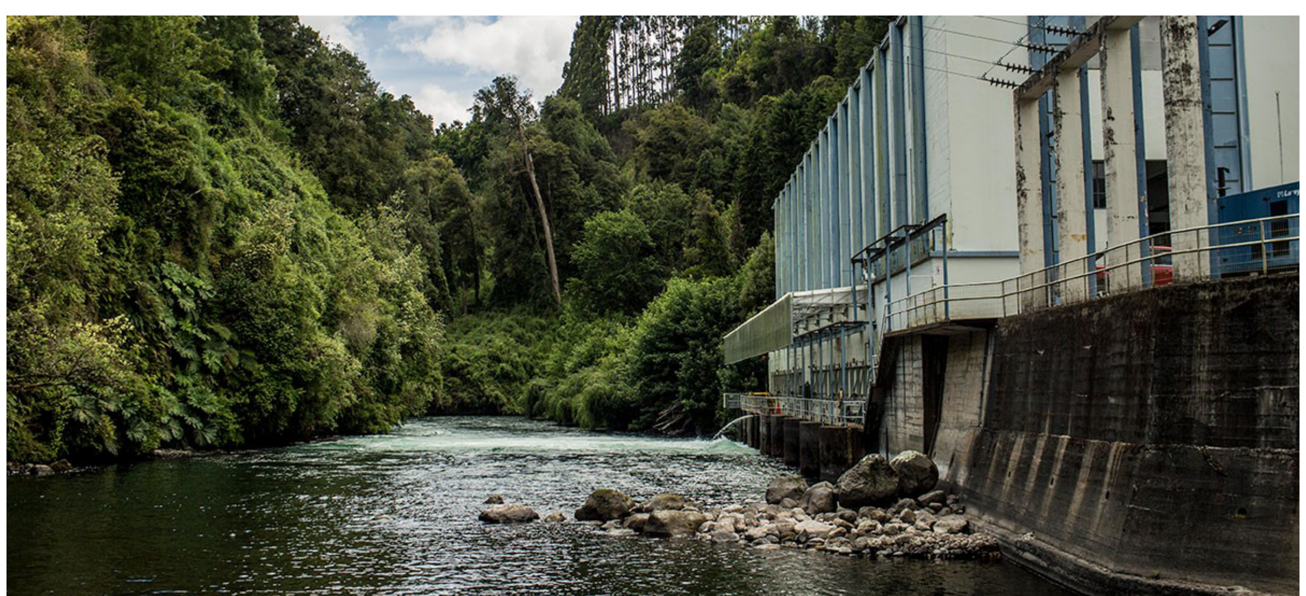
Earth science is an indispensable tool for planning the rational exploitation of natural resources and for understanding the causes of the natural phenomena that affect us and how human beings influence nature through their actions.

On the other hand, geoscience allows us to understand the natural processes that have favored and/or threatened human life. Their study is linked both to the investigation of energy flows in nature and their use, and to the prevention of environmental risks.

accident the senior executive refers to, took the form of Enel's frustrated venture into geothermal power production in El Salvador. What had begun as a promising expansion of a geothermal field already in operation became, with the change of government authorities in the Central American country, a corporate nightmare. The high profitability of geothermal production, which competed with an oil price of around 100 dollars a barrel at the time, led successive Salvadoran administrations to consider it as a way of distributing profits. Ignoring the contracts signed. The conflict ended with a long and complex international arbitration. Only then Enel could definitively leave behind what had been the beginning of a great expansion project in Latin America.

At the same time, Enel had a minimal presence in the Chilean electricity generation market. A small share in the hydroelectric sub-sector stemming from the ownership of the Pullinque run-of-river plant and the Pilmaiquén power plant, both in the southern part of the country. With the aggravating factor of very low rates, close to 35 dollars per megawatt hour, the situation seemed to advise the multinational company to liquidate its assets and simply leave Chile.

"The promise of geothermal energy, as well as other renewable energies, allowed us to stay in the country at that time," recalls Cecchi. The acquisition of Endesa followed as well as many other factors that made Chile a strategic focus for the group. But before this happened, I would say that the promise of geothermal energy and the idea of finding a strategy to expand Italian geothermal energy around the world was a combination that led us to say: let's try to see if geothermal energy can be explored in Chile".



Pilmaiquén hydroelectric power plant. Enel (Chile).

Pullinque run-of-the-river power plant. Enel (Chile).

There was only one obstacle left from Enel's point of view. A strategic partner in the public sector was indispensable. "That is when we found the Enap partner," the Italian executive says.

Energy crisis

For the Chilean state, the stakes were also rising. In 2004 the first reduction in natural gas shipments from Argentina took place. Chile had invested in a costly pipeline system and relied on it to sustain its then fragile energy matrix. This occurred only four years before the perfect storm. The total natural gas supply cut-off by Argentina in 2008 and a prolonged drought from 2007 to 2008 hit hydroelectric production hard (37.6% of the total energy generated at the time), and forced a reconversion to diesel that involved a serious environmental impact and a loss of efficiency of 14%.

For Cecchi, the Argentine natural gas supply cut-off triggered a crisis that "was a huge awakening in Chile, where the law of the free market, a *laissez faire* without a long-term strategy, is perhaps short-sighted. So much so that, after the cut-off of Argentina's gas supply to Chile, they found themselves in the middle of an energy crisis, and prices rose enormously. I believe that in some cases they exceeded 100 dollars per megawatt hour. Look, from 35 to 100 dollars a megawatt hour…. Consequently, regardless of all the risks involved in geothermal energy in Chile, the risk of exploration in this country became somehow manageable".

The ENAP-ENEL partnership was first materialized in 2005 with the acquisition by the Italians of 51% of the equity of Empresa Nacional de Geotermia (ENG). Then, in March 2006, it grew with the purchase of 51% of the shares of Geotérmica del Norte (GDN). Only in the latter company did Codelco continue to control a small shareholding. The French company CFG sold its interest in ENG and withdrew.

"Finally," says Cecchi, "once Enel entered, the run on geothermal concessions was unleashed. This usually happens in industries. It's called *"follow the leader"*. We were the leader and everyone else came after us. And then earnest companies, adventurers, speculators... joined. But we opened up the field. We were pioneers in this sense as well. Several years later, of all those who entered, the only ones who survived were us."

Returning to El Tatio

The ENAP-ENEL association thus had a clear path, and took control of the most advanced geothermal projects at that time in Chile (El Tatio-La Torta and Apacheta in the north, and Calabozo and Chillán in the central-south zone), carrying out new studies and drilling in those areas. As expected, specific attention was focused on El Tatio, one of the largest geothermal fields in the world. After new studies and technical and environmental assessments, exploration drilling resumed. It had been abandoned in 2002, when the national government decided to suspend ENAP's geothermal activity. The work focused on an area far to the southeast of the geysers, known as Quebrada El Zoquete.

"Everyone agreed to do exploration in El Tatio," says Valerio Cecchi, "everyone was in favor. We took many trips to Italy, and we realized that many industries could be developed through geothermal energy. Not only electrical energy, but also the use of steam in greenhouses, fruit farming, curing, cheese production.... So much so, that at that time the most enthusiastic about the El Tatio initiative were Toconce and Caspana.... People migrated to other places. They saw an opportunity in which the group could contribute in a corporate social responsibility initiative, and also to develop smart tourism, with all the Italian experience in this area... Creating industrial and archaeological tours of interest in Toconce and Caspana, which would make those settlements something very similar to what can be found in Iceland, in New Zealand, where other industries and geothermal exploration coexist."

"A safe card"

"Enel's people brought their momentum to develop geothermal projects here in Chile," recalls Carlos Ramírez, Enap's geologist at the time, who assures that they wanted to start specifically with El Tatio, because it was "a safe card", which is how technicians called the projects developed with previous exploration and studies.

They carried out a very detailed mapping of the state of the Corfo wells in El Tatio," Ramírez says. To determine whether they could be used in this new attempt, or whether new wells had to be drilled to put the deposit into electrical production. They then determined that it was more convenient to drill new wells with leading technology and leave Corfo wells for reinjection purposes. That´s a very

GND's geothermoelectric project was positively evaluated by the communities of Alto Loa. In the image, view of the town of Caspana. Marcela Mella.

important aspect. After a geothermal well is drilled, if its characteristics are positive, it is necessary to test the well. And testing means making it produce for at least six months, during which time condensed steam is extracted to the surface, and water has to be disposed of somewhere. And both by law and by ecological awareness, you can't just come in and dump the water on the ground. Therefore, the recommendation was that these large diameter wells Corfo had left behind should be used to reinject the fluid that would come out of the new wells".

Everything was running "smoothly ". But on September 8, 2009, the unforeseeable happened. After the successful completion of a first new 8MW well, a technical failure in the production tests caused a steam leak from one of the old wells drilled by Corfo in the 1970s, which was being used as a reinjection well. It was well 10, drilled between November 4 and December 1, 1973, with a depth of 1010 meters.

"Something broke below"

"It wasn't dangerous," recalls Ljubomir Tomasevic. I had to go when they told me what had happened. I was in Santiago and took the plane. I went to Calama to ask the firemen for help and went up with two firemen from Calama. We went up with three special asbestos suits, which are no longer used, to get closer to the head, because it was a cloud of steam. Nobody knew what had happened. So, I went in myself with the two firemen who accompanied me, tied up with ropes, and we went and opened the valve. I noticed that the head was down. I said: something broke down here. At first, I thought it was a valve or a flange, and I opened the main valve, the valve that faces the vertical. With the two firemen, we opened the valves. It took us most of the day. Going in, going out... We didn't have the equipment to last long, even though we were on oxygen. It was a very heavy task. So, we just let it flow, and then we started the operation to control the well. That took us many days. Putting everything together. The problem was that we had nothing in the area. We had to bring special pumping trucks from Bolivia, we had to bring a piece of equipment that we had nearby, we had to bring elements, tanks, build the water pipeline...to organize the work, to be able to control the well.... That took a long time. And finally, it was controlled. So, why do I say that it was not dangerous...Because it was the same as seeing a geyser flowing."

"We made three attempts to kill the well, Tomasevic continues. On the third attempt it worked. Now, the third attempt was very entertaining, because we were there and Enel's head of security showed up and said that the police were outside, the PDI (investigative police), that they wanted to enter. About 15 PDI officers had arrived and they wanted to talk to us... We sent them outside to talk and, in the end, they managed to enter. In the meantime, it worked out and we killed the well. All of a sudden,the well level starts going down, down and stops. Those guys were lucky enough to see how the well was killed. That was the best, they filmed it themselves. The best footage ever, if you want to have it, is that of the PDI. Because none of us filmed. We were busy working on something else.... Then we talked to them... There I discovered that all those who arrived were environmental, flora and fauna engineers.... I found it very interesting, very well-prepared people. They understood everything, and afterwards the reports were all favorable to us."

A new challenge

Therefore, the drilling of well 10 did not cause any major damage nor it triggered a significant environmental impact. It was confirmed by several external investigations, including one by a committee of international experts from the United Nations convened by the Chilean government. They ended up recommending the immediate resumption of the work - which had been totally paralyzed - in order to implement electricity production from the geothermal field.

But although at first there was no reaction, when the news of the event was unreleased, its coverage was in some cases sensationalized by the media, as Tomasevic recalls: "...They said there were casualties.... If you read the press at the time, the first pieces of news were pretty disastrous.... saying that we were going to ruin all the tourism in El Tatio, because that well was wasting steam...."

Opposition to GDN's project grew out of control. "We went from being heroes to being judged in the public square," Valerio Cecchi says. They presented it like a British Petroleum-type disaster in the Gulf of Mexico, which was obviously not at all the case.... Tourism companies were mobilized against it. And between one thing and another, exploration in El Tatio was suspended, in spite of having demonstrated an enormous potential".

Faced with huge media, social and finally political pressure, GDN ended up canceling the drilling program. Also, geothermal exploration in Quebrada del Zoquete (El Tatio) was suspended indefinitely. "I don't remember the exact amount, but there must be $25 million buried there, between us and Enap. Waiting for better times, should they ever come," Cecchi laments.

An unfortunate and unsubstantial incident in Quebrada del Zoquete operations seemed to put an end to the history of Chilean geothermoelectric production even before it was born. After so much effort and care, was that even possible?

Steam leak from well 10 had no negative environmental impacts. In the image, a group of vicuñas crossing the Quebrada del Zoquete sector today. Marcela Mella.

PART THREE

A PROMISE FULFILLED

Cerro Pabellón power plant at dawn.
Enel (Chile).

CERRO PABELLÓN: AN UNEXPECTED DISCOVERY

Ever since Ettore Tocchi's epic expedition to the mountain foothills of the Atacama Desert and for almost a century, El Tatio had been in the minds of all those who wished to develop geothermal energy in Chile. And not without reason: it is one of the largest geothermal fields on the planet.

"We in El Tatio can get to the Putana River and it is possible to reach 400 MW. And that is a lot for a single deposit. In a very short distance," says Ljubomir Tomasevic, a bit nostalgic. If we had developed that, today we might have 300 or 400 MW with different conditions, which would have been installed at other prices. We would be selling energy at a very cheap price, and who would be winning? The country."

When the door closed on geothermal development in Quebrada del Zoquete, south of the Tatio field, all seemed lost. Years of effort and painstaking work, million-dollar investments: all thrown away. "They called us the lost people of Atacama, because there was no light at the end of the tunnel," recalls Valerio Cecchi.
Would there be another chance for geothermal energy in Chile?

Throughout the 20th century, El Tatio was in the minds of those who wanted to develop geothermal energy in Chile. In the image, landscape of Quebrada del Zoquete. Marcela Mella.

Looking for a new field in 130 locations

"Thanks to Enel," says Cecchi, "and the ability to move forward.... I would say that the will and persistence of local leaders was also important. They pushed to continue with so many concessions we held, to continue with geothermal energy and to look for another field."

Another field? Good idea, but it wasn't a matter of searching for a new field thousands of kilometers along the Andes Mountains. Or was it?

"We were looking for it," Gianni Volpi assures us. One hundred and thirty volcanoes, one hundred and thirty sites with geothermal reservoir potential, with different background and very basic studies, which are essentially surface studies, measurement of faults, geochemistry of springs. And from there we classified the most appealing projects, based on what we call an exploration risk manual. We selected the four that GDN already had when Enel partnered with the company. There are several parameters: logistics, the power line, that it is too high or too low, the presence of vegetation, its potential environmental impact, its potential impact on society, and so on. Then, what was finally selected were 6 or 7 prospects that we took forward and explored. Quebrada del Zoquete, a few kilometers from El Tatio geothermal field, for example, which is famous. But we discarded it very soon because of the significant environmental and social interference it has. There were projects in the seventh and eighth regions, which we progressively discarded due to their complex morphology. You may think that a project in the seventh or eighth region may be easier, because the mountain range is much lower, one thousand, one thousand five hundred meters... But there are other risks. First of all, access to these valleys is much more complex, involving work on rocks and the construction of bridges. There is an important hydrological risk, because all rivers have a torrential character and a highly variable water flow depending on rainfall. And you can build a facility and then it is washed away by a flood."

"Finally, we chose Cerro Pabellón in the Apacheta field. As it is a blind system, it lacked geochemistry. Therefore, it had associated risks due to the absence of one of the four methodologies that we use to explore resources based on our protocols. It was a flat project, in the middle of nowhere. A completely flat pampa, all the civil infrastructure to be implemented was 'cheap', there were no problems with vegetation. There were few social and environmental issues, and finally the decision was made. It wasn't just scientific considerations, but a set of risk analyses."

Phases of geothermal energy 1 Exploration

Exploration is the first step in the identification of a geotermal field, to determine its reservoir, fluid, seal layer and heat source. It is divided into **surface exploration** and **deep exploration.**

Surface exploration uses geology, geophysics and geochemistry to detect, from ground level and without drilling, the existence and main characteristics of a potential geotermal system.

Geology studies the magma chambers of volcanoes. The system of faults and fractures present on the surface and related to the reservoir and the stratigraphic sequence (levels of rocks one below the other) that characterize a given site. In order to see if the conditions exist for the development of a geotermal system, a reservoir, a heat source.

Geophysics uses indirect (electrical, seismic, gravimetric, magnetic) methods to try and define in the best way, from the surface, the volume of the potential reservoir present in the subsoil. To establish its minimum depth (the point where it will be appropriate to start drilling). And also, to confirm if there is a seal layer above the reservoir that will allow thermal energy to be retained and not escape to the surface.

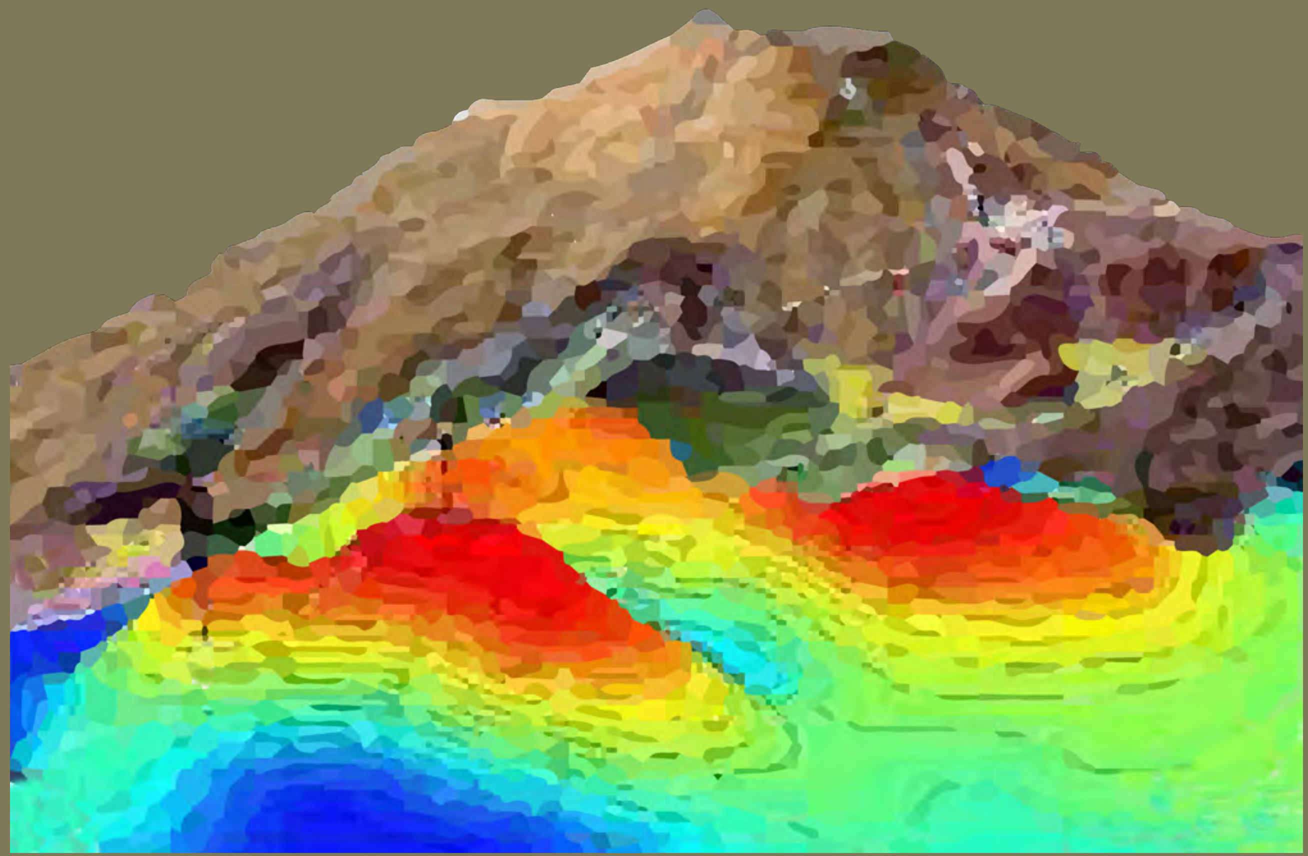
Geochemistry is very useful in the presence of termal manifestations, such as geysers, fumaroles or springs, which can be sampled and analyzed. Based on the chemical composition of the manifestations, it is posible to reconstruct what type of geotermal reservoir they are connected to, what is the degree of connection and to estimate the temperatura of the deep fluid, which will then be intercepted by the boreholes.

All this information is finally put together in an **integrated 3-D model.** Its objective is to reconstruct in the best posible way what is believed to be the subsurface of a given geotermal zone. And thus provide the correct input for the **deep exploration** stage.

Deep exploration uses geotermal wells of small diameter, about 3 to 5 inches, whose objective is to confirm the existence of the resource. Among these, first of all, there are **thermowells,** which only seek to confirm the existence of high temperatures (generally > 150-200 °C). At Enel Green Power, they are widely used. They reach a depth of about 1,000 meters. Enel Green Power's deep exploration technique is oriented to make this type of low-cost wells (approximately USD$ 1 million each) and confirm the mere existence of high temperature, even if the fluid is not intercepted. If there is high temperature, the fluid is undoubtedly below the bottom of the thermowell and will be intercepted by drilling a conventional well (9 to 23 inches). In addition, there remains a project asset that will eventually feed the geothermal plant.

Other type of wells used in deep exploration are the so-called slimholes. These are real geotermal wells of steel and cement, but of reduced dimensions (5 to 7 inches). They are generally drilled to about 1500 m to find the resource, not just the temperature. They are wells that prove with greater certainty the existence of a resource, but they are much more expensive (between USD$3 million and USD$4 million) tan thermowells. Their disadvantage is that in the end they will not be used to supply the plant, because they are too small.

The surface exploration and deep exploration stage –using thermowells- takes between one and two years, based on the difficulty of accessing the area and obtaining the relevant environmental permits.



Francesco Starace's tenacity

"This whole Cerro Pabellón project came about undoubtedly because of the tenacity of Francesco Starace (Enel's current global CEO), who instructed the construction of the plant," Carlos Ramírez says. They wanted to have a plant in South America; they wanted to be the first to have this plant in South America. And the Apacheta field is an extraordinary field."

Likewise, Ljubomir Tomasevic thinks that "there are two main factors here: Cerro Pabellón was developed with Enap. We held 49% of the shares, and trying to develop it, we gradually disposed of our shares and today we have a lower percentage in the Geotérmica del Norte company. And the rest is because Starace was there. He is the Chief Executive Officer of Enel. He is a true geothermist. He is a nuclear engineer, but he worked all his life for Enel, he held the top position, but in Enel Green Power. And then he went on to manage the whole company."

Discovery and exploration

"This whole project was undoubtedly the result of Francesco Starace's tenacity," says geologist Carlos Ramírez. In the image, the CEO of Enel Global speaks during the opening ceremony of the Cerro Pabellón Power Plant, September 12, 2017. Enel (Chile).

The Apacheta field is located in northern Chile, on the border with Bolivia, about 120 kilometers northeast of the city of Calama. It is a blind field, which means that there are no surface geothermal manifestations. Despite being a remote place, since the last decades of the last century it has good access infrastructure, thanks to the presence of groundwater extraction areas that supply the copper mines in the area. The area with geothermal resources ranges from 4,500 to 5,200 m.a.s.l., inside the Inacaliri graben (tectonic trench), in the eastern sector of Cerro Apacheta and the surrounding Pampa Apacheta plain.

Pampa Apacheta is a "blind" geothermal field, without any surface manifestation. Marcela Mella.

But how was this geothermal field discovered, if there was no surface manifestation? The story goes back to the 1990s. "Basically," says Carlos Ramírez, "what led to the discovery of Apacheta-Cerro Pabellón was the information shared by our colleague Leonardo Mardones, from Codelco, who in those days was in charge of groundwater exploration in the area. Leonardo informed the Enap-Unocal geothermal geologists that he had observed two remote fumaroles near the summit of Cerro Apacheta, and that during the groundwater exploration, steam came out of one of the water wells they had drilled in Pampa Apacheta."

A lucky discovery

In 1993, Mardones had found steam at a depth of 180 meters. Encouraged by this information, Enap-Unocal geologists began exploration in the area in 1999. To obtain gas samples, they ascended to the fumaroles at the summit of Apacheta hill, some 4.5 kilometers west of the steam flowing well drilled by the Codelco geologist. They measured flows of 109°C and 118°C. Meanwhile, the steam flowing from the well reported by Codelco yielded a temperature of 88°C. All the samples taken were sent to Termochem laboratories in Santa Rosa, California, and the results were encouraging: the existence of a geothermal reservoir at depth, with temperatures above 250°C, was very likely.

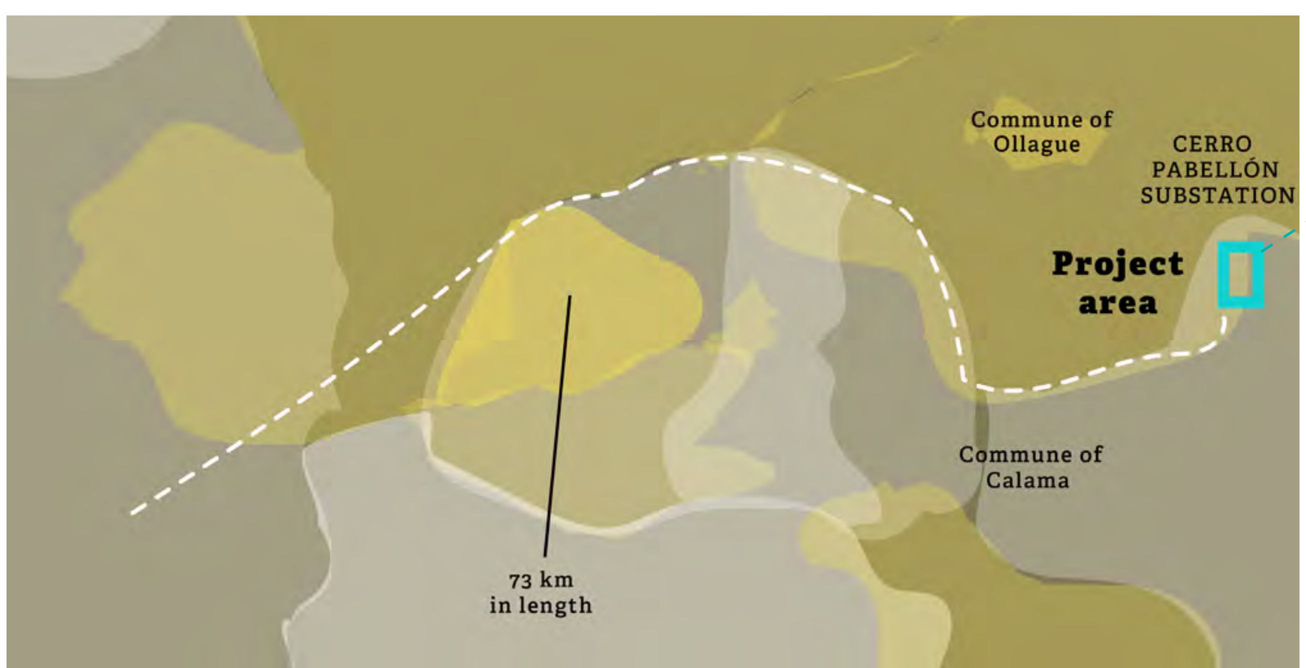
Exploration continued by Geotérmica del Norte, recently formed by Enap and Codelco, which in 2002 obtained a concession for geothermal exploration in the area. Geological, geophysical and geochemical studies were carried out which increased the evidence of a high temperature geothermal system (250°C-325°C based on gas geothermometers). But when the drilling of exploratory wells was being prepared, Enap had to suspend all its geothermal activities by government order.

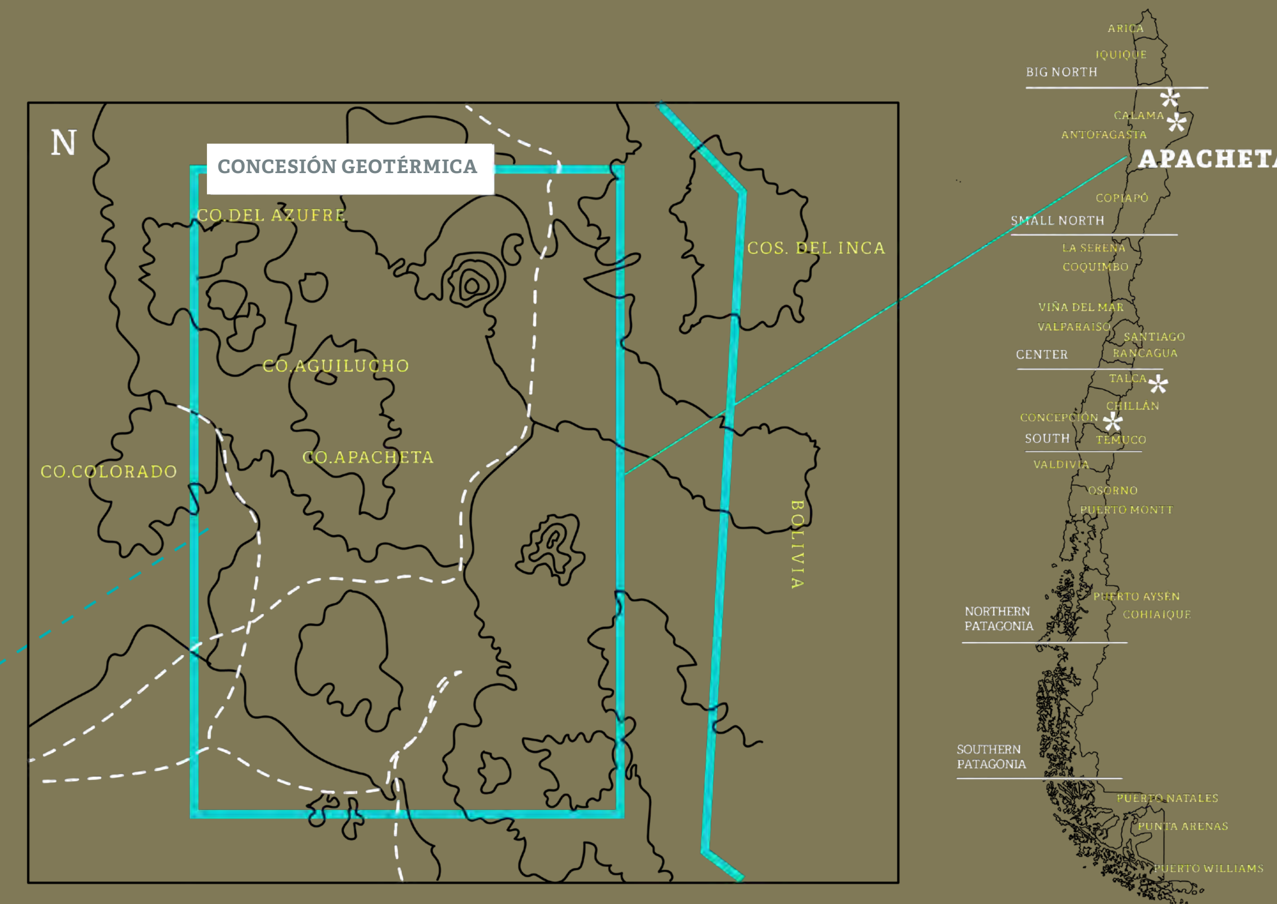
In 2006, GDN - now strengthened by the inclusion of the giant Enel in the partnership - carried out additional geophysical and geological studies. In late 2007, a first small-diameter well was drilled at Pampa Apacheta, finding a temperature above 200°C at a depth of 550 meters.

A tailor-made solution for the Andes

Gianni Volpi was one of the key players in the whole complex exploration process of the Apacheta-Cerro Pabellón field. There are different methodologies," he explains, "depending on the location of the field. For example, all the experience gained in Tuscany, in Italy, or even in the United States, did not help us. Because the rock environment in general and at the bottom of the reservoir, that set of rocks that contains water in liquid state and a certain fraction of vapor, is different. Then, while the seismic is widely used in Italy, here, with the volcanic rock environment of the Andean Mountain range, electrical tomography has been widely used. This gives you an idea of the relatively high resistance of the ground. For sure, the high-temperature saline fluid provides a very noticeable presence and allows defining the reservoir."

Map of the Apacheta geothermal concession.





Access to Apacheta-Cerro Pabellon Hill

Panoramic view of the sector where the only geothermal power plant in South America is located. Enel (Chile).

"And another methodology we applied was structural geology. The active faults that are in the Cerro Pabellón area were measured, identified, and are still in microseismicity. In fact, there is microseismicity all over the area. It allows this reservoir to remain active; otherwise, it would tend to be sealed over time by its own fluids and by the encrusting minerals left by the fluids. It is very important that Cerro Pabellon be located in a tectonically active zone. In addition to the geophysics, we focused on structural geology, to finally land on the heat source, which provides heat to the reservoir in a given area. There are 200, 300 volcanoes in Chile.... It does not necessarily mean that there are 200, 300 geothermal systems.... The three things need to be combined, and the manifestation was precisely in Cerro Pabellón. And we named the project after this outflowing volcanic manifestation. We dated it and it was less than 50 thousand years old. Therefore, undoubtedly it was a surface manifestation of a deeper magmatic chamber. And having the heat source identified, a geophysicist that worked in such volcanic rock reservoir environment, and an active structural context, encouraged us to take a chance with the first exploratory well.

The well to overcome doubts

"It is important to point out that the fourth leg of the table is missing in Cerro Pabellón, which is –in my opinion- geochemistry, the thermal manifestations, which do exist in El Tatio. It is a completely blind system. There is a seal layer that isolates the reservoir from the surface, so nothing is visible. At the beginning, that was a big challenge. There was a lot of discussion as to whether Cerro Pabellón was the most suitable project, due to the absence of manifestations. And what settled many doubts, beyond geophysics or structural geology, which are indirect methods, was the drilling of a 560-meter, 4-inch well, a mining well, a classic $800 thousand dollar well, very cheap. As a reference, a geothermal well costs 10 million dollars. This well encountered fluid already at 550 meters.... That opened our eyes to say yes; it is a blind system, but it is a system that exists with all its ingredients."

Volpi says, "I never thought it was such a complex challenge. And in fact, both at Quebrada del Zoquete and Cerro Pabellón we succeeded at the first time. In brief, at Cerro Pabellón, out of 12 wells drilled we had 12 successful wells. I think that it is a world record. I don't believe that in any other *greenfield* (undeveloped field) a 100% drilling success rate has been achieved. A very rewarding experience, very nice."

Guido Cappetti recalls that "in 2009-2010 the first 4 deep wells were drilled to about 2,000 meters. With these wells the presence of a geothermal reservoir with very interesting features was demonstrated. With temperatures of 260 degrees Celsius and high productivity of the wells. With these data from the exploratory wells, a development project began, with drilling of production wells and the construction of a power plant."

The time had come to make an old dream come true.

Cerro Pabellón power plant operators.
Source: Enel (Chile).

TIME TO WORK

Great hardship and constraints had apparently been left behind. For the first time in almost a hundred years of turbulent history, the way was clear. With "hard" exploratory data in hand, a development project involving the drilling of production wells and the construction of a plant began to be elaborated. At the same time the procedures to obtain a favorable resolution from the authorities based on an environmental impact assessment were underway.

"Breathless"

Giuseppe di Marzio, an engineer and PhD in electrical energy systems, was appointed by GDN in May 2015 as project manager for the complex work ahead. He already had the experience of building a 25 MW binary cycle geothermal plant in Utah as well as commissioning a number of other major wind and photovoltaic projects in the United States and in Romania.

"When I arrived in 2015 at Cerro Pabellon," he recalls, "it was a wasteland. There was nothing. You really ran out of air due to the lack of oxygen, but you were also out of breath because of the challenges you were facing then. At 4,500 m.a.s.l., in the middle of a mountain, a volcano. At that time, it was hard for me to believe that Enel would start such a project in those extreme conditions."

One of the first decisions made had to do with the choice of the type of plant to be used in the project.

Cerro Pabellón opted for binary cycle technology in order to meet the highest environmental standards. Source: Enel (Chile).

"It was a challenge to install a geothermal plant at more than 4,500 m.a.s.l., with an extreme climate and far from the city of Calama, where some of the supplies for the project could be found," recalls geologist Carlos Ramírez. And we had to select the right plant technology to be applied in this field. Because you have to bear in mind that every deposit created by nature is a 'different beast'; I mean, no plant is available, in the first instance, where you can arrive and install yourself just like that."

Binary cycle

Binary cycle technology was chosen, in which the fluid from the reservoir is used as a heat source to raise the temperature of the secondary organic fluid, which in the case of Cerro Pabellón is isopentane. Then, isopentane is used in a closed circuit to generate electricity.

ORC, Ormat Rankine Cycle or Ormat Energy Converter, are today the state of the art for binary geothermal plants," Gianni Volpi says. The history, the great support that a world leader like Ormat Technologies can give you, led us to decide to go with them. Beyond quotes and budget issues, Ormat plants are a guarantee in this sense. And we were strongly advised to choose a binary cycle plant by the Regional Water Directorate. Because our Cerro Pabellón project, located in the Atacama Desert, is very close to the interests of the mines, which exploit surface water resources for their processes. And it was clearly going to step on the country's interests a little. Being pioneers in Chile and South America, people were afraid of geothermal energy. Its possible alteration of shallow aquifers, and in a desert area, with many interests of large companies such as Codelco or Minera El Abra, we were advised by the relevant environmental authority to use a binary cycle. And in the context of binary cycles, I believe that Ormat with its organic cycle is the world leader. That's what led us to approach them."

"There is a technological optimum, related to the reliability of Ormat plant systems with facilities in various parts of the world," Giuseppe di Marzio says. But it is also influenced by the environmental context, and in this sense it has clearly been ideal for us. There are other technologies, such as flash technology, which have an invasive use of water resources. In the case of Cerro Pabellón, the national State has other interests regarding the maintenance of its water resources, so our option implied a technological and environmental optimization. And in addition, a one hundred percent automated plant gives greater guarantees in terms of efficiency."

Phases of geothermal energy 2. Drilling

Enel Green Power applies the following principle in relation to drilling: if it is necessary to spend many millions of dollars to drill a safe geothermal well, in steel and cement (of any diameter, but not a thermowell), then it is better to avoid slimholes. After thermowells, you go directly to large diameter wells (between 9 and 23 inches and up to 3,000 meters deep). They will remain as assets of the project and will eventually, one day, feed the geothermal plant. The construction of this type of geothermal well takes about 3 months, with an average cost ranging from $7 million to $10 million.

For large diameter wells, a distinction is made between exploration wells (the first 2 or 3 to be drilled) and project development wells (which follow the first wells if a go-ahead green light is given). Development wells are drilled in sufficient number to be able to feed the plant to be built. And also to have the necessary reinjection capacity to close the "production-reinjection" circuit.

Construction features of geothermal wells (deep exploration and/or development)

Geothermal wells are drilled using equipment with specifications very similar to those of the oil industry (Figure 1). Although adapted to the high operating temperaturas of geothermal energy (> 200 oC). In specific cases such as Cerro Pabellón in Ollagüe, also adapted to the low environmental temperaturas on site at night (known as "winterized" equipment).

Equipment is installed, for the 2 to 3 months it takes to drill a well, in an esplanade of about 100 x 70 m2 on average (it is the "drilling platform").

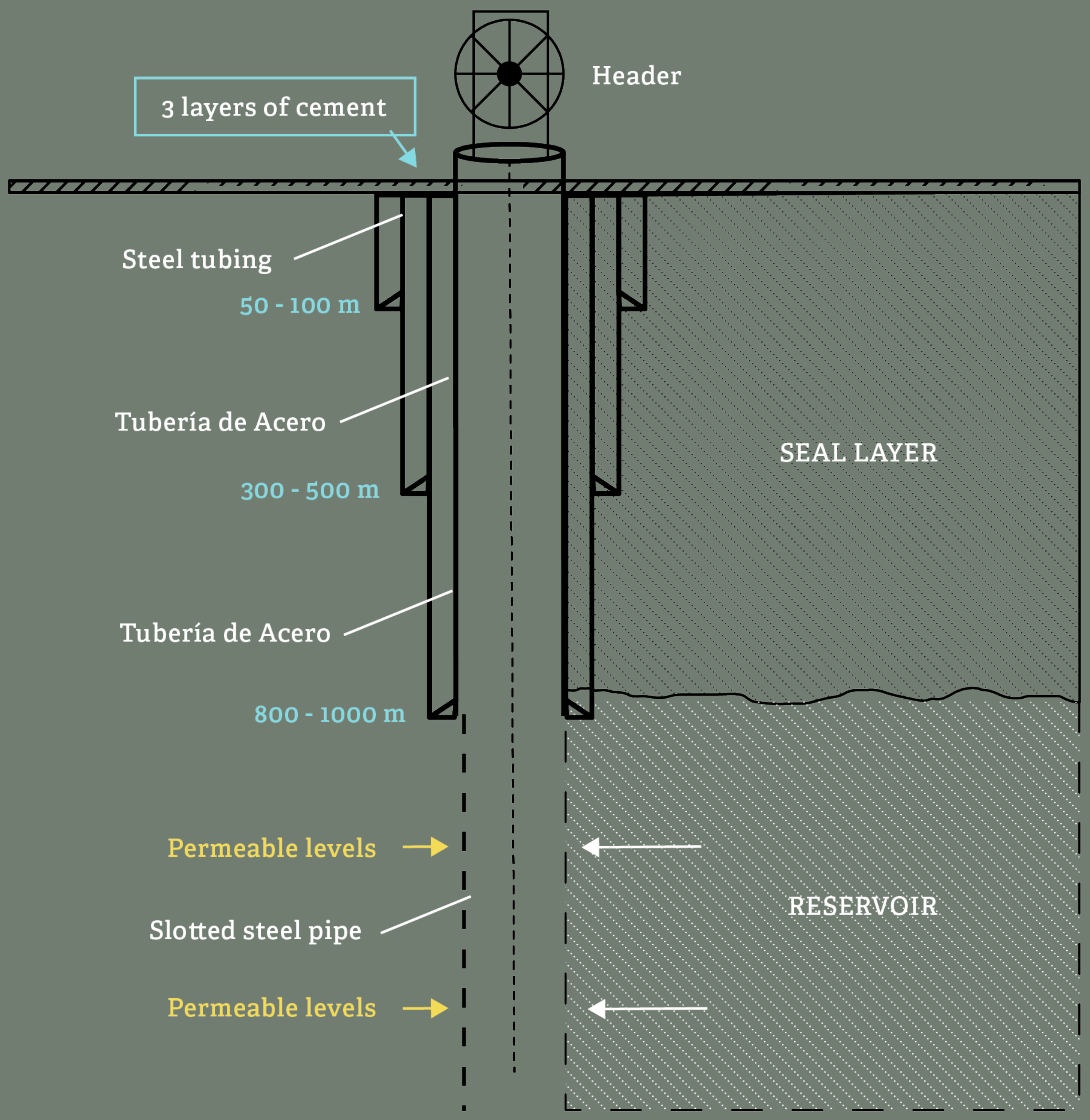
They are telescopic wells (with 23-inch diameter in the superficial sections and finished at the bottom in 9 inches, according to the type of rock found). Using a drill, based on the core destruction technique. Drilling with this technique, the rock cuttings are brought to the surface by the drilling fluid, which is water or benthic mud, and selected for studies (or disposed in dumps).

Each stage (also known as "phase" or "diameter") is cased and cemented to prevent any interaction with shallow aquifers both during drilling and later when the geothermal wells are used for production or reinjection.

Each stage has a progressively smaller diameter, and the drilling equipment (rods + drill bit) performs the deepening work by passing inside the casing and cements already in place.

A geotermal well is therefore a steel and cement construction that does not come into contact with any shallow water body until it reaches the reservoir.

Only once the wells have penetrated the geotermal reservoir, the hole is cased with a slotted pipe (not cemented), to allow the geotermal fluids to enter the well or return to the reservoir, depending on its further use: production or reinjection.



Outline of construction of a geothermal well.

An indispensable refuge in a harsh natural environment: the Cerro Pabellón camp. Enel (Chile).

- 30°C at night

At the height of the plant's construction process, a total of 1,600 people came to work on site. And conditions were extreme. "You were working at temperatures that often dropped to 20 or 30 degrees below zero at night," Guido Cappetti recalls. And with those temperatures, you kept drilling wells. Because drilling activity doesn't stop overnight."

"In my personal experience, this has been the most challenging project I´ve ever faced. From a technological, environmental and logistical point of view," Di Marzio says. We had to put together the entire logistics for building a camp. The first question is: where can we sleep? What facilities will we provide to our workers? A camp was built, a small village at 3,800 meters so that the workers could rest in acceptable conditions. We had to learn a lot about the social context, with the attention to the community, but we also had to take into account the natural context. We learned about the Bolivian winter season, in order to plan some activities. We knew that during those periods there was a decrease in activities, because in the morning we woke up and saw a clear sky, and at two o'clock in the afternoon a thunderstorm started and we had to stop working. We learned all this during the construction of the project. Yes, we encountered very challenging conditions. We had to build an 80-kilometer power line. That gives you the dimension of the distance to the infrastructure, electrical in this case. The distance to the substation closest to the point of generation. And we also had to build access roads. When we arrived there were almost no roads, there were no mining roads. So all the logistics for the transportation of heavy supplies, technological supplies, was very complex. The rest we learned over the years, since 2015."

Everything in place

Once the plant was installed, the production wells were connected to it, and in turn the plant was connected to the reinjection wells.

"The plant is a total condensation plant," Cappetti explains, " which means that all the fluid produced at high temperature, which is a mixture of water and steam, is sent to a production plant where the heat of the fluid is transformed into electrical energy. Then the fluid, which is cooled at temperatures of 90 degrees or so, is replenished again with another well to the same deep reservoir. The final objective of this whole cycle is only heat. With this technology we are extracting the heat stored in the hot rock of the subsoil. Unlike the oil sector, where the resource is the fluid itself, oil, gas, these types of resources, in geothermal energy the resource is the heat of the rocks. Therefore, it is an emission-free system. There is an impressive heat stored in the rocks in Pampa Apacheta, a volcanic system of very high dimensions. And it is also a matter of sustainability, because our resource is not going to run out quickly. We have been operating the Larderello field since 1913. That is more than 100 years. The system is sustainable over time."

“We decided to produce more energy.”

At the end of March 2017, the first unit of the plant was activated. Followed in September by the second unit, each with 24MW of power. Already with this first production, Cerro Pabellón began to supply a demand equivalent to 165 thousand Chilean homes with clean and renewable energy.

“The wells we drilled have very high characteristics, among the highest in the world, in terms of productivity, Cappetti continues. And therefore, the decision was made to go ahead and produce more, because the capacity of the wells already drilled went beyond a production of 48MW.”

Therefore, it was decided to build a third 33MW unit. Added to the previous units, this totals a capacity of 81MW at Cerro Pabellón. With this capacity, the emission of a total of 280,000 tons of carbon dioxide per year will be avoided.

“Personally, admits Guido Cappetti, this has been a unique experience. I started my activity with Enel in Larderello. Then I went to Tibet for a while, for the development of geothermal energy in Lhasa. And then I participated in projects in several other countries around the world. And this was the last assignment, the most difficult one. For me it has been an adventure. And I can tell you that we have carried out this project with a team that has worked very closely, with a very strong commitment, with a great sense of friendship, with a very committed participation.”

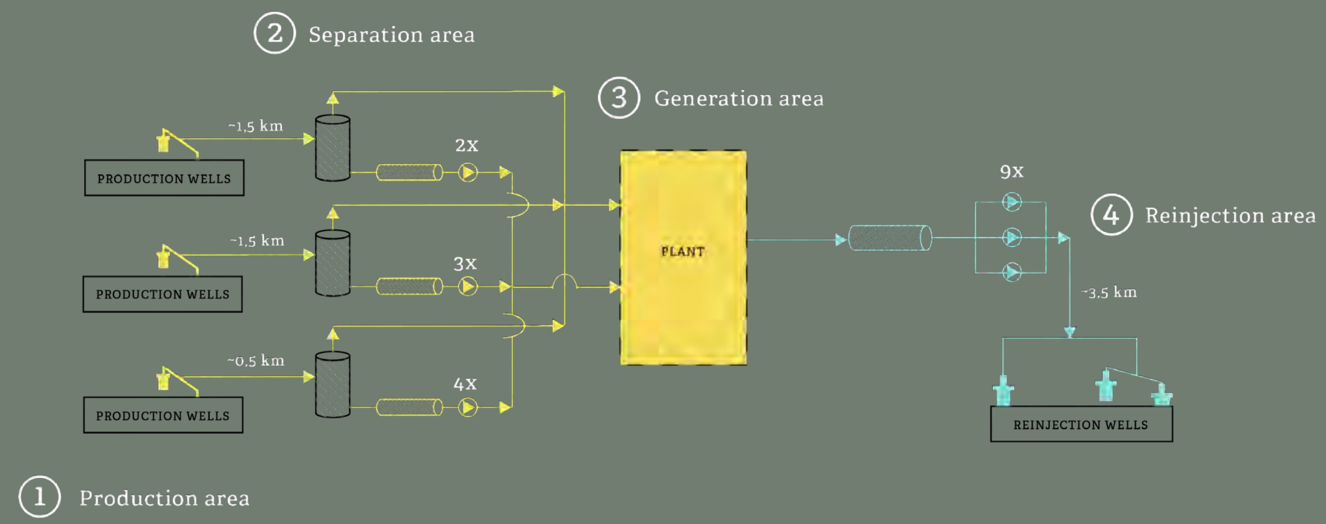
The icing on the cake

“For me, this is the peak, the summit, the end of my career, of my professional life. I started working in geothermal energy in 1976. But Cerro Pabellón is a fantastic project, unique in the world. And it operates at the highest altitude on the planet. Because the one we have in Tibet is at 4,300 meters and doesn´t have the industrial characteristics of the plant in Chile. And so for me this has been…. how do you say when you eat a dessert, you put the cherry on top, right? That has been for me, the most important thing in my whole life. I consider myself lucky. In spite of having worked very hard, as you can imagine… But in the end it turned out very well.”

Pipelines for isopentane (center of the image), a secondary fluid that enables the re-injection of geothermal fluid into the subsoil and prevents possible environmental impacts. Marcela Mella.

Phases of geothermal energy 3. Plant construction and operation

The simplest way to describe a geotermal plant and its building and operating process is shown in the figure below. Four main areas are identified: production, separation, generation and reinjection.



Layout of the main areas (sectors) of a geothermal plant.

Production Area

The production area includes the construction and subsequent operation of:

- Production wells, i.e., the geothermal wells that will allow to extract the fluid from the reservoir (the fluid comes out spontaneously; it is not pumped, due to the existing pressure in the reservoir).
- Steel pipes of 20 to 30 inches in diameter (about 0.5 to 1-2 km long) that allow connecting the wells to the separation area and the power plant (both described below).

Production wells are constructed in groups of 2 or 3 from a single surface location (drilling platform). The first well drilled is vertical, the successive wells have a vertical section of a few hundred meters and then deviate with a maximum angle of about 20 to 30 degrees.

The fluid that comes out spontaneously from the production wells can be water, steam or a mixture of the two phases. At Cerro Pabellón, the latter is the case. For this reason, the pipelines that connect the production area with the separation area are called two-phase pipelines.

Various types of valves are located at the head of the production wells, both shut-off and regulation valves, most of which are automated and controlled from the plant's control room. The same applies to two-phase pipelines, where valves of various types are used to divert the flow, for example, to temporary fluid storage ponds located near the wells.

In short, the production area is the set of production wells, pipelines, valves and all the electronic and wiring system that allows its remote operation. Construction is under EPC contracts (Engineering, Procurement and Construction, an option in which the contractor is responsible for all activities and acquisitions until the asset is handed over to the owner). Carried out by specialized external companies and supervised by Enel Green Power on-site personnel. It usually takes about 2 years from obtaining the relevant environmental permits.

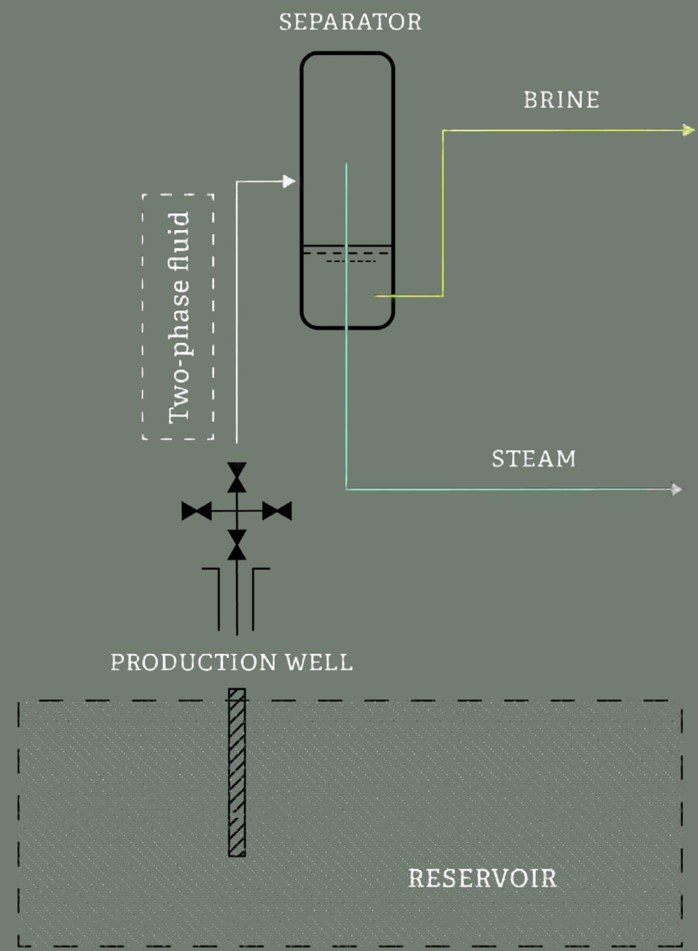
Separation Area

As mentioned above, the fluid that comes out of the production wells is a mixture of water in liquid state (brine) and in steam state.

Due to the thrust that this aqueous fluid receives from the reservoir pressure, the two-phase fluid moves without pumps in the two-phase pipelines, until it reaches a second area of the geotermal plant: the separation area.

It is called «separation area» because it is aimed to separate the liquid phase from the steam phase, so that these two phases can be sent to the power plant through independent pipelines.

The separation area is centered in equipment called ciclone separators, where the two-phase under pressure enters, separating its liquid phase towards the lower part of the separator and its steam phase towards the upper part (figure below). Both phases thus proceed separated towards the generation plant.



Conceptual layout of the liquid and steam separation area.

This schematic is a general outline. The separation area is a complex and very expensive sector of the plant (several tens of millions of dollars), where in addition to the cyclone separator there is a flow and pressure control system for both the liquid and steam phases (in order to prevent excess flows or pressure incompatible with the plant design). The entire separation and control system is monitored from the plant´s control room by a system of valves, mostly remote controlled.

Once separated, the liquid and steam have different destinations in different sectors of the power plant (as described below).

On concluding the description of the separation and control area, it is worthy to note that, in addition to valves, it has pumps that operate only in the circuit of the separated liquid phase (brine). These pumps are used to raise the brine pressure and thus overcome the hydraulic resistance generated by the plant's heat exchangers.

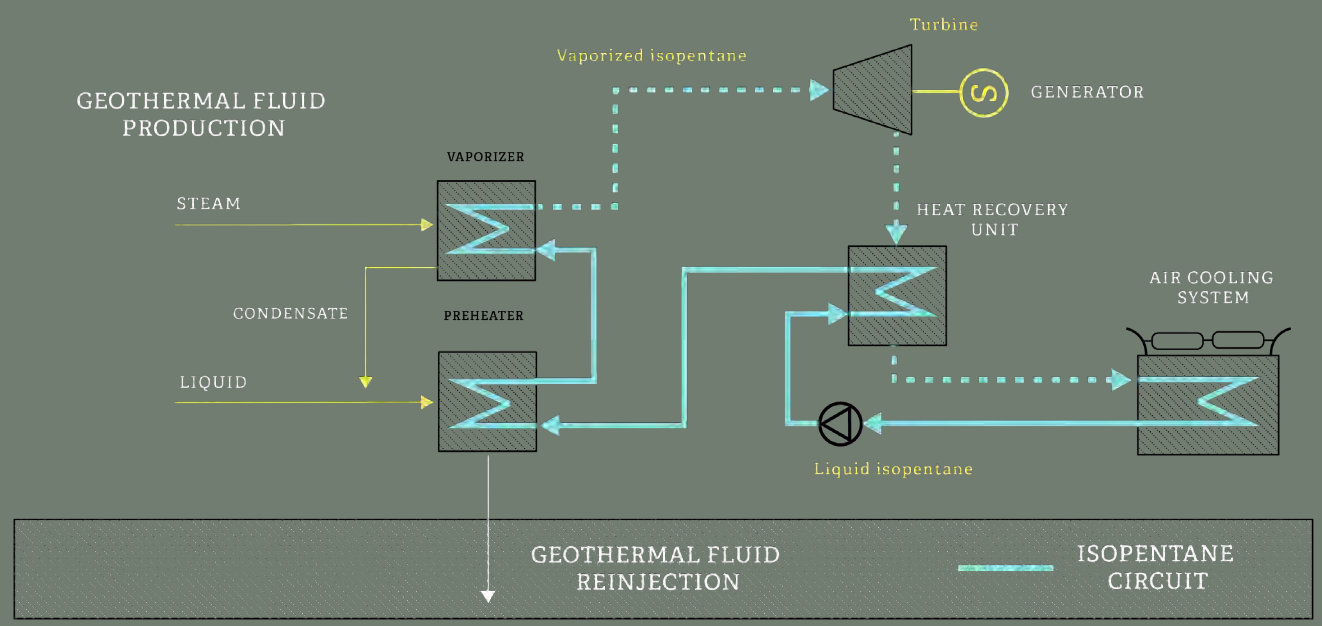
The construction of the separation area usually takes about 2 years after obtaining the relevant environmental permits. It is carried out through EPC contracts and is executed in parallel with the construction of the other areas described here.

Generation area

This is the heart of the plant, where the thermal energy contained in the geothermal fluid (separated liquid and steam phases) is converted into electrical energy. The generation area consists of a primary circuit and a secondary circuit.

The primary circuit is the geothermal fluid (brine and steam) that provides the thermal energy.

In the secondary circuit, the fluid that receives the thermal energy circulates, vaporizes, expands and finally drives the turbo-generator. This fluid is a light hydrocarbon with low termal capacity and boiling point. In the specific case of Cerro Pabellón, it is isopentane.



Conceptual layout of the generation area of a geothermal power plant.

As shown in the diagram, the separated steam and brine (yellow lines) transfer their thermal energy to the isopentane (light blue lines) through two types of heat exchangers: the vaporizer and the preheater.

Steam gives up its thermal energy, progressively condensing (at constant temperature) and being successively reincorporated into the brine flow ("liquid" in the figure above).

Brine gives up its thermal energy by progressively lowering its temperature. Both steam and brine enter the heat exchangers at about 160°C.

Finally, only the liquid phase leaves the heat exchangers, at a temperature of about 90°C. The secondary circuit (the isopentane circuit) is responsible for driving the turbo-generator. The liquid isopentane circulates at a temperature of about 48 °C, and is heated by passing through the preheater and the vaporizer, vaporizing and expanding to a temperatura of about 155 °C. The liquid isopentane circulates at pressures between 20 and 22 bars.

Both the primary and secondary circuits are pressurized circuits with pumps and valves. The entire process is operated and monitored from the control room.

There is the possibility of "by-passing" the vaporizer, the preheater or both, by means of valve systems. The secondary circuit also has bypasses that control the flow of isopentane that comes into contact with the brine and steam, respectively. This is in order to always have the possibility of optimizing the plant's performance.

The isopentane circuit is cooled from 150 °C (output from the turbo-generator) to 48 °C (input to the preheater) by a system of air cooling towers (fans).

The construction of the generation area usually takes about 2 years after obtaining the relevant environmental permits. This is achieved through EPC type contracts and is executed in parallel with the construction of the other areas described here.

Reinjection Area

At a temperatura of about 90°C and a pressure of about 5 bars, the liquid phase fluid leaving the preheaters is directed to the reinjection area. The pipeline section that transports this fluid for about 2 kilometers to the reinjection wells is a pressurized aqueduct.

Reinjection pressure can be managed from the control room, since before reaching the reinjection wells the fluid passes through a system of pumps acting in parallel. If necessary, the pressure of the reinjected fluid can be raised up to 25 bars. The reinjection well layout is identical to that of a production well. The only difference is that in this case the fluid enters the reservoir and does not leave it.

In order to make the operation of the plant more flexible, reinjection platforms also have temporary storage ponds to discharge the water, to allow maintenance of the reinjection pumping system or to test the wells with probes.

These ponds are not usually used during normal plant operation, but primarily during plant maintenance activities.

It is essential for each well platform to have a temporary fluid storage pond to be used in case of need in order to make the operation more flexible. For example, during plant shutdowns or during periodic well unloading tests to measure physical (pressure, temperature, flowrate) and chemical parameters.

The fluid discharged to the ponds is continuously pumped to the reinjection, "by-passing" in this case the generating station (it cools down a lot, reaching temperaturas of 40 to 50°C, and is not useful for the production process).

It is worthy to note that during the operation it is not convenient to close the production wells, unless the plant is under maintenance for long periods of time (weeks or months). Being made of steel and cement, opening and closing wells repeatedly could be harmful to their integrity, due to the different termal expansión of these two construction materials.

The construction of the reinjection area usually takes about 2 years after obtaining the relevant environmental permits. It is achieved through EPC contracts and is executed in parallel with the construction of the other above-mentioned areas.

The refurbished church of Ollagüe.
Enel (Chile).

GEOTHERMAL ENERGY AND CULTURES: COMMUNITIES AND TERRITORIES

Relations with the communities, particularly those of Alto Loa, were built since the inception of the geothermal exploration and exploitation project in the region.

First approaches

"The need to enter from the beginning into a relationship with the communities is based on the fact that geothermal energy is a science that does not manifest itself. It is not wind, it is not sun, it is something hidden, which is generated underground," explains Antonella Pellegrini, Enel Chile's Sustainability Manager, "and for the Atacamenian communities the earth has an important meaning in their cosmovision. From the beginning, we detected that this gap between a science-based project, with a high level of technological development, and the communities with their knowledge and ancestral cultures, could have generated important asymmetries of information. And that would have become a stumbling block for the good implementation of the project. So, we soon began to socialize in these communities. First the company, Enel Green Power, and then the project. This first project consisted of exploring the possibilities of geothermal energy in a field located in the area of a tourist concession granted by the Chilean State to the communities of Toconce and Caspana. These two communities were the first group with whom we started this conversation, which has been going on for fifteen years to date."

Gonzalo Salamanca, External Relations Manager for Enel Green Power Chile and Andean Countries, is one of the professionals who addressed from the beginning the task of approaching the communities. Establishing relationships with them and creating a system of understanding. "Enel had a project to explore the possibilities of geothermal energy in the area of El Tatio, in the Quebrada del Zoquete. The same area where Ettore Tocchi demonstrated that there was steam in 1922. But we needed to enter into a relationship with the communities, socialize the project with them, obtain their approval and, if possible, get them involved."

From Atacama to Toscana

Before drilling the first well in Quebrada del Zoquete, in the socialization phase of the first project near El Tatio, well before Cerro Pabellón was even conceived, Enel Green Power professionals approached the communities with an open spirit of getting to know them. "You cannot tell a community that you are going to build an industrial project in their territories, which is like their home, without establishing an authentic relationship with them," says Gonzalo Salamanca, "and to do that you have to know them, know who they are." This resulted in them participating in several "payments to the land". And above all in the traditional canal cleaning ceremony, which is the most important ceremony in these communities. "Community members open the floodgates of the canals at dawn, once they have been cleaned," says Salamanca, "and then they sing some songs in Kunza, the native language of the Atacamenian people, of which they currently understand some words but not all of them. It is an ancestral ritual and the fact that we were invited to participate with them cemented a relationship of trust. Geothermal energy is a construct, something difficult to understand. So, the first thing we proposed was to take the leaders of Toconce and Caspana communities to Tuscany, where Larderello- the largest geothermal development in Italy- is based. The idea was to show the community leaders how geothermal energy can coexist - in a region of high cultural value - with the wine culture, art, architecture, handicrafts, without altering the landscape or productive activities. And this is the best proof of the sustainability of geothermal energy. But also, in Tuscany you can very easily understand all the other uses of heat, from residential use to greenhouses, cheese making or brewing."

The Communities themselves are monitoring

"That trip allowed the community leaders to understand on site what we were proposing to do in the future. Their first concern was for us to assure that exploration would not affect the geysers of El Tatio (even though the exploration was taking place six kilometers below). We created a program for them to directly monitor the height and temperature of the El Tatio manifestations. And

The need to communicate the characteristics of a new geothermal project to the communities generated a "conversation that has been going on for fifteen years to this day," says Antonella Pellegrini, Sustainability Manager of Enel Chile. Enel (Chile).

at the same time, we asked the geologists to teach them how to identify the heat manifestations: geysers, mud pots, bubbling waters.... There are more than five hundred manifestations listed in El Tatio. This totally prospective work (we had not yet put a single machine on the ground) was carried out by the communities themselves. This allowed people in these territories to know, first of all, what they had and, then, to be able to measure it and notice variations in real time."

Antonella Pellegrini adds, "Relations with Caspana and Toconce communities have been strengthened over time and are based on mutual respect and trust. So much so that when we had the incident that led us decide to abandon the El Tatio project; it did not generate any conflict with the communities, but a request for clarification. They wanted to understand what had happened. But it was far from being the end of geothermal, nor of Enel Green Power's relationship with the communities." And what had happened? "A well head broke, as a result of the pressure," explains Gonzalo Salamanca, "that incident resulted in the closure of the well. And although a UNDP committee later determined that there had been no environmental damage whatsoever (what comes out is steam and limestone material) it was decided to end exploration in this area."

Joint design

Then we began to develop the Cerro Pabellón project," says Antonella Pellegrini, "and that meant another issue. The seventy-kilometer line project passed through an indigenous territory of more or less six communities. Conadi, the National Corporation for Indigenous Development, told us to acknowledge the indigenous demand and to build, together with the communities, the perimeter of cultural relevance of the territory. And that´s what we did. We designed the entire perimeter with them, bearing in mind the different demands they had. And we drew up a map based on what we were able to effectively identify through an impact assessment of the project. And then we began a conversation about the project design. Cerro Pabellón is not a project that was developed only in the engineering departments of Enel Green Power's offices in downtown Santiago, or in those of Pisa, Italy. Cerro Pabellón is a project developed in the field, in agreement with the communities. We have made changes to the project design. Especially in the power line, because the communities let us know that some sections of the line were impacting their territory in some landmarks that we were not supposed to impact."

Value creation

"The ongoing conversation and that final co-design of the project was the key to implementing what has been in fact a consensual project. And not only consensual, but it has also brought value

The need for new services generated by Cerro Pabellón has directly benefited several communities in Alto Loa. Enel (Chile).

The new 24-hour energy availability has allowed women to access attractive job opportunities without being forced to leave their former occupations. Enel (Chile).

to the communities. When we entered the construction process, opportunities arose. But first we had to resolve the impact issues, implementing the corresponding changes to the power line and in the design of the route we were going to occupy. A camp that was being established in a certain area, provided with a power line that covered seventy kilometers, required services, beyond labor, and the communities were interested in offering them. Although initially they had no experience in these areas, it was very interesting and very nice to see the proactivity that this inclusion generated. With the opening of the company to the inclusion of the offer of services by the communities, the barrier generated by the impacts of an industrial action was completely reversed. Instead of distance between the company and the communities, an integration and alignment of purposes was achieved. So, as a result, an industrial project has become a great opportunity for local development."

Services and human and social development

What services do the communities provide at Cerro Pabellón? "One of the needs," says Antonella Pellegrini, "was to transport people. The people who worked in the camp had to travel to Calama. So, a transport service company, a SME, was set up. The other need in the camp was housekeeping. The communities took on this task and there are still cleaning businesses contracted to work in the camp. Ollagüe was the only community that held water rights. They set up two laundries, working later for the Ministry of Public Works, which was building a highway in the area. This gave them other job opportunities. The camp also has a kiosk. You have to take into account that the Cerro Pabellón camp is isolated, practically in the middle of nowhere. To find any store you had to go to Ollagüe or Calama, which means driving for an hour and a half. But with the kiosk, people were given the possibility of having all the essential items at hand, from toiletries to snacks and fast food. This interaction within the camp created a very close relationship between professionals and technicians working for the project and people from the communities also working for the project. Friendly ties were built, and we don´t mean contracts or corporate social responsibility. This is something that goes much further. An ethical bond is established between people, especially between women. Because we haven't said yet that women in these communities play a very relevant role."

The leading role of women

"The family dynamics of the Alto Loa communities is that men live most of the time in Calama, because they work in mining. And in the communities, women are the ones who assume most of the tasks related to the family and survival. For the most part, they are single mothers who have developed a great proactivity with respect to their own undertakings. They consider them, in fact, as an opportunity to educate their children, to improve their homes with their income and also to expand their role within the communities. Thus, Cerro Pabellón has represented growth not only in economic terms, but also in terms of human and social development within the communities. Most of these women are now leaders in their communities, but not only because they have managerial positions, but also because of what they do and their contribution to the community. In short, I believe that this experience confirms that, in the end, ethics in what you do is fundamental. Both from the company and from the community. If there is an ethical relationship, it seems to me that things work, and work in the long term. If there is no ethical relationship, things may work only for some, in the short term, but not for all the people involved."

Environmental dimension

"The environment was the other important aspect – Antonella Pellegrini continues - in this need to integrate the company with the territory so that the project would be successful in all its dimensions, not only in the technological or economical aspect.

To address this area, we added to the environmental monitoring people from the communities, trained to understand an environmental qualification resolution. We have our environmental consultants, archaeologists, biologists, but many times these academic backgrounds and approaches do not include an ancestral vision of the territory. And sometimes it happened to us, not only in Alto Loa when we realized that we didn´t have a complete record of the environmentally generated impacts. This can happen if you limit knowledge to an academic approach without considering what is important for the people who have always lived in the territory. So, we integrated community monitors, who accompanied the archaeologists and biologists, to have a more holistic awareness of the potential impacts we could generate. There are plants that are not significant for us, but they are for them. And there are places that archaeologically are not identified as relevant, but they are important places for the indigenous vision of the territory. So, the initiative will always go in the direction of integration with all the dimensions of the territory, including the environmental and archaeological, as well as the social, economic and human development dimensions."

Barefoot College and "solar moms"

"Antonella -intervenes Gonzalo Salamanca-, by the way, I wanted to draw your attention to the Barefoot College initiative and the experience of women from the Alto Loa communities who were trained as 'solar engineers' in India."

"Indeed, Barefoot College was an interesting experience," recalls Antonella Pellegrini, "because it is further proof of our understanding of development as a collective endeavor, as a network of human, social, economic and environmental development. Barefoot College is a partnership between Enel and this Indian NGO of the same name. Its objective is to solve the problem of the lack of access to electricity affecting the communities, through the training of women. There are many communities in Latin America that are very isolated from the areas the States can intervene to supply electricity. The solution in these places is that the people themselves must manage the energy supply. This means that technology must be brought down to the level where users can take on the task of providing energy to their own communities. Barefoot College was born as a result of that. There is a village called Tilonia (in the Ajmer district of Rajasthan) where women from all over the world come to the school to learn how to assemble, install and repair small solar panels connected to a battery. And these women stay at the school for six months. From Chile, we brought women from Caspana, Toconce and Ollagüe to the Barefoot College, who stayed in India for the six-month course and returned to their communities as community solar

The "solar moms" provided communities with a new energy autonomy, based on renewable resources. Enel(Chile).

leaders. These were women who left their communities for the first time and there, together with other women who speak other languages, they learned simply by hands-on operation and gestures. That created women's leadership that otherwise would never have happened."

Energy autonomy

"The Latin American group included women from nine countries, coming from more than forty communities. These women, upon their return to Chile, installed equipment and electrified their communities. We call them the solar moms. And they still maintain and take good care of their panels in these communities. Nowadays, one of them is also dedicated to the maintenance of the Ollagüe solar plant, which is a much more complex system, as it gives them the possibility not only to light their houses, but also to use household appliances and other devices. The beauty of this project is that it has had a great impact on many women and communities in Latin America. And it is another aspect that adds to the ongoing construction of the relationship with the Alto Loa territories."

"To better understand this course of action," adds Gonzalo Salamanca, "perhaps it is necessary to explain that most of the communities' demands are associated with energy and local infrastructure. The communities, in general, have no energy and operate with oil-fired generators, which is expensive and polluting. We are looking for agreements with the communities that include the improvement of local infrastructures. Such as drinking water, livestock. Project portfolios that directly benefit the communities, generating local strategies that are sustainable, such as promoting local production or tourism. On the other hand, the great challenge today is to transfer knowledge: the question is how to collaborate in the management of renewable energies by the communities themselves, because today there is a great governance deficit, both at the level of municipalities and communities."

Knowledge transfer

"It is about training and educating people. In Ollagüe, for example, we implemented a hybrid plant that works with photovoltaic panels and a wind tower, linked to batteries. The idea, in the medium term, is to transform the Ollagüe plant, in association with the municipality and a university, into a practical school for the knowledge and operation of off-grid renewable energy systems for remote communities. The idea is to create a small-scale training center for young people from the communities to meet the needs of small villages. But we have also created, at the Valle de los Vientos wind farm near Calama, the Desert Interpretation Center, the CID, in which all the communities of Alto Loa are involved. It is not only an interpretation of the Desert in terms of energy, but also from the perspective of ethnobotany and anthropology. We are currently working on the association of the communities to the management of the project. Understood as a "pedagogical platform" of access to the desert, as a geographical and cultural space. As a result, we have photovoltaic energy in Toconce and Caspana, and in Ollagüe, the hybrid plant I have just mentioned. In Caspana, we also have a plant for dehydration and packaging of local products, connected to a photovoltaic system. In addition to the herbs typical of the high-altitude desert, these oases of Alto Loa produce excellent garlic, apricots and other vegetables and fruits. And these projects are more sustainable than just laundry, kiosks, cleaning or transportation. The future lies in them, we think."

In a project of Enel, the municipality of Ollagüe and a university, the town's hybrid power plant will be transformed into a practical school for the operation of renewable energy systems, says Gonzalo Salamanca, EGP's External Relations Manager. Enel (Chile).

GERMÁN GONZÁLEZ PANIRE
"If the earth were dead, it would give nothing."

Germán González Panire is the *yatire* (highest community authority) of Caspana. He has a hard face, worn by the desert. He is a slender man, not very tall. He speaks slowly, in a very low tone. As if he were measuring, with precision, what he is going to say.

Since when did you start having responsibilities in the community?
Since 1985. I was about 23 or 24 years old. The first position I held within the community was that of canal cleaning captain.

What does this position consist of?
Well, the captain directs the cleaning of the canals, he organizes everything. And at the end he is accountable to the community, in an assembly that is held once the cleaning is finished. The new captains for the next year are also elected there.

How is the calendar for the cleanup?
Work begins on July 26. That is the first cleanup, let´s say a smaller one. Then the actual cleanup begins on August 15. There are two stages. It starts on Wednesday with a huaqui, which is a ceremony that consists of asking permission from the earth to begin all the work. On Thursday a section is carried out and another one on Friday. The work ends on Saturday, when we reach the top of the ravine.

And where is the water before it is released?
It is left running for irrigation. Afterwards we have a community gathering, someone offers lunch, so the party goes on.

And when does the cleaning of canals end?
It ends the day you hand over the job. On Wednesday, once all the canals have been cleaned, the whole community meets. Then you hand over the job. It lasts a week, from Wednesday to Wednesday.

Where do the songs that you sing in this ceremony come from?
They have been preserved for years. The first people I met used to know the complete songs. But as time went by, parts of them were lost. The customs have also been lost. I was investigating these songs, because they have a mixture of Kunza, Quechua and Aymara. They are written in the same way, but the pronunciation is different. That is very confusing.

What do the songs say?
Well, as far as I know, they are related to land and water....

Do you understand what these songs say?
No, there are some people who still understand them, but not everyone.

You also work as a natural health practitioner. Do people come to see you?
Yes, I work in an office back in Calama. They are always calling me. I don't attend much, because I don't have time. When I had time, I attended on Mondays and Wednesdays. That's part of a program called Con Salud del Pueblo Indígena (With Indigenous People's Health). The national State provides resources.

What specifically did you do in El Tatio? What is your experience with geothermal energy?
Well, geothermal energy had been around since the 1960s, with Corfo projects. But then it all came to a halt, during the time of the military government.

But what were you doing in El Tatio?
Mostly we collected yareta, which is a plant on the hills, a bush that is used as fuel. It dries by itself and provides a lot of calories. Before, all the mining companies used it for their operations, but now it is protected. When I was fourteen, I started to go around with animals, collecting yareta, because it was the only way to make an income at that time. I was mostly around El Cenizal hill, which is in front of El Tatio. They raised a lot of cattle back then. Now, people are more involved in agriculture.

And how did your relationship with geothermal energy begin?
A closer relationship began when Enel did explorations in Quebrada El Zoquete, near El Tatio.

And how was the work, the relationship with Enel?
We as a community had no problems with Enel. But there were some neighbors who did have certain fears. Because of misleading information, they thought that the water springs were going to dry up, that they were going to be contaminated. And to this day the springs are still the same. In other words, the project has not affected anything.

You as a community were able to verify this.
That's right. We ourselves, with Enel, monitored the geysers in terms of temperature and height, to see if there was any effect, and there was none. So far there has been no repercussion. And everyone is happy.

How long did this process with Enel last?
It lasted quite a long time. I was there for two years, but there were other leaders before that. I would say that in total it lasted about five years.

Your role was safeguarding that no harm is done to the earth.
That's right; because our belief is that everything comes from the earth. It gives you food to eat, to drink. And then everything goes back to the earth. So, you respect the earth, because it gives us absolutely everything. Many say that the earth is dead. And the earth is not dead. If it were dead, it would give nothing.

CORALINA ANSA
"In this job you learn and keep learning things."

"I am a janitor here at Parhua Company. That's my job, I do the cleaning here in the camp. The Enel offices, the polyclinic, the gate house and the corridors. Also, the bathrooms and the dining hall. Up there, in the plant, the same: offices, the surroundings and the control room. "

And at what time do you do the cleaning?
Well, here in the camp we start from six-thirty in the morning until about one in the afternoon. And my colleagues go up there at about nine o'clock. As you know, it's a half-hour trip to get to the plant. They start at nine thirty in the morning. Until about half past twelve. Then they have to come down here for lunch at one o'clock.

So, their workday is from what time to what time?
From six in the morning to six in the afternoon. The shift is 10 x 10. Ten days on and ten days off.

Are you from Ollagüe?
Yes, I´m from Ollagüe. I am indigenous of Quechua origin.

So, you speak a little bit of Quechua.
Yes, I understand some words and a bit more, because I have a Quechua mother.

And the Parhua company, is it a family company, or is it an Ollagüe company, with members of the community?
No, this is a family business. The partners are my sister and my mother. But we work with women from Ollagüe.

How many workers does the company have?
There are four of us per shift. Three cleaning workers and a supervisor.

And how many shifts are there per month?
There are two shifts. On my days off, the other shift comes in. In total, the company has eight women.

How long have you been working here?
Since Parhua started its activities here, in 2019. On April 6.

What has this work experience meant in your life, has it been good, bad?
Look, it has been good all around. Because I had never left my home, Ollagüe, I had always worked there, with my family. And it has been a very good experience, to come to a camp and learn, because here things are all different. And you learn and keep learning things. And it is also useful for us when we go to other places, to mining companies, to provide services.

This means that from this experience with Enel, the company intends to expand its services to other companies.
Yes, to mining companies. They also have partnerships with our community: Collahuasi, Quebrada Blanca and El Abra. We also want to provide services to these companies. That is why we are taking our experience from here. Since Enel gave us the opportunity, so....

This was the first opportunity you had.
Yes, and it is also the first time I have left my home.

And economically speaking, has your situation changed? Have you been better off?
Yes, because we have a secure job, a secure salary to maintain our income. Because I have a daughter who is studying at the university.

Where is she?
She is studying in Santiago. Architecture. She's already been there for three years.

At what university?
Universidad Mayor.

And who does she live with in Santiago?
No, she lives alone. She is renting.

And you finance all that?
Yes, I finance everything.

And what did you do in Ollagüe, Coralina?
In Ollagüe... we have a hostel. And that's where I worked. But with the pandemic that happened last year, we had to close it.

You are all women entrepreneurs, aren't you?
Yes, those of us who are working, those of us who do the cleaning are all women. We only have one man who is a supervisor.

And what do you think is special about this group of women leaders? How would you like to be remembered when you look back over the years?
What I would like us to remember is that we are fighters, hard workers. Because we all work for something. For our salary, to support our children, because most of us are single mothers.

JORGE PÉREZ BACIGALUPO
"Operating a geothermal plant at 4,600 m.a.s.l. is a great challenge."

What is your role here at Cerro Pabellón?
I am the HSEQ (Health, Safety, Environment, and Quality) coordinator, in the health, environment and quality aspects of people safety. In other words, risk prevention.

And what does your work consist of?
I am part of a risk prevention team that is composed of a coordinator and six task managers, who have a slightly more field-based role. We also have an environmental specialist and a control called ATC, which is a documentary control. Our job is to enforce the company's protocols and policies regarding the care and safety of people. And last but not least, protection of the environment.

What are the most serious risks?
The main one, and the one that characterizes our project, is related to the protocols required for exposure to high geographical altitude. Not everyone is adapted to carry out normal work. We control from the base, making sure that all the people who come here have a previous high-altitude test. And then we check: how is oxygen saturation, blood pressure. Afterwards, the risks will be linked to the productive activity we are involved in. This is a project where the mechanical, electrical and civil areas converge in the construction and then in the operation of a plant. Operating a geothermal plant at 4,600 m.a.s.l. is a great challenge.

Is there a polyclinic here, an ambulance for serious cases?
Of course, and they operate 24 hours a day. We have a first aid room here at the camp. And in Pampa Apacheta we have another one with permanent support. Two paramedics and an ambulance with direct communication to our nurse here and also the support team. In terms of practical health issues, how a body performs here. And then there is the work aspect, which is assembly, construction and operation, with work at high altitude, of course, and associated with extreme weather conditions. This is an area of great thermal variation. We have two winters to start with. We have to be prepared for the emergencies of these two winters. The seasonal winter, with 25 degrees below zero, snow, rainstorms, thunderstorms...

25 degrees below zero?
Yes. And with winds of 40 to 60 kilometers per hour. Snow winds. That´s why we have emergency plans activated, with the necessary resources, road habilitation and communications. And then we have the other winter, which is the Altiplanic winter, very beautiful. It is wonderful to see the mountains in those conditions, but it is also very complex. We have thunderstorms from one second to the next. And we get a lot of lightning. We are always very attentive to prevention and activations of alert states, which includes preparations with drills.

In these high-altitude conditions, what are the risks posed by machinery?
A piece of equipment has a technical specification and an operating range. To move, a flexible or a conveyor of a hydraulic fluid has certain temperature range. And if that specification is not in line with what we are talking about, the 25 degrees below zero, the progressive deterioration of those elements increases.

Are you linked to a seismic monitoring system? What happens if a volcano erupts?
Yes, of course. We work on the basis of a matrix emergency plan. The problem is obvious, here at the camp we are surrounded by three volcanoes, San Pedro, San Pablo and Panire. And at the plant we are very close to the Apacheta volcano. Ten kilometers away, we can even see the fumaroles. And, of course, our emergency plan involves monitoring. We have monitoring done by Sernageomin, the service of geology and mining.

In case an evacuation is necessary, how much time would you have available?
It depends on the type of emergency we have. We may face a containment situation. In the case of very severe weather conditions, such as possible road blocks that prevents us from securing distribution routes. In that case, the first priority is to secure vital supplies. We are confident that we can operate the camp for four, five or six days without any problem and, of course, with rationing, we can stay much longer. And if there is any eruptive volcanic activity, then the criteria and the norm is to evacuate immediately.

And what happens to the plant in the case of total evacuation?
If necessary, the plant can operate autonomously. We have a control room here, and we also have a control room in Santiago. The plant can be operated remotely.

MIRIAM YUFLA CRUZ
"Generations to come should think about occupying more clean energy."

You are one of the people in charge of the solar energy projects here in Toconce. Tell us what that is like, what exactly is your job.
I am president of the solar panel committee in Toconce. I am also part of the board of the Toconce community: I hold two positions. This is the result of an electrification project with solar panels by Enel and Codelco. They gave us ninety solar panels.

Only for Toconce.
Yes, at the beginning we had a hard time with the committee because people here are not used to pay, as they are in Calama. Here we decided on a fee of five thousand pesos, which is only for the cleaning and maintenance of the solar panels.

Five thousand pesos to be paid monthly by the town residents.
Yes, only for cleaning and maintenance. Because we hire a person to take care of that.

A person who comes from somewhere else?
No, from the community.

And that person was trained by Enel?
Right. Enel trained the person who is currently in charge of the maintenance of the solar panels. The problem is that there are people who are not used to paying for electricity or water. They think that these energies are in nature and should not be exploited, nor should we pay for them.

And before you had solar energy, what kind of energy did you have?
We had a diesel generator. That engine gave us three hours of electricity. But now, thanks to solar panels, we have power all day long. Now the solar panels cover basic consumption, a refrigerator or a washing machine, but they do not allow us to use bigger appliances, like a "cookie maker" for example, which consume more electricity.

But with that basic consumption, do you have electricity and appliances all day long?
Yes, we have been interviewed by many people and some of those interviewed were the artisan women here in Toconce. They were very grateful for the panels, because they work their land during the day and make their handicrafts at night. So, light was like a blessing for them.

In other words, electrification with solar panels was a good contribution.
Yes, a very good contribution.

Why were you chosen as the solar energy representative? Were you particularly interested in the subject?
Yes, I am very interested in the issue of climate change. I think that we, the youth, the future generations, should seriously consider the need to use clean energies.

What do you do, Miriam, apart from this representation role?
I work in mining. I am an autonomous truck operator for the Gabriela Mistral mining company.

Do you work long shifts?
Seven days up there and seven days here. I leave my house half past five in the morning and return at ten at night. In Wednesday-to-Wednesday shifts. While I am working, I live in Calama and when I am off, I come here.

As the person in charge of the energy from the solar panels, would you like to say anything else?
I would just like to thank Enel, because this energy is very beneficial in terms of climate change. Also, to tell them that we in Toconce and Caspana have been privileged with this energy, but there are many other towns in the surrounding area that should also receive it.

GÉNESIS ANSA
"Three women on the hill"

Tell me what you do here in the Cerro Pabellon camp.
I sell at a kiosk. It's called HuarnikunaUrkoPatapi. In Quechua it means 'three women on the hill'. It's because there were three partners.

Are you of Quechua origin?
Yes.

And where do you live?
I currently live in Calama. But I studied and lived in Ollagüe.

Are you one of those three women on the hill?
No. There were three partners, and two of them left. My mother was left in charge. And since she had to work in shifts, she hired me.

So, you come from Calama. How do you do it?
We have 15x15 shifts. When I'm not here, although my house is in Calama, I go to Ollagüe, because my daughter studies there.

What does the kiosk sell, what does it offer?
Everything that is sweet, salty, cigarettes, herbs, toiletries...

How does the kiosk work? Where do you stock up?
On my days off, we go down a day earlier and take the opportunity to buy things in Calama, in the stores. And the next day we bring them back with my dad, who comes to drop us off. And then we transfer to another pickup truck.

And how is daily life here? What time do you get up?
The shift is from ten to ten. I get up at about nine o'clock and at ten I open the kiosk. Then I close at six o'clock and have two hours to rest, and then I open again at eight o'clock at night. And I close again at ten o'clock.

Those three women on the hill, do they belong to the same community?
Yes, the one in Ollagüe. All those SMEs received benefits here. My aunt was given benefits, too.... Oh, what's the name of her company? Pargua! It's a cleaning company. From Ollagüe.

And in Ollagüe those three women already had businesses.
No, nobody had any business. They started here.

Have you been doing well?
At the beginning, in 2019, we did so-so. We didn't have a lot of sales. Then in 2020 and up to now, we have been doing well. There are more people. We did much better.

Would you say that working here has changed your life at all, or not?
Yes, very much so.

Why?
Because I had never worked before in my life. This was the first job I ever had. And, honestly, I bought several things that I had no idea I could buy and I didn't even know how much one can earn.

What did you buy?
I bought a car. An MG ZS.

Wow!
Last year we did very well, so we raised the money and I was able to buy my little car. And now I'm building a room.

In Ollagüe.
Yes, my dad has a hostel in Ollagüe. The hostel is called Mamá Urku.

What does urku mean in Quechua?
Woman.

Is it a sacrifice for you to stay here for fifteen days?
Yes, because I have a baby. That's why I tell my mother no more than fifteen days.

Are the herbs you sell from Ollagüe, or where do they come from?
From Ollagüe, from the Ollagüe hill.

What herbs do you have?
Wow... I have a catalog, if you want to take a look later... I have rica rica, yareta, chachacoma, chuchi... chuchiandia, I think it's called... torakiru. We sell various herbs. My mother collects the herbs.

How does she know them?
My mom has known them since she was a child. My mom is Bolivian. That's why...

And you speak Quechua?
Me? no (laughs)... My mom is the one who knows how to speak Quechua.

And would you like to learn?
Yes, I would. The basics.

The Future

The next step in the development of Cerro Pabellón is to transform it into a hybrid power plant. Enel (Chile).

It was apparently paradoxical. More than a hundred years after the first geothermal power generation technologies were developed in Italy, Chile and the South American Andean region - one of the most active subduction zones with the highest concentration of active volcanoes in the world - still didn't have it in their energy matrix. But everything changed with the commissioning of Cerro Pabellón power plant: in 2017, Chile finally joins the "geothermal club". And subsequently, Cerro Pabellón's installed capacity increases to 81 MW, with the commissioning of its third unit.

This is the history, including the most recent. It is the history we have told in this book. Now we have to wonder about the future of geothermal energy in Chile and around the world. In a context of imperative decarbonization of the energy matrix and of accelerated and massive technological transformations in reference to energy storage, electricity generation and, in general, in the use of renewable energies.

A changing scenario

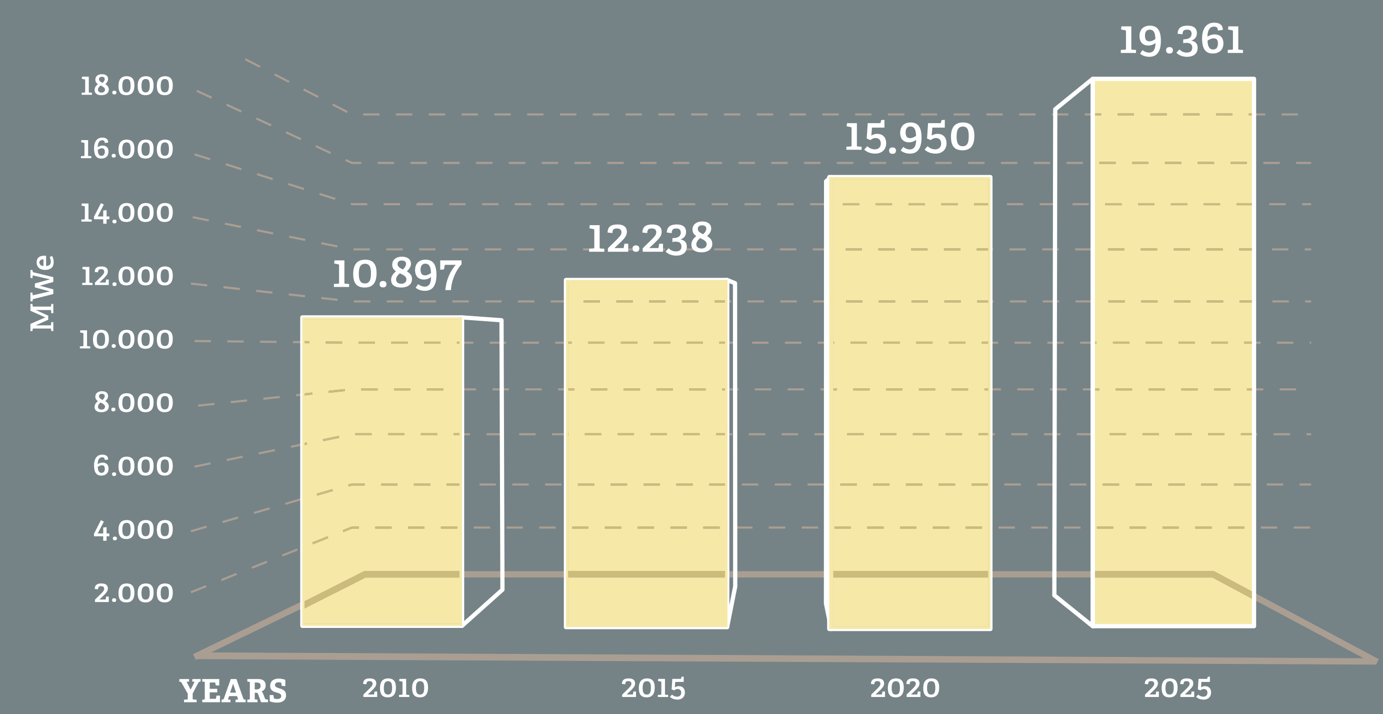
In an updated report presented to the 2020-2021 World Geothermal Congress, the keynote speaker Gerald W. Huttrer remarks that the United States continues to be the country with the largest installed geothermal power capacity around the world (in 2020 it had 3,700 MWe). Although it is estimated that by 2027 it could be surpassed by Indonesia (the world's second largest producer, with 2,289 MWe in 2020). Thanks to a public-private development program endorsed by the World Bank in this Southeast Asian country that has vast geothermal resources.

Huttrer adds that in recent years, five new countries have started generating geothermal power for the first time: Chile (81 MWe), Belgium (0.8 MWe), Croatia (16.5 MWe), Honduras (35 MWe) and Hungary (3 MWe).

According to figures from the International Geothermal Association (IGA), global installed geothermal power capacity increased from 10,897 MWe in 2010 to 12,283 MWe in 2015. By 2020, this figure had already increased to a total of 15,950 MWe, and by 2025 it is expected to reach 19,361 MWe, which is a decrease, although still modest, in the growth rate.

In the medium and long term, the World Energy Council foresees three different scenarios for the growth rate of installed geothermal power capacity in the world for the period 2015-2060: the first, "optimistic", of 5.4%; the second, "conservative", of 4.6%, and the third, "pessimistic", of only 3.4%. None of these three scenarios comes even close to the 18.5% growth projected for the 2020-2025 five-year period.

TOTAL INSTALLED GEOTHERMAL POWER CAPACITY IN THE WORLD 2010-2025



Huttrer, Gerald W. *Geothermal Power Generation in the World 2015-2020 Update Report.* World Geothermal Congress 2020

Causes of slower growth

Several analyses -including the one stated in the aforementioned report and the most recent World Geothermal Congress- agree that the reasons for this decrease are various. But among them we should highlight the competition at much lower prices from solar and wind generation, as well as from natural gas. In addition to the reluctance of many governments to invest in *greenfields* (new geothermal developments), due to the slow return on investment, risks and high financial costs of the exploration activities. On the other hand, as Valerio Cecchi points out, this trend is further aggravated by the remarkable development of energy storage technologies. In particular the recent introduction of lithium-ion batteries, which in the medium term would substantially mitigate the smaller plant capacity factors of wind and solar generation.

"I would say that today geothermal energy, especially in terms of the competition it has from other renewable energy sources, is still profitable in fields that are already exploited to some extent," Cecchi says. "Being already exploited, the new well you drill will probably have a 70% or 80% probability of success, because you already know the field a little bit. Fields that we call *brownfields*,

Great night view of Enel's Valle de los Vientos wind farm, located in the municipality of Calama. Enel (Chile).

Photovoltaic panels at Cerro Pabellón camp. Enel (Chile).

which are already known and exploited, can be expanded this way. I would say that in that case geothermal development remains attractive compared to other competing types of technology. In particular, solar and wind energy, which still have the characteristic of being intermittent. While geothermal energy can be 'white coal', because it is renewable and uninterrupted 95% of the time, the other technologies are intermittent. They produce when there is wind, when there is sun, when there is water; if not, you have to burn coal, gas or diesel, or whatever."

Cecchi adds that, however, "today these intermittencies are already being reduced, because of the battery system. Batteries will be the big thing of the future. They will make it possible to store excess energy that is not consumed at the moment."

Hybridization of geothermal power plants: The promise of green hydrogen

Giuseppe di Marzio shares the following diagnosis and points to development alternatives for the geothermal industry: "Clearly, the context of lower energy prices and the competition from other renewable energies make geothermal industrial activity very difficult, very complex. It is difficult to think today of a future expansion at Cerro Pabellón with a fourth plant. But we can continue to grow by hybridizing the plant. Something that has already been done in other countries. In the United States, for example, the Stillwater plant, which began as a binary plant, was later integrated with a photovoltaic plant and a third thermodynamic plant.

Enel's geothermal-solar hybrid plant in Stillwater (Nevada, United States). Enel (USA).

Combining geothermal technology with a photovoltaic plant is an excellent solution. Why? Because the small drop in the generation of the geothermal power plant during mid-day is exactly compensated by the peak generation of a photovoltaic plant. Combining these two profiles gives us an even 'flatter' generation curve, which in commercial terms of integrating renewable energies into a country's system is certainly an achievable goal."

Another alternative is the associated production of the so-called "green hydrogen," as hydrogen generated by low-emission renewable energies is called (this is the big difference with the so-called "blue" hydrogen, extracted from natural gas, and "black" hydrogen, obtained from coal or oil). Carlos Ramirez points out that green hydrogen "is produced with sustainable energy, because in order to produce hydrogen, water is electrolyzed. Electrical energy is added to the water, H_2 evaporates, and this H_2 can now be transported by truck. So, for example, there is a great interest in mining companies to improve their carbon footprint and that their giant trucks, which spend about 7 thousand liters of diesel per day, can move with green energy. And that this green energy is produced here".

And how does geothermal energy fit into this?

"If you have the geothermal power plant there at the end of the world," Ramirez continues, "in the mountains and a hundred kilometers from Calama, you don't need to lay a transmission line; instead, you attach the hydrogen plant to the geothermal plant and

Cerro Pabellón would provide energy for the on-site production of a green hydrogen plant for mining activities. Enel (Chile).

CAPACITY AND GENERATION BY COUNTRY 2015-2025

COUNTRY	Capacity MWe 2015	Energy GWh/yr. 2015	Capacity MWe 2020	Energy GWh/yr. 2020	Forecast for 2025 MWe
Argentina	0.00	0.00	0.00	0.00	30.00
Australia	1.10	1.50	1.62	1.70	0.31
Austria	1.40	3.80	1.25	2.20	2.20
Belgium	0.00	0.00	0.80	2.00	0.20
Chile	0.00	0.00	48.00	400.00	81.00
China	27.00	150.00	34.89	174.60	386.00
Costa Rica	207.00	1,511.00	262.00	1,559.00	262.00
Croatia	0.00	0.00	16.50	76.00	24.00
El Salvador	204.00	1,442.00	204.00	1,442.30	284.00
Ethiopia	7.30	10.00	7.30	58.00	31.30
France	16.00	115.00	17.00	136.00	-25
Germany	27.00	35.00	43.00	165.00	43.00
Guatemala	52.00	237.00	52.00	237.00	95.00
Honduras	0.00	0.00	35.00	297.00	35.00
Hungary	0.00	0.00	3.00	5.30	3.00
Iceland	665.00	5,245.00	755.00	6,010.00	755.00
Indonesia	1,340.00	9,600.00	2,289.00	15,315.00	4,362.00
Italy	916.00	5,660.00	916.00	6,100.00	936.00
Japan	519.00	2,687.00	550.00	2,409.00	554.00
Kenya	594.00	2,848.00	1,193.00	9,930.80	600.00
Mexico	1,017.00	6,071.00	1,005.80	5,375.00	1,061.00
Nicaragua	159.00	492.00	159.00	492.00	159.00
N.Z.	1,005.00	7,000.00	1,064.00	7,728.00	200.00
P.N.G	50.00	432.00	11.00	97.00	50.00
Phillippines	1,870.00	9,646.00	1,918.00	9,893.00	2,009.00
Portugal	29.00	196.00	33.00	216.00	43.00
Russia	82.00	441.00	82.00	441.00	96.00
Taiwan	0.10	1.00	0.30	2.60	162.00
Turkey	397.00	3,127.00	1,549.00	8,168.00	2,600.00
USA	3,098.00	16,600.00	3,700.00	18,366.00	4,313.00
Short-term potential					
Dominica	0.00				7.00
Montserrat	0.00				3.00
Nevis	0.00				9.00
St.Lucia	0.00				30.00
St. Vincent	0.00				10.00
Canada	0.00				10.00
Greece	0.00				30.00
Iran	0.00				5.00
Ecuador	0.00				50.00
TOTAL	12,283.00	73.550.30	15,950.46	95,098.40	19,331.01

Source: «Geothermal Power Generation in the World 2015-2020 Update Report». Gerald W. Huttrer, 2020

then move it by truck. It's quite an important saving, because the geothermal deposits in Chile are in the mountains, far from the interconnected system."

The future in Chile

During the second decade of the 21st century, investment in exploration, development and construction of geothermal power projects in Chile totaled more than US$500 million. The so-called Geothermal Roundtable - made up of the Ministry of Energy, the Business Geothermal Council and major universities, among other industry stakeholders - estimates the "exploitable" potential for geothermal power generation in the country's Andes Mountain areas at 3,500 MW. 72% of this potential in the regions of Arica and Parinacota, Tarapacá and Antofagasta, and 28% in the area between the Metropolitan and Los Lagos Regions. Of course, the actual Chilean geothermal potential is much higher. With an estimated potential of around 16,000 MW for at least 50 years based on geothermal fluids with temperatures above 150°C and located at depths of less than 3,000 meters. In the 1980s, researcher Alfredo Lahsen mapped some 300 geothermal areas associated to Quaternary volcanism. Enel's experts are more conservative: Gianni Volpi estimates the Chilean geothermal potential at around 10,000 MW.

Advanced geothermal power projects

At present, Cerro Pabellón is the only fully implemented industrial initiative. However, there are two additional projects with some degree of progress. The first one is Mariposa, located in the Andean Mountain Range of the Maule region, 280 kilometers south of Santiago and 100 kilometers southeast of the city of Talca. It extends over the northeastern flank of the Pellado volcano, between 2,400 and 2,800 m.a.s.l. Still in the exploration phase by Energy Development Corporation (EDC), the largest geothermal power generator from the Philippines, Mariposa is estimated to have an inferred capacity of 160 MWe.

Another project with significant exploration progress is Peumayén (former Tolhuaca), a site located 550 kilometers south of Santiago and 90 kilometers northeast of Temuco, on the northwestern flank of the Tolhuaca volcano between 2,000 and 2,200 m.a.s.l. The concession is currently operated by the Dutch company Transmark, with an inferred capacity of 70 MWe.

Despite their great exploration progress, both projects have registered minimal progress during 2020 and 2021. What are the reasons that prevent or delay their industrial implementation? As we have already seen, it is not a matter of legal or technical obstacles, but of the current prices in the Chilean electricity market. They make a technology that, like geothermal power, requires relatively costly initial investments, uncompetitive.

In Chile, the system is the market," says Guido Cappetti, "so all activity is left to the market. And when you leave everything to the market, clearly the price of gas and oil is lower."

Geothermal as a core energy source

Should the national state go beyond its current market regulatory role? In relation to geothermal, many experts believe that, one way or another, it should. "The state should intervene in some way, because the resulting benefits of a geothermal powerplant have a high social impact, with strong benefits for the communities," Diego Morata says.

Looking at the history of geothermal energy development in the world," says Cecchi, "in most countries it was through state intervention. The State took the initial risk, which is the exploration risk. A risk that not every electricity company is in a position to face".

A strong argument in favor of greater state involvement in geothermal power development lies in the ambitious decarbonization plan whose commitments have been ratified by Chile, which requires replacing thousands of MWs of fossil fuel generation annually. Climate change and the decreasing availability of water resources are evidencing the vulnerabilities of an energy matrix that, as of November 2019, still relied 27% on hydroelectric generation. This is without considering the still very high 51.7% share of highly polluting thermal sources such as coal, natural gas and oil.

Direct uses of geothermal energy

But not only electricity generation can benefit from a greater use of the abundant geothermal resources available in Chile. There are several domestic and industrial processes - air conditioning, heating, greenhouses, aquaculture, agriculture, swimming pools and thermal baths - that use geothermal heat for their operation. Unlike the indirect handling of the high temperature resource in electricity generation, this is the direct use of low temperature or low enthalpy (below 150°C) geothermal resources. And their comparative abundance opens up enormous possibilities for the future.

In fact, global foremost geothermal powers such as Iceland began their relationship with geothermal energy through direct-use technologies rather than geothermal electricity generation. As the latter was achieved by large district heating projects that to this day directly harness geothermal heat, distributing low-enthalpy fluids through pipelines to specific urban or semi-urban areas.

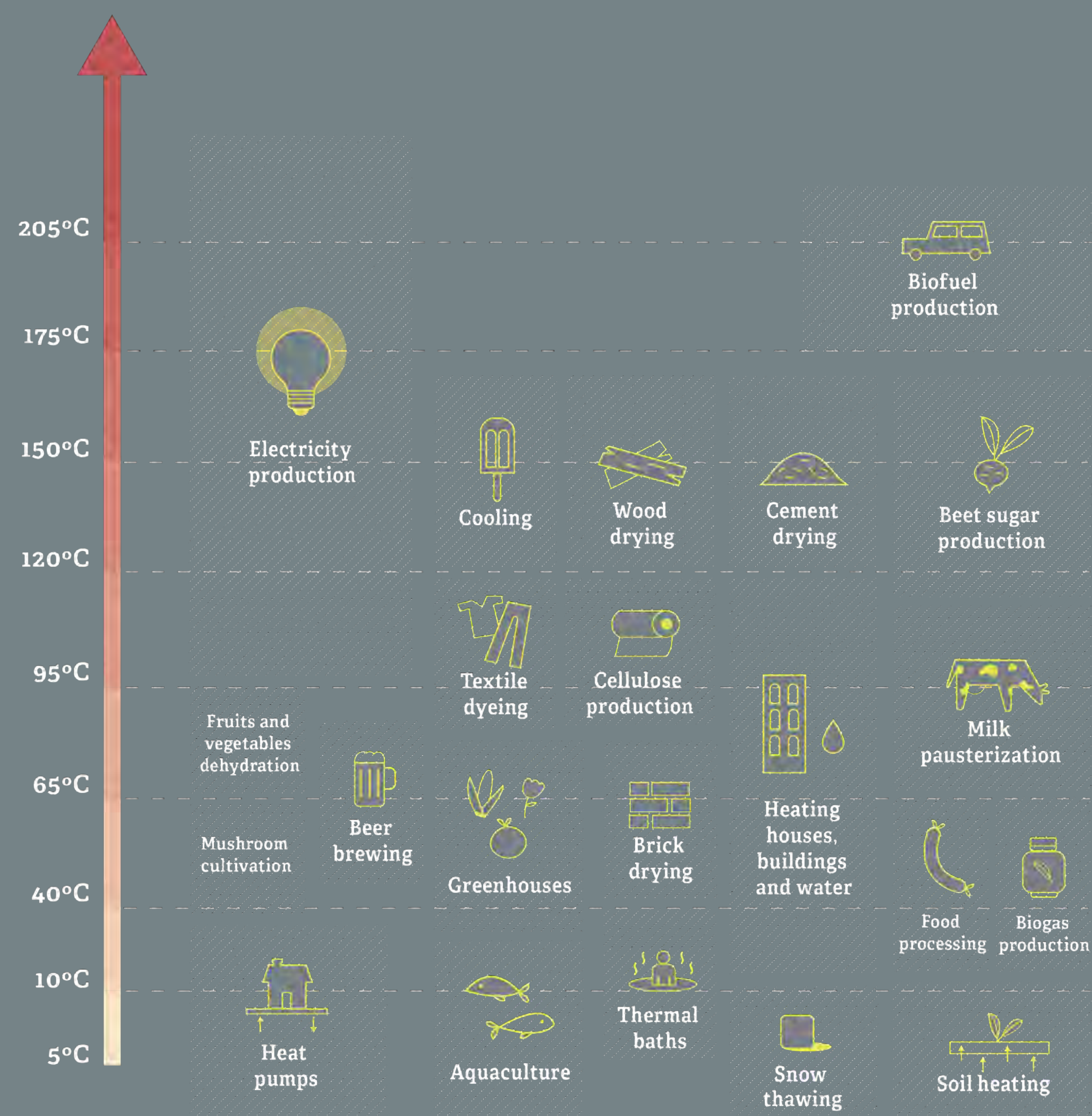
"Direct uses clearly have a huge market in Chile," says Guido Cappetti with district heating in mind. For example, in the South

GEOTHERMAL POWER PLANTS AROUND THE WORLD

Source: ThinkGeoEnergy

USES OF GEOTHERMAL ENERGY AT DIFFERENT TEMPERATURES

Geothermal energy can be used to generate electricity and to heat and cool houses, buildings, entire neighborhoods, and to use this energy for almost any production process that requires heat.



Adapted from:: http://geothermaleducation.org

Geothermal energy is already making an important contribution to the decarbonization of the Chilean energy matrix. Enel (Chile).

you have quite a lot of resources and it's quite cold, so it's very convenient. Geothermal energy can replace firewood, fundamentally eliminating a serious environmental issue. These projects should be developed at a local level. Mainly small projects, with strong municipal or state engagement at a regional level."

Ground source heat pumps

Traditionally, the direct uses of geothermal energy in Chile were restricted to natural hydrothermal resources, for health, tourism or recreational purposes. This began to change in 1996 with the arrival in Chile of the first geothermal heat pumps (or ground source heat pumps, as engineers prefer to call them to avoid any confusion with geothermal electricity technology). It is a type of heat pump that heats or cools an indoor space by exchanging heat with the ground, usually using a vapor compression refrigeration cycle. Ground source heat pumps collect the heat absorbed by the ground from solar radiation without any intermittency (the temperature at a depth of 6 meters is relatively equivalent to the annual average air temperature in the respective locality). These pumps are more energy efficient because temperatures under the ground are more stable than air temperatures throughout the year.

According to CEGA, at least 8 MWt of ground source heat pump capacity has been installed in the country to date. And the number is likely to be higher, given the difficulty of gathering public information on the subject. The new technology has already been used in large projects, such as the air conditioning of two large public hospitals in the cities of Rancagua and Talca. Ground source heat pumps are also being used to heat several educational establishments in southern Chile (Puerto Montt, Villarrica and Coyhaique, among other locations). In the industrial sector, the technology has been successfully introduced in aquaculture, greenhouses and wine companies.

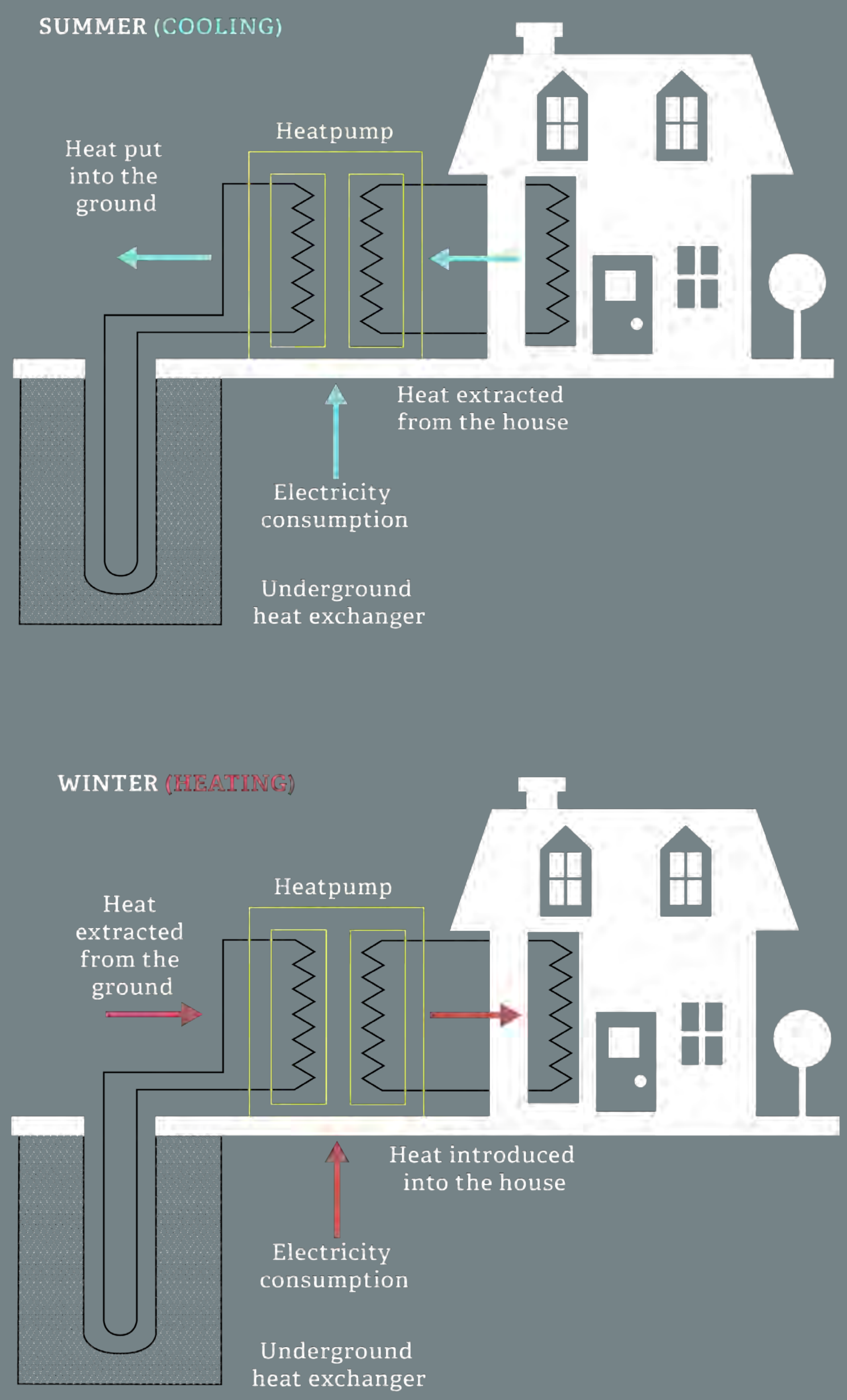
The democracy of heat

You can use it directly in any part of the territory," says Diego Morata enthusiastically. It is the most democratic way of generating heat, because you don't even need to have volcanoes, you can use it anywhere. And that's when you ask yourself: Why isn't it developed more? Why aren't there more projects?"

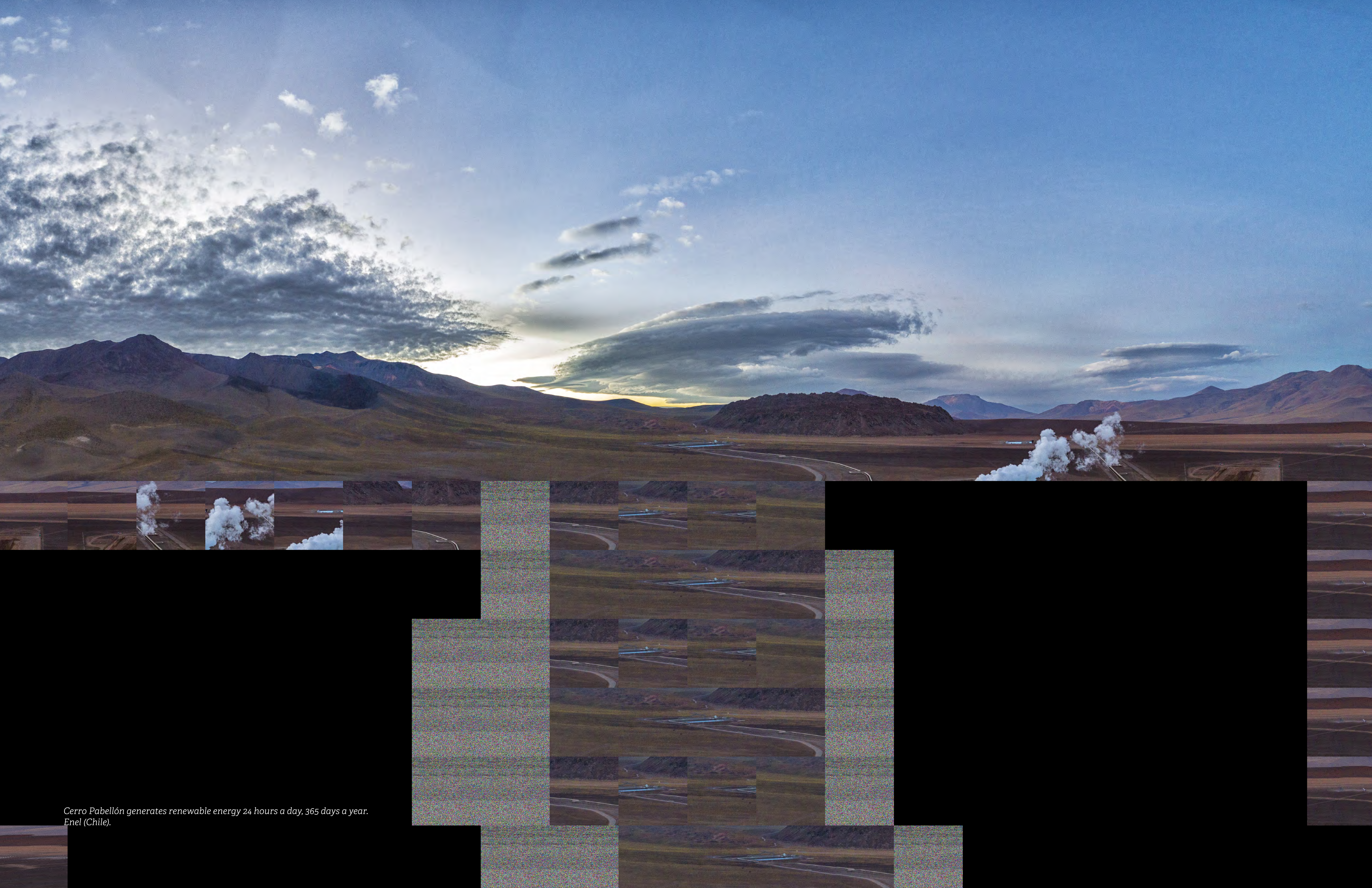
An important part of the answer to these questions lies in the imperfections of the existing specific legislation in Chile. An initiative that "perfects Law 19.657 on geothermal energy concessions for the development of projects for the shallow exploitation of geothermal energy" has already been proposed to the legislative process. The initiative intends to promote the direct uses of geothermal energy through the removal of significant administrative barriers. The aim is to overcome a dysfunctional situation in which comparatively small direct use projects have been subject to the same concession regime as large industrial geothermal power projects.

In Chile, progress will be made towards the fulfillment of that old promise of the heat of the earth. The same promise that one hundred years ago thrilled the engineer Ettore Tocchi on the heights of El Tatio geothermal field.

OPERATING DIAGRAMS OF GROUND SOURCE HEAT PUMPS



Source: IDAE



Cerro Pabellón generates renewable energy 24 hours a day, 365 days a year. Enel (Chile).

LUCA ROSSINI

Head of geothermal operations and maintenance (Italy) at EGP:

"Cerro Pabellon has all the lessons learned in 200 years of geotermal energy". "

At the age of 62, Luca Rossini has behind him a lifetime devoted to the development of geothermal energy and renewable energies. Responsible for the construction of geothermal, wind, solar and hydroelectric plants in 18 countries and 4 continents for a total of 17 gigawatts of installed capacity, his personal and corporate contribution to the global development of renewable energies has been decisive.

"After 100 years, we now have in Italy 916 MW of installed capacity. And worldwide, Enel Green Power is the first to have geothermal plants outside its own country. In North America 160 MW, and 81 MW in Chile," he says with a certain pride.

And as the great enthusiast of his work that he is, he does not want to stop. He confesses with humor that he is already in his "third youth", but says that "I have to reach at least 95 years of age. That's why I don't want to retire."

Born in 1960 in Pisa, the intellectual and scientific cradle of the global development of geothermal power technology, Rossini graduated in Mechanical Engineering from the prestigious university of his hometown. In 1989 he joined Enel's geothermal plant engineering department, where he soon excelled in his work, being appointed project manager for new plants in Pisa, Siena and Grossetto. He later held the position of Operations Manager at Larderello for three years. "That's where it all began," he recalls.

In 2006 he moved "with the whole family" abroad for the first time, to Costa Rica, as construction manager for renewable energy plants in Latin America. Already in 2002, Enel Green Power (EGP) had acquired "two companies, one in North America and one in Costa Rica, based in San José, which developed renewable energies." According to Rossini, the objective was "to develop renewable plants in North and Central America as well. EGP already had projects under development, but did not have geothermal."

A new portfolio

Indeed, it was Luca Rossini who for the first time included geothermal energy in EGP's international portfolio, despite a conflictive and frustrated incursion into geothermal power production in El Salvador. "We had several concessions in Guatemala, Nicaragua and Chile," recalls Rossini, " the Costa Rican company also had concessions in Chile, the first hydroelectric plants in Latin America, Pilmaiquén and Pullinque. Those were the plants in Chile, and another one in Guatemala and a smaller one in Costa Rica. We developed wind power with EGP in Costa Rica, and we began to look for geothermal energy in Nicaragua, Guatemala and Chile. They were the only countries that allowed the development of the free market through laws.... We drilled wells in all three countries. But we found resources only in Chile, in El Tatio and Cerro Pabellón."

As the person in charge of managing the construction of renewable energy plants throughout the region, Luca Rossini was responsible for the development of the Cerro Pabellón project, against all odds and in spite of countless obstacles. A complex and challenging project, the only industrial geothermal power plant built in the middle of nowhere at 4,500 meters above sea level.

The sky is one of the things Luca Rossini remembers about Cerro Pabellón: "The sky you see at 4,500 meters is of a blue that you don't see anywhere else. Night and day. It's a unique thing."

Lessons learned

What lessons did the experience of building this true geothermal crown jewel leave you with? "The most important one is that it changed the basis of the criteria for the development of surface research - reflects Rossini-. With surface exploration we can see where there is hot water, fumaroles. In short, the manifestations that specialized geologists think are indispensable. Without this, nothing exists. Cerro Pabellón was found because Codelco, which was our partner, together with Enap, drilled wells to find water for a copper mine, and they found hot water. When natural manifestations are present, it is simple. But Cerro Pabellón has no natural manifestation. So it was more complex."

"The other big lesson learned was to work at 4,500 meters," says Rossini. By the standards established in long years of industry practice, the project was simply "crazy." And one proof of that was that the cost estimate failed. "We were wrong four times. The cost estimates had been made by the best people in Pisa, the best Enel experts (...) Here in Pisa you can know how much an Ormat plant costs in Tuscany, in Larderello, in all of Italy, in all of Europe as well. But in Chile, at 4,500 meters (...) That is the second great lesson. It took us a long time to develop Cerro Pabellón (...) The plant has all the lessons learned in 200 years of geothermal energy. That is the advantage that we bring. We bring 100 years of geothermal production. Because the most important thing is what happens underground, it's not the plant above ground. And we can find someone to build the plant almost anywhere. But to find someone able to tell you how much is the maximum of resources you can extract, and how much and where to reinject, to guarantee that it is really a renewable energy, is not so easy. Here in Italy we have 500 wells that allow us this expertise (...) In geothermal energy the resource is the heat under the ground. Steam is a vehicle through which we extract the heat, the energy under the ground of which all geothermal experts say that we have extracted 5% worldwide, with all the plants that are in operation. About 17 thousand megawatts. Why 5%? Because water is missing to make the full cycle (...) This is called sustainable development (...) This is what we bring from Italy to Cerro Pabellon."

"The challenge has been extremely high.... The relationship with the indigenous communities, working at 4,500 meters, and a team that did not exist, because when I arrived in 2006 there were only three people, with a hiring plan of at least 50 or 60 people (...) The Enap-Enel synergy has been fundamental. Clearly, the political backing. That has been very important (...) I always believed that it was possible to achieve it. That is the magic key".

The future

After the challenge experienced at Cerro Pabellón and now back in Italy, Luca Rossini was appointed global head of Construction at EGP, then head of Global Project Management at EGP, and in 2019 he became head of the Execution area for North America, Central America, Africa, Asia and Oceania at the same company. Finally, in January 2021 he came to his current position as head of Geothermal Operations and Maintenance for Italy. This is a vast track record that already allows him to reflect on the future of geothermal technology.

Rossini is optimistic about this. On the one hand, he points to synergies with other technologies. "We have a plant in Italy that partners with biomass to heat geothermal steam. We increase the performance of the plant by almost 10%, sometimes 15%. It's a hybrid example. Another hybrid example is the plant in Cove Fort (United States), which started with a geothermal plant generating resources that were far from outstanding. And we added first a concentrating solar thermal plant with mirrors, and then another photovoltaic plant to improve the efficiency of the whole system. Those are two examples of synergy, unique in the world, that demonstrate Enel's pioneering character."

Beyond ongoing developments in district heating in Germany and Italy and new chemical plants for the extraction of lithium in geothermal brines, Rossini firmly believes that geothermal is not finished, "because as I said, only 5% of the heat is exploited. We have to improve the way we extract the water to get that heat, which in a lot of places is not there. And when in 1980 in Italy it was thought that geothermal energy was finished, we had, I think, 400 megawatts, 50% of what we have today, and wells were only drilled at two thousand meters. It was thought that two thousand meters was the maximum depth. Then someone thought that deeper wells could be drilled and we started to drill them. Now the maximum depth reaches 4,500 meters. And also in reinjection.... In 1970, with the same steam, 30% more energy was produced. The answer is no, geothermal has not said its last word, I think there are a lot of developments (...) In Italy we will have 200 megawatts in the next three years, that is more than a 35% increase in the installed power we have."

Cerro Pabellón geothermal plant.
Enel Chile

Production well and steam pipeline.
Cerro Pabellón geothermal plant.
Marcela Mella.

JAMES LEE STANCAMPIANO
CEO of Enel Generación Chile

"Cerro Pabellón is a dream come true for all of us"

A graduate in Environmental Economics from the University of Siena, James Lee Stancampiano arrived in Chile in 2012 to become head of Business Development for the Southern Cone at Enel Green Power. "I came for two years, and I'm growing old here, because I fell in love with everything we can do in this country," he admits enthusiastically.

In his key role as "pitcher" within Enel for large energy projects in the region, a particularly complex milestone for him was achieving approval for the first industrial geothermal power plant in South America. With the large initial investments and the high financial risk involved in any new geothermal project, and with production prices on a sustained downward trend due to the eruption of new renewable technologies, "the numbers were not enough. The project was very close to not existing. Of not being born... And that would have been a total disappointment. Because the wells had already been drilled. It took seven or eight years of work. Families, people who came from other countries. And we had a partner, because Enap also dreamed with us. They helped us a lot."

A unique project

"We are not an NGO. If the numbers are not enough, and the technicians present a risk matrix that cannot be approved, there is nothing you can do. So, we abandoned the geothermal project for a while, and said, 'We have to optimize this'. It was submitted for approval about four times. And it was always rejected. I don't like to give up: we spent time thinking about these financial models, pushing them a little bit with the love you have for your baby. To force the dream a little bit, right? We were very professional, looking for innovation and *energy management* solutions. We did, really, what has never been done in any other project. Because I repeat, it is a unique project. And it will continue to be so."

"Whoever has visited the plant cannot help but fall in love. The plant leaves you with something. I have visited many plants in the world, but this one is special. Solar and wind colleagues get a bit angry; they tell me: 'you always with your geothermal energy'.... There are many colleagues who worked for years to achieve Cerro Pabellón. Obviously our number one dreamer, a great teacher, is Guido Cappetti, who taught us all a lot of things we didn't know. Also, Martino Pasti, Gianni Volpi, Germain Rivera, Carlos Ramirez, who dreamed about the geothermal fluid.... There are so many people that you could make an endless list..."

"And let's not forget Francesco Staracce. Because if Francesco, who is our CEO, had not dreamed with us.... Many times, when they have to give you money, they don't let you dream much. He allowed us to dream. Actually, he was the first one to do it. We also had great technical participation from our Israeli partner, Ormat. They are also part of the story. So many people... Giuseppe di Marzio, who was the head of this plant for many years. And Simone Vilani, who has a relevant role which is basically to give the final blessing. He is the one who connects the cables. He comes from Italy to start the electricity.... So many people. Some of them are gone, or they have other destinies, but they are part of us and we have to remember them."

Hybridization

Although the development of new geothermal projects in Chile does not seem feasible under current market conditions, Enel's Innovation Department is considering various attractive alternatives offered by the hybridization of the Cerro Pabellón plant. "The first one is green hydrogen," points out James Lee Stancampiano, "based on the great advantage that geothermal has: unlike new renewable technologies, it has a 24/7 operating range. It is not intermittent. Adding an electrolyzer to the geothermal plant for hydrogen production at some point during the day seems to be a super-competitive and obviously appealing solution. You don't inject part of the generation that you would inject into the grid. You take it directly to the electrolyzer, where hydrogen and oxygen are separated in ponds. We are studying collaborations in the North regarding the use of hydrogen. It's a fuel, look at it as a fuel. Clean only if renewable energy is used to produce it. If not, it is dirty just like other fuels.

"Second point, always talking about hybridization. We have already developed a solar photovoltaic plant associated with geothermal generation, since the geothermal plant left a free space for feed-in to the grid. It only needs to be approved from the environmental point of view. It's a 100-megawatt line, and we actually achieved 81 megawatts. When there is sun in the daytime, the efficiency is lower. This is because of the heat during the day. We are going to inject into the same substation with solar photovoltaic panels."

"And a third point: our Innovation Department, together with other international stakeholders, has started to study a process that basically consists of extracting minerals from geothermal fluids. And this has an advantage, because actually, some minerals that for us are not so favorable, since they imply a deficiency in the performance of the plant, do have economic value. Such as silicon and lithium. And several companies worldwide have already knocked on the door, because they know that we are based where the underground minerals have a lot of value. In Apacheta, in the north of Chile, are the leading mining companies of the world. And that is why transforming a cost that limits generation is a value for Chile and for Enel itself. This is groundbreaking, because nothing like this has ever been seen before."

Recalling the hundred years of geothermal exploration in Chile, James Lee Stancampiano says that "today with Cerro Pabellón we have contracts with the mining companies. The geothermal power plant is already supplying renewable energy to the mining industry. So, the dream, the vision of Ettore Tocchi, has already been fulfilled."

Decarbonization and electrification of consumption

Based on Enel's goal of achieving *net zero* (zero emissions) by 2040, James Lee Stancampiano points out that "there are several aspects that we are pursuing with great conviction. And there is no turning back. The first mission is to absolutely decarbonize our generation matrix, with a major investment plan in renewable energies. We have already presented the new plan, 3,300 megawatts. We are talking about 2.5 billion dollars in investment, more or less. The renewable energies project mainly consists of solar and wind power."

"In the second place, is the electrification of energy consumption. There are many, many uses, including the needs of each of us in our homes that can be electrified. And they must be electrified, because in the end they will be more efficient and more sustainable for the country. Transport as well. Together with the Ministry, we were the first to invest in the first electric buses. Many said we were crazy."

ACKNOWLEDGMENTS

During the century that has passed since the engineer Ettore Tocchi came from Larderello to start geothermal exploration in the Chilean highlands, the historical, scientific and technical ups and downs of geothermal development in Chile have been multiple.

This book aims to provide an account of what we could call the history - or the adventure - of geothermal energy in Chile in the clearest and most concise way possible. Because it is not only intended for specialists, but also for students (and not only those of geology). In general, for all those who are interested in the development of science and its technical applications.

The history of geothermal energy in Chile goes from the beginning of the 20th century to the beginning of the 21st century. Or, in other words, from the first explorations of Ettore Tocchi in El Tatio to the first plant in South America, Cerro Pabellón, which injects renewable energy into the National Electric System. This book is therefore dedicated to all those who made this process possible.

And, in particular, we cannot fail to express our most sincere thanks to the experts. Without their highly competent and always friendly collaboration, this book could not have been written.

We have asked them to introduce themselves.

GUIDO CAPPETTI

Italian. Chemical Engineer from the University of Pisa.

I worked until the first semester of 2021 as general manager of Geotérmica del Norte S.A. (GDN). A company formed by Enel Green Power Chile and the state-owned Enap, with the objective of exploring and developing geothermal resources in Chile. Under my leadership the company carried out the Cerro Pabellón project. The first geothermal power plant in the country and in South America inaugurated in 2017.

Since I joined Enel in 1976, I have participated in the development of several geothermal projects in different countries, including Italy, Greece, the United States, Indonesia, Bolivia, China and Central America. Between 2001 and 2004, I chaired the International Geothermal Association and have published more than 40 scientific studies.

GIANNI VOLPI

53 years old, Italian; at Enel Green Power Chile I am "Head of Subsurface Activities" for geothermal technology.

Graduated in Geology at the University of Pisa, Italy, in 1993. PhD in Geophysics at the University of Pisa, in 1996. I have been involved in geothermal energy since 1998, when I was hired by Enel Green Power Italy.

Since then, I have been traveling to three different countries with Enel Green Power (El Salvador, Nicaragua and Chile). Always as a resident, building my career until I reached my current position.

Geothermal energy for me is my job, my "adult working life" and a great technological challenge that has led me to travel the world. Being part of renewable energy plant generation projects is a source of pride and great satisfaction. Even at my age... I have absolutely no intention of changing my career path. Geothermal energy in Chile has great potential and I want to be part of its future!

GERMAIN CHRISTIAN RIVERA ROMERO

Chilean, Geologist from the University of Chile, Diploma in Applied Geomatics and Master (c) in Sciences –Major in Geology. Professional with 15 years of experience in geothermal exploration and exploitation. Linked to Enel Green Power Chile, where I currently work as Senior Geologist for the Geothermal Center of Excellence.

My first approach to geothermal energy was in the Volcanology course, given by professors Alfredo Lahsen and Carlos Ramirez from the University of Chile in 2000. And then as a trainee and in my thesis project, to ultimately work for ENG and GDN (ENAP - Enel Green Power Companies) in 2006. And then directly for Enel Green Power, which has also allowed me to travel to Italy and Peru.

In my professional life I have chosen to work in geothermal energy, which has given me the opportunity to make a social contribution by taking part in the development of clean and sustainable energy, which I am proud of. We have made history. Starting with the exploration of this energy resource and realizing it at Cerro Pabellón, the first geothermal plant in South America.

CARLOS FELIPE RAMÍREZ RAMÍREZ

Chilean, geologist from the University of Chile (1975), MPhil in Volcanology at Open University. Professional with 11 years of experience in geothermal exploration.

At the start of my career (70s-80s), I worked in volcanology in the Andes of northern Chile, getting to know some places suitable for geothermal energy extraction, which was my first approach to this discipline.

I wanted to contribute to the development of geothermal energy exploration in Chile. I had the opportunity to visit geothermal plants in the United States, Mexico and Italy, which helped me a lot to understand this way of exploiting a resource from the depths of the earth. I participated in explorations by Enel Green Power and ENAP (ENG and GDN). Covering a large part of the country, and prospects in southern Peru, continuing in the same work until the opening of the Cerro Pabellón Geothermal Electric Power Plant (2017).

I was very proud to collaborate in the search for places that could be of interest for this type of energy, given the sustainability of this resource.

We thank those who have been part of this story. In the photograph part of the team at the inauguration of Cerro Pabellón. Enel (Chile).

Operators, top executives and government authorities pose for a panoramic photo on the day of the official opening of the geothermal power plant. Enel (Chile).

LARDERELLO

SpA

DEPARTMENT OF GEOLOGY

Eng. E. Tocchi

EL TATIO

EL TATIO

Although the direct objective of my recent trip to Chile was the study of the steam manifestations in the El Tatio region mentioned in this report, which should essentially refer to such study, I consider it appropriate and useful to start with an overview of the "department" of Antofagasta as a whole. In its eastern corner, on the border with Bolivia, there are such manifestations that if used for the production of electrical energy, in a similar way to what has been skillfully done in Larderello, could become one of the most valuable factors of progress in this department (rich, as we shall see, in undervalued natural resources to date).

From 18 to 27 degrees south latitude -between the Pacific coast and the Andes- we have the almost always desolate northern region of Chile, which includes the Atacama Desert. Between the department of Tarapacá, cradle of the saltpeter industry in the north, and the department of Taltal, in the south -precisely between the 21st and 24th parallel and from the Andes to the ocean, covering an area of about 120,000 square kilometers- we have the "department" of Antofagasta, with an official population of 250,000 inhabitants (a little more than two inhabitants per square kilometer).

A large portion of this territory, which was formerly Bolivian, passed together with the Peruvian provinces of Tacna and Tarapacá into Chilean hands after the victorious war they fought in 1879 against allied Peru and Bolivia. In the forty years since that war, the progress of these lands has been remarkable: the city of Antofagasta, little more than a small village of 7,000 inhabitants in 1879, did not take long to become the capital city of one of the richest districts of the Republic of Chile. The discovery of saltpeter in its territory had a great and decisive influence on its rapid development. Despite the most unfavorable conditions, starting with the absolute lack of water, which for years had to be imported from distant ports and today is brought from the borders of Bolivia with a 450-kilometer aqueduct, its population has increased tenfold. Today the city has 70,000 inhabitants and, as mentioned above, the entire department has 250,000. Whereas, in the not so distant times of Bolivian domination, the city had 7,000 and the province barely totaled 30,000 inhabitants.

Antofagasta now ranks fourth among the Chilean cities in terms of population. And its port under construction is about to surpass that of Valparaíso, which, due to so many favorable circumstances, still holds the first place. There is no doubt that the port of Antofagasta in a few years will not only surpass that of Valparaíso, but will become the most important port in South America on the Pacific coast. Just think about its privileged position: located in a region rich in minerals, it offers a natural outlet to the Pacific Ocean to both Bolivia and some provinces of the Argentine Republic, which are undervalued due to the huge distance that separates them from the Atlantic.

The Antofagasta-Bolivia railroad, built by the same English company that has provided drinking water to the city and the offices of the Pampa salitrera or the region of nitrate deposits in northern Chile, is a very important factor in this development. With the railroad, Argentineans are now moving from the province of Catamarca towards the Chilean border. In connection with the Puna de Atacama (which is perhaps one of the most interesting and richest territories of the Province of Antofagasta). And the Chileans are currently discussing the most convenient option for the route to link their port through the Pampas and the Puna with the Argentinean lines. This would provide a new Andean pass that would have an advantage over the existing one due to its geographic position of never being interrupted by snow.

State interests -both Chilean and Argentinean- and private interests are working to streamline the construction of this relatively short railroad (less than 500 kilometers from Antofagasta to the border) and without any difficulties to overcome. Considering the nature of the terrain of large flat extensions and absence of important watercourses to cross.

The Puna de Atacama -which this railway line must necessarily cross- and which today we can say, apart from being a convenient transportation route, is extremely rich and its mineral wealth is hardly known. The exceptionally pure and abundant rock salt, which covers the bottom of an ancient dry sea: the Salar de Atacama. In addition, there is borax, sodium carbonate, gypsum, sulfur, copper in its natural state, silver and perhaps petroleum and bituminous shales. Without any water resources, moreover very scarce on the surface, the soil has become sterile in vast extensions. However, it can be very fertile as soon as it is irrigated, as is demonstrated without exception in the few localities where fortunate geological circumstances allow waters -which must run abundant in depth- to surface. There are also oases of very rich meadows with fruits of all kinds that benefit from a pleasant climate, due to the balancing of the opposite effects of the low latitude (23 and 24 degrees) and the remarkable altitude, regularly above 2000 meters.

An efficient driving force put at the disposal of agriculture and mining, ensuring an easy communication to the sea via the railway, would bring about a marvelous transformation in the conditions of this rich but underdeveloped territory. Unfortunately, due to water scarcity, this driving force will always be difficult to supply, unless other energies, including geothermal energy, are conveniently used.

Not only in the Puna de Atacama a remarkable development is possible, but in the entire district, which is still far from being fully explored from the mining and industrial perspective. The lack of water is the reason why vast extensions of the desert territory have never been crossed, not even by the resilient indigenous people themselves. Nevertheless, it could contain deposits that could be profitably mined with modern transport and supply systems.

The railroad to Bolivia and the aqueduct, its essential counterpart, have already provided a first clear evidence. Other railroads and other aqueducts have brought work to the heart of the lost regions of the Pampa salitrera. Where the daring explorers discovered the precious "caliche" or cornstone with high nitrate content, often suffering the agony of hunger and thirst.

The Pampa salitrera in the outback of Antofagasta thus came to compete with that of Tarapacá -previously exploited- and its nearly three million tons per year, which represented the entire Chilean production.

But studies and possible exploitations are not limited to saltpeter. The vast Ascotán salt flat, located on the railway line to Bolivia, has produced in the last five years more than 100,000 tons of borax. And the borax that exists in other salt flats left as reserves is not exploited due to the lack of affordable means of transportation. And this in circumstances where concessions have been granted for the exploitation of borax in 150,000 hectares. In addition, there are more than 79,000 hectares of potassium salts concessions and it is certainly to be expected that the attention of explorers will also be directed towards this important resource.

Sulfur is available in large quantities in the many extinct volcanoes of the Andes. It has long satisfied the local demand for the production of black gunpowder necessary for the nitrate production of the region. And now it will certainly find use in the production of sulfuric acid in the great Calama establishment of the powerful North American Dupont Company, for the manufacturing of explosives.

Dupont, with its Calama plant, will not only have the advantage of supplying sulfur and nitrate, but also a large customer base likely to grow near its facilities: the large copper mines of Chuquicamata, another North American company, the reflourished and already famous silver mines of Sierra Gorda and Caracoles, the countless copper mines of the Coastal Mountain Range and the metalliferous chains that lie between this latter and the Andes Mountain Range rising from the central highlands, as well as the operations of the Port of Antofagasta, and so on.

The relatively scarce limestone in Chile, importing almost all the cement it needs from Europe, is present in large deposits on the coast near Antofagasta. Also very close to the sea and the city, along the railway to the very near port of Mejillones, gypsum is abundantly found.

Alum, sodium sulfate, iron sulfate and sodium carbonates are also waiting to be exploited.

I do not dwell on the hematite deposits near the sea, nor on the almost constant presence of gold in the ores of many copper mines in the region.

In contrast to this encouraging context of wealth lying under this truly impressive natural landscape, lies the Chilean capitalists´ indifference to business in the north. Apart from the now customary nitrate business, the lack of roads (barely 1 km every 40 square km) and the total absence of water and driving force.

Pampa salitrera establishments burn no less than 300,000 tons of oil per year. This oil, already expensive since its landing, still has to undergo the railroad transportation costs at a remarkably high rate.

The large Chuquicamata mine, located near the small town of Calama, a station of the Antofagasta Bolivia railroad, imports this way only the oil necessary for the operation of the furnaces and locomotives. While the energy for the electrolytic treatment of the mineral, for the mechanical services of mineral preparation, for the repair shops, for lighting, etc., comes from the power plant of Tocopilla, by the coastline.

To give an idea of the potential of this company, daily production is currently around 300 tons of electrolytic copper bars, for the production of which 500,000 KWh are required. The Tocopilla power plant - comprising four 10,000 KVA turbo-alternators, of which only two are normally in operation - supplies only 2% of this demand.

I believe that this brief example is sufficient to justify the vote that the continuation of the studies that I have fortunately begun at El Tatio will confirm the possibility of installing a powerful geothermal power plant. Whose energy - distributed to the users of the mining companies, the offices of the Pampa salitrera and the distant city- will contribute to the valorization of the great and not fully known resources and natural wealth of the region of Antofagasta.

THE STEAM MANIFESTATIONS OF EL TATIO GEOGRAPHICAL LOCATION

From the chain of the Andes mountain range at the border with Bolivia, at latitude 22°.20 south, a short range of mountains stands out, turning to the west, which takes its name from Cerro Tatio (Monte Quemado, literally translated as "burned mountain"). These mountains are all under the imprint of a volcanic activity that ceased in a quite recent era, geologically speaking, perhaps when the first human inhabitants of that region arrived.

Parallel to the hills of El Tatio, to the west, there is a group of peaks that culminates in the trachytic summit of Copacoya, to the north and with the Tuckle Hills to the south. Being thus delimited and enclosed between them a vast plain sloping slightly to the southwest. In a multitude of slopes scattered throughout the area, the waters of the Salado River are born, which given the relatively flat slope of the plain, in some places at a standstill, and in the center, collecting in many streams, meander to the confluence with the Tatio River.

These springs are all thermal and are accompanied by jets of steam. For this reason, the locality is called "Hoyada de los Géiseres" or "Hollow of Geysers."

In this area of the Salado River watersheds, and on the slopes of the surrounding hills, the concession of the Preliminary Community of El Tatio, established in Antofagasta for the study of an exploitation project of that steam (through a power plant similar to that of Larderello) extends for more than eight kilometers of surface.

As mentioned above, the altitude of the plain where the geysers emerge, which constitutes somehow the central body of the concession, is almost 4,300 m.a.s.l. And the geographical position of the Camp, which, at the foot of the Copacoya hill, dominates for some meters the same plain, is indicated by the coordinates below:

68 1´ 36´´ W. Greenwich longitude
22 20´ 9´´ south latitude

ACCESS ROADS

Let me indicate the distances in a straight line, from El Tatio to the nearest and most important places in relation to potential power lines:

From the Ocean, at the height of Tocopilla	230 km.
From Calama	100 km.
From Antofagasta	350 km.
From San Pedro - F.C.A.B. Station	75 km.
From Chiu Chiu	65 km.
From San Pedro de Atacama	70 km.
From San Bartolo	50 km.
From Tuina La Nueva	70 km.
Caracoles mine	150 km.

To get to the El Tatio concession, leaving from Antofagasta, you can follow the routes below:

With the railroad to Bolivia until Calama Station (238km - 2260 m.a.s.l.) and from there on horseback, for another two days passing through Chiu Chiu (km 33 - 2320 m.a.s.l.) to El Tatio Camp (70 km) passing through las Vegas de Turi and the indigenous village of Toconce where you spend the night.

Leaving Chiu Chiu, instead of going towards las Vegas de Turi, at the foot of Cerro Ayquina, staying a little further south and crossing that small mountain range, you reach the town of Caspana, and the next day El Tatio.

In both cases, the route to travel differs a little in distance and is equally rough. The apparently flat Pampa is unexpectedly divided by deep canyons carved by the streams of the Salado River.

Hidden from the traveler who crosses the Pampa, the indigenous villages of Toconce and Caspana are built on these cliffs of almost always vertical walls.

The construction of a road, easy up to the Cerros de Ayquina, would become virtually impossible a little further on.

If you continue from Calama by rail to San Pedro Station, at the foot of the imposing volcano of the same name, you can reach El Tatio in a day and a half, and by a much better road.

Leaving the San Pedro station (312km from Antofagasta - 3223 m.a.s.l.) through the desert pampa covered with lava fragments, and following the drinking water pipeline next to the road of the same aqueduct, you arrive at the gatehouse just after km 31. Further on you will find the Ayaviri's house in the Inacaliri valley, 48 km from the station. The road crosses the valley and continues along the hills to reach the border with Bolivia in the Silala, where six kilometers after the line, you will find the construction site of the Antofagasta aqueduct dam (58 km from San Pedro).

To reach El Tatio, from the Ayaviri's house, it is advisable to leave the service road of the aqueduct and head on SE to the pass between Cerro Toconce and Apagado. On this stretch, the first cart crossing allows you to get a perfectly practicable trail. And, from there on, to the pampa that extends to the foot of the Linzor.

From the Barranco de la Media Quebrada, which delimits this pampa to the south, the path for the carts had to be painstakingly searched for and built. This one begins, with direction towards the East, to ascend the Media Quebrada, staying on the slopes to the right until surrounding the top for at least four kilometers towards the border, at 4500 meters above sea level. From the top of the Media Quebrada, the direction of the route, in spite of the numerous serpentines, remains definitely towards the south, with a small deviation to the west. Crossing the Cricero pass, at 4550 meters of altitude, the road descends towards the Putungo area. Passes the Hoyalar without the need of a bridge, with a perfectly solid base. And climbs again towards the foot of the Copacoya hill. Joining the ancient road of the Incas that goes from Bolivia, through the Silala pass, to San Pedro de Atacama. A little further on it enters the concession and reaches the camp of El Tatio.

To avoid excessive slopes and civil works, this road has deviated completely from the old road. Starting from the Linzor area, the latter goes through the rocky areas of the Media Quebrada valley. Skirting the Crucero massif to the northeast and east, to reach the hollow which collects the waters of the Hoyalar. From here it leaves by crossing other rocks and ravines that are at the foot of the Copacoya, shortly before reaching the boundary of the concession.

The road used by the carts, from the Linzor area to the camp, is approximately 30 kilometers long, while the distance in a straight line -which is slightly separated from the indigenous people's path- does not exceed 17 kilometers. However, the better conditions of this latter widely compensate the longer distance. To the point that, in case of an emergency, it has been possible to reach the station of San Pedro in just thirteen hours.

The layout of this road is in need of minor improvements. Something that is generally mandatory, given the topographical conditions of the area. Enormously uneven a little above and a little below the narrow area in which it runs. The major drawback, currently, are stretches of sandy terrain that present a serious obstacle to vehicles. However, beyond the fact that a car has already reached El Tatio, it would be advisable to implement, in due course, a rail transport for the machines and material to operate a potential plant.

TOPOGRAPHY AND GEOLOGY

As pointed out above, the heart of the Preliminary Community of El Tatio's concession is formed by the plain where the waters of the Salado River rise and retreat. A plain between the El Tatio chain to the east, the Copacoya and the Tukle Hills to the west. Dominant hills are: Cerro Tatio, 5 450 meters; Cerro Volcán, 5 570 meters; and Copacoya, 4 820 meters. These hills, although they do not appear to be so, are all of volcanic origin. Made up of emissions, lava flows and veins of trachytic, granitic and porphyroid rock. There are also tuffs and breccias. Real mortal remains containing fragments of pumice, which make the imprint of relatively recent eruptions more evident.

The plain is totally white, due to silica incrustations and effluvia of saline essences. Signs of an impressive hydrothermal activity in the past. Which still continues as water emissions, all of them hot, between 25 and 87 degrees Celsius, which flow from countless cracks, cavities and geyser cones. The hottest manifestations naturally emit abundant steam. Either because the water at such an altitude boils between 86 and 87 degrees. Or because the steam of a different deep origin crosses the non-aquiferous zone without condensing, coming from fractures of sufficient size for this phenomenon to occur.

The action of steam and superheated water acidified by carbon dioxide, on the rocks it passes through, determines the alteration. By removing the silicon, which then, on the outside, is deposited again in irregular encrustations materialized on the edges of the basins of boiling water, forming mounds around the outlet cones of the geysers.

The largest geysers belong to a violent phase of activity now extinct. There are some taller than three or four meters, with wide bases, ten meters or more. And craters that are currently invaded by vegetation. Relatively close to collapsing because of the cone itself, which clearly reveals the successive overlying strata, like a mantle that forms it.

Carefully observing these phenomena of alteration of the cones, which have become inactive. Arranged in large circular areas, marked by the chromatic difference and the outline of white slabs of siliceous rock that are barely visible. We can determine the traces of even older geysers, whose detritus have greatly contributed to form the white extension of the Hoyada de los Géiseres.

At points where the feldspar in the rocks has kaolinized, diluted clay permanently fills the cavities. Along with this, little carbon dioxide is observed. And the existing carbon dioxide appears to lack methane or other hydrocarbons.

On the slopes of the Copacoya, a little further up the Hoyada plain, according to two alignments about two hundred meters south of the Camp, there is evidence of steam emissions with the absence of water and two true soffioni: El Tocchi and El Huracán.

Between the ridge of the mountain range and the plain of El Tatio, there are ravines between moraines that allow us to imagine how imposing the glaciers were that covered these high areas of the Andes in the ice age. After the time in which volcanism raised them from the bottom of the Jurassic sea.

At the bottom of these ravines, in East-West correspondence, on the top of Cerro Tatio, there are great manifestations of residual endogenous activity in the "Domeyko", "Reloj", "Pisis" and "Philippi" caves and soffioni.

Volcanism, followed by hydrothermal phenomena that persist, and the disappeared glacier, are the two essential factors that determine the physiognomy of these regions in the current structure.

A fairly detailed description of the most relevant points of the concession is illustrated in the map accompanying this report.

At the foot of Cerro Volcán and the moraine that stands out, going west, is the highest part of the Hoyada de los Géiseres, where you can find the remains of a very old hydrothermal activity revealed by the existence of vast circular areas. Slightly sunken and surrounded by slabs of whitish siliceous rock, porous and very similar to the one that with superimposed layers, models the cones of the geysers still active or recently inactive but still preserving their entire structure.

The observation of these cones with their different degradation stages leads us to clearly view the almost erased remains of ancient geysers in these slabs. Still arranged circularly, and in the accumulation of silica detritus that fill the slight hollow that surrounds them.

In the same upper part of the valley there are also conglomerates and sands of undoubtedly volcanic origin. Cemented by the silicate waters that once flowed, and a kind of siliceous travertine, porous and very light that, I believe, must have been formed by the encrustations of plants whose organic matter has disappeared. Leaving just a few voids of tubular shape, straight and slightly twisted, densely arranged in parallel bundles that make the rock very light.

Cold or barely warm water begins to appear a little further down. Especially in the plain at the foot of Cerro Volcán, in an infinity of small pools linked by small streams. In a terrain formed by lapilli and detritus of the above mentioned siliceous rock. In this true swamp it does not take long for currents to emerge which, joining a little further on, where its bed widens, form the "black lagoon". So called because of the dark color it acquires due to the black algae that proliferate at its bottom. The main arm of the Salado River flows from this lagoon and starts to receive from the right a number of small streams of water flowing in from countless hot springs and geysers of the hollow. While, from the top, to the east of the Hoyada de los Géiseres, they descend very gently. To the north and west, they descend steeply, and at some points with real falls of dozens of meters that reveal the unevenness of the sunken areas. Typical, from this perspective, are the areas of "San Román" and "Campamento".

Cerro Copacoya, on its eastern slope, rises from a flat rocky step covered by fine silica sand. And, in some areas, by blocks, often enormous,

of trachytic rock that emerges from the internal mass, where wind erosion has shaped the most surprising forms of castle towers, monstrous crouching animals and gigantic mushrooms. Precisely along the northern edge of this step, you descend through a chaos of trachyte blocks to the San Roman basin. Sprinkled with hot springs, whose waters, gathered in two streams, flow into the main channel of the Salado, beyond the Black Lagoon. This basin, observed from above, wide open to the south over the Hoyada, gives the impression of a crater filled with materials that have fallen off the edges. The impression is even more vivid when discovering several steam plumes rising, here and there, from boiling water pools. As well as several gravel craters crowning mounds made of mud splashes coming from the bubbles of steam and gas that continually agitate the mud that fills the cavity. And that certainly, although during my stay I did not have the opportunity to verify this, it must overflow through small eruptive paroxysms.

There are more than a hundred vents scattered over a dozen hectares. Of varying diameter, ranging from a dozen meters to a few centimeters. The temperature is not equally high in all of them; there are also some just lukewarm. The material which fills them and which flows, passes from a liquid state to have the consistency of a thick mud like molten fish. Stirred by a movement of large bubbles of steam it produces a noise in some small vents, very similar to a grunting sound, which the indigenous call "chanchos" (pigs).

Towards the southern end of this zone, there appear dips where clean salt water springs from silica-encrusted cavities begin to prevail. And a large cone of an extinct geyser indicates its border. Beyond that point, other salts are diluted, here and there, at the foot of the slope. And the slope of the hill presents, according to an alignment parallel to the horn of the valley, lines of clay soil reddened by iron oxide, with holes and cuts through which steam escapes.

In a small lowland patch, in the middle of a slope between San Román and Campamento, the waters of the Black Lagoon meet. And in front of this point, on the plain, at the foot of the slope, those of the Blue Lagoon. Warm and fed by hot water springs with gas bubbles.

At a short distance from the Blue Lagoon, a cone of an extinct geyser, whose crater is invaded by herbaceous vegetation, marks the beginning of an area full of active manifestations. These are simple fissures, small cones, mounds ending in craters. All embedded in silica, often forming beautiful concretions, which also cover the ground. One must be careful, and realize, in some areas, the fragility of the crust on which the foot rests. Boiling water, in violent agitation, and steam are released from all these eruptive holes, among which "El Toro" and "El Constante" stand out. Separated from each other by about two hundred meters from the Camp; "El Toro" to the North, "El Constante" to the South.

El Toro with a sound comparable to that of a boiler heating through a large pipe, and continuously emitting steam that escapes from cracks of a few centimeters in a pool of almost a meter in diameter, filled with violently boiling water. This is poured out in endless creeks between encrustations deposited by it on the slopes of the wide cone, from which several other mouths emit steam and boiling water.

Instead, El Constante has its silica cone at the center of a large pool a few centimeters deep. With a diameter of about twenty meters that it has built itself with the silica deposited by the water that continuously pours from a jet a few meters high, violently lifted by the steam.

El Toro and El Constante immediately attract the attention of those who arrive at El Tatio from the Copacoya hill. Whoever arrives from Caspana, climbing up the steep slopes of the Salado Canyon, sees to their right the river running between steep hillsides. Broken by fissures from which streams of hot water sprout, and plumes of steam rise. Also on the other bank of the river, similar vapors can be seen rising up in the river bed, near the confluence with the Tatio River, this bank also has some small steam springs in its bed.

Not all these springs are constant, indeed, most of them have paroxysms separated by more or less long intervals of time, during which the water seems to accumulate and gradually heat up in an internal vortex from which it is then violently expelled, accompanied by steam that only falls back down at the end of the eruption.

This intermittency seems to be typical of this area, relatively at low altitude. In the plain, up to the vicinity of El Constante, only a small variation is noticeable. And it cannot be completely excluded that it is a simple appearance. But further down, in the middle of the plain, there is a remarkable example in the geyser that has been justly baptized with the name of "Intermittent". It springs from a crack in the bed of a stream, and does not show anything relevant on the outside for long hours. In its phases of activity, a column of water, foaming but not high, rises from the crack. Letting steam escape in the form of a thick, tall, imposing plume, which can be seen from the camp every morning from eight to nine.

Much less variable, indeed, almost constant, "the Bertrand" in the midst of a plain covered with concretions, between infinite veins of hot water -almost a veil covering the surface- meeting a little further on in a stream which flows to the left into the Salado. It opens into a large basin of boiling water raised in a high foaming dome by the profusely released steam.

The abundant hot and acidic waters, which from time immemorial sprout from many, and some imposing, geysers in the area extending to the east and towards noontime of the "Bertrand", have left descriptive traces of their action on porphyritic pebbles of the moraine through which they made their way. Deep and peculiar corrosions have emptied these pebbles and some thick rocks in such a way that they mislead about their origin that, spontaneously, we could connect with the idea of a real volcanic eruption of rocks and rubble.

Higher up, at the bottom of the ravines, southwest of the Bertrand, the hydrothermal activity reappears in the boiling springs of the "Reloj", "Domeyko", "Pisis" and "Philippi". These last two are close to the origin of the Tatio River, at a fairly high altitude (over 4500 m.a.s.l.) and at a distance of 5 km from the Camp.

The "Pisis" with its crater of more than 5m in diameter, from which steam arises with a loud noise. It is a real soffione that springs from a pool of about twenty meters in diameter, with several steam puffs around it.

Unfortunately, due to its height and relatively difficult access, far from the center of the manifestations, it would be difficult to use it. However, this is a proof of the extension of the area over which the residual volcanic activity of El Tatio unfolds.

In this context, it should be noted that, at the foot of El Tatio itself, on the Bolivian side, there are equally important geysers and hot springs, as the indigenous people have unanimously told me. If circumstances beyond my control had not prevented me from doing so, I would have sent the proposal to extend my exploration beyond the border. However, for obvious political reasons, it would not be possible to think of uniting the two centers of activity in a single business. There is the greatest skepticism about the possibility of exploiting the Bolivian springs with a company per se, given the absolute isolation of the southern province of Lipez, where the Bolivian area of El Tatio is located.

Opposite the Bertrand, in a symmetrical position to it, in relation to the Salado River, we find a narrow valley that branches upwards into two short ravines, with almost vertically cut walls in the trachyte. In correspondence with its peak, two large rock formations with deep vertical divisions that suggest the columnar structure of basalts rise. The slope that descends to the east of this relief of trachyte shows signs of being made up of an incoherent rock, with embedded pumice pebbles, which in my opinion is actually cinerite. Fragments of pumice are also found to the south and north of this point, which would seem, therefore, to correspond to one of the last small homes of the authentic volcanic activity of El Tatio.

Four hundred meters east of the aforementioned trachyte pilasters, high up on the slopes of the hill, steam blows noisily from the six square meter mouth of El Huracán.

If we imagine a direct line to the summit of El Tatio, it would pass through a similar manifestation, located almost at the same height of El Huracán and at the base of its eastern side. It is a small soffione that has been useful mainly for my observations. For this reason, the fiscal surveyor has baptized it with my name.

A worthy-to-mention phenomenon manifested itself there: its volume of steam, as I have explained elsewhere, was very little. After a few days of experiments, in December 1922, due to the weather, outdoors work had to be abandoned and this soffione remained -without being able to vent its steam - under pressure for many weeks. It could then be observed that the steam came out of the iron tube with increasing violence and that the surrounding vegetation was drying up with the gradual increase of ground temperature over an increasingly larger area. There were successive leaks inside the intake chamber and the clear impression of a noticeable increase in its volume. It would seem that the increasing pressure had removed some obstacle to the outflow of steam: water in the fissure from which it was released? This is the hypothesis I have reached by observing a similar phenomenon in the later drilling.

Observing the position of the different manifestations described, it is easy to be convinced of the existence of two directions according to which they are approximately aligned, in an East-West direction the first one and 50° North the second one. These two directions are also repeated in the orientation of the watercourses and in the easily observable soil fractures in the Hoyada de los Géiseres plain. It would not only be a question of two fractures in the directions described and through which the deep steam would make its way. But of two of these systems, it could be observed that, those more eastern in the first case and those southern in the second, correspond to the most ancient manifestations of which, as I have said, only a few traces remain. It is as if in parallel fronts the phenomenon had gradually stopped and, at the same time, decreased in intensity: today we see the most important active slopes at the foot of the ravine that descends from La Hoyada in its western part and also in the Pisis-Huracán line. It would seem, as in the case of the metallic veins, also in this case, that the richest area is represented by many springs located to the south of El Constante with El Intermitente and El Bertrand.

By analogy with other similar manifestations, it seems to me that in the El Tatio phenomena we can observe the late consequences of a very remote and enormous eruption of trachyte, whose fumaroles, having completed the usual cycle, after being strongly acidic and sulfurous, are today predominantly made up of steam. Accompanied by little carbon dioxide, destined in a distant future to remain only as a gaseous component of it, transformed into simple fumaroles and cold gaseous water springs.

CLIMATE

Although the observations had to be carried out with very little material in terms of instruments, the peculiar characteristics of El Tatio's climate can be summarized briefly in the following data.

According to the great altitude and the geographical position (tropical zone) the temperature presents strong variations, especially between day and night. Being much less important those due to the season of the year. I found in my notes temperatures of about ten degrees above zero, in the shade, in the hottest hours of the summer, and temperatures of 10 to 18 degrees below zero at night. The fact that I found geodes with crystallized water in a manganese vein at a depth of one meter, in the vicinity of the camp, leads me to consider an average temperature below zero.

The barometric pressure presents small and slow variations around 458m/m. (reduction made at zero) and with a maximum of 461m/m. in some observations in December to a minimum of 455, in September. The dryness of the air is striking, even to the least observant. And that, together with the effects of altitude, the constant and abundant electrical activity makes the slightest touch and often the simple exposure to the sun, on a rock, of an object of wool or fur enough to have crackling sparks on contact with the hand. It is enough to break a piece of paper for it to stick to the hands and produce flashes and sparks when removed, visible at night.

These phenomena, rarely observable in our climates, are so normal in these parts that the natives marvel at them and consider them an intrinsic quality of some substances.

The crackle and sparkles of a poncho by the simple fact of folding and unfolding it, is for the Indigenous the best proof that it is truly made of vicuña wool.

However, in contrast to what I have mentioned about these electrification phenomena, I have not had occasion to observe, during my stay in El Tatio, exceptional lightning discharges, San Telmo fires, or other similar manifestations. However, I have constantly observed the remains of flares in the rock on the hills of the Copacoya summit and small flares with fusion in bottle-green glass, in some parts of the plain.

Even the few observations made with the hygrometer confirm with numbers this remarkable and constant dryness of the air. Exceptionally, on not very cold mornings, 62 p.100 has been obtained per unit; considering that normally it was 25p. 100.

The wind is remarkably constant. Regularly a cold wind begins to blow at 11 o'clock from the SW, and lasts, intensifying in the afternoon until almost sunset. After a few hours at night the wind wakes up and continues to blow until dawn, in the opposite direction of the day.

In spring and autumn, especially in September, it blows with notable violence, but rarely reaches hurricane speed.

It is worth noting that the direction is perfectly aligned with the position of the peaks and with the direction of the valley. Nights and mornings are normally calm and serene. In the summer and winter months, with the entry of the wind around noon, it becomes cloudy and in the afternoon it rains, snows and hails almost every day. However, the highest precipitations do not occur in winter as shown also by the flow diagram of the Salado River. With only one relevant peak, lasting a few days, in February, which corresponds to a flow rate six times higher than normal.

I have not observed torrential rains or exceptional snowfalls. The maximum height of snow has not exceeded fifty centimeters (May 15th). Based on the comments of the indigenous people of Caspana and Toconce who were with me in the camp and were worried about having to stay there after the first of May, I should deduce that during this 1922 the winter was mild.

STEAM STUDIES

As soon as there was a conviction that a great amount of energy was at stake in the phenomena that occurred in the area of El Tatio, in a considerably larger extension of active terrain in relation to Larderello, it was decided to proceed with a safer and more reliable approach: drilling.

All kinds of setbacks considerably delayed the start of the drilling. Therefore, in order to transport the equipment, it was urgent to study an access road, and the subsequent construction of some thirty kilometers of road in the high mountains. With an upcoming winter season and the justified concern of a paralyzation due to the intense cold and snowfalls of the winter ahead, it was necessary to build well-protected houses and store fuel and supplies.

While waiting for drilling equipment and personnel, the time was used in different ways, according to the possibilities that the weather gave us. With very specific visits to the concession and its surroundings, surveying and sampling, observations and studies on the water and steam.

With a tin funnel about a meter in diameter it was possible to close the mouth of the small soffione on the side of the hill. At the foot of the Copacoya which, as I have mentioned above, was baptized as the "Tocchi" soffione. Its perimeter was appropriately covered with straw and earth. The little steam that came out of the tube was conducted through a small pipe of three quarters of an inch to the device that I had built in Antofagasta for its analysis.

Likewise, as we practiced at home, natural steam is condensed in a copper coil, tin plated on the inside and immersed in a refrigerant. The condensing water is collected in a Wolf bottle, and the gas sucked into brass containers is collected in the same way to be measured at room temperature and pressure.

Without reporting here the results of the specific analyses, it will be sufficient to indicate the average result:

On 100 kg of condensation water, 16.8 liters of gas were collected on average, reduction was carried out at a temperature of zero degrees and at a pressure of 760m/m of mercury; composed of carbon dioxide (98%).

With sufficient approximation, being the p.s. of the carbon dioxide of 0º and 760m/m, 1.98, we can then give, in weight, the composition of the vapor of that soffione.

Steam kg	1000
Gas	0.33

A truly minimal proportion of gas, which would hopefully remain in the steam coming from the boreholes, which is, moreover, very likely.

In the condensation water that presented a slight acid reaction, the sulfur acids were not found. A slight cloudiness of silver nitrate makes me suspect small traces of hydrochloric acid and, with the typical turmeric paper test, almost negative, very small traces of boric acid.

An analysis of the water from the hot springs, carried out with rather rudimentary means, which were the ones I had at my disposal in El Tatio, has yielded on average:

per liter:

crystallized salts	14.60 g
dry amorphous silicon	0.53 g
sand	0,07 g
	______
TOTAL	15.20 g

as dry residue of evaporation

Thus collected, the salt consists almost entirely of chlorides. Boric acid, although in small proportion, is clearly identified either by the turmeric paper test, in the presence of sulfuric acid, or by alcohol flame staining. As a base, sodium is undoubtedly present, perhaps potassium. Calcium and magnesium are practically absent.

In the general description of the concession, I have already pointed out the presence of salt outcrops covering some spots of the Hoyada de los Géiseres soil. In the portion of the plain between the Salado and the streams coming down from the east, in the Bertrand area, these outcrops are particularly abundant. These would be composed of an insoluble part, most likely formed by calcium sulfate and silicon. And a part (the prevailing one) perfectly soluble in water, which turns yellow; treated with alkali, the characteristic white precipitate of aluminum is obtained from this solution. Excluding the presence of chromium and manganese, I have nothing left but iron to explain the yellow coloration that I have pointed out.

Analyzing the acids of the solution, the hydrochloric one prevails together with sulfuric and boric acids. It would seem, therefore, that these outcrops should contain: calcium sulfate, silicon, potassium sulfate, sodium and aluminum, in addition to sodium chloride. For reasons of analogy with what has been verified and can be observed in similar soils, it is possible to think that the soluble sulfates represented by the common alum as well as the boric acid are combined with sodium.

INVESTIGATION WORK

Drilling started with great difficulty at the end of June, at a point very close to the camp where we found indications of small steam emissions that had stopped a long time ago. Crossing a little more than three meters of loose and porous ground, consisting of detritus and slight layers of geyserite, soaked with water, the drill has penetrated a compact and hard rock of trachytic type. This type of rock has constantly remained, until finding small fissures, almost always vertical, from which steam escapes, as shown by a sudden rise in temperature. At forty-eight meters, a higher volume of steam has caused remarkable phenomena that will be interesting to summarize. The temperature has risen to 77 degrees in the part closest to the surface of the water column going into the hole when drilling. The carbonic acid bubbles have become more numerous. Water contained in the hole has begun to come out with an ever powerful jet, from the tube that constitutes the line of the head of the rotating drill rod that we were operating. After a few moments, accompanied by a noise, a first puff of water came out of the borehole in a powerful jet immediately followed by a violent jet about twenty meters high, made up of finely pulverized water and steam, that completely emptied the hole. Once the jet stopped, steam only continued to come out for about twenty minutes and slowly diminished. After about half an hour, the cycle was repeated and so on for about half a day, stopping only when the water accumulated again.

With the presence of water, kept cool by pumping from outside, it was possible to resume work and continue drilling to 50 meters. A portion of the water was then released by the rapid raising and sinking of the drilling rig. The above mentioned phenomena manifested with greater violence and did not stop from that moment on. Increasing to such an extent, according to the news coming from El Tatio, that it was impossible to resume work. Because the successive expulsions of water ceased and gave rise to a continuous flow of steam.

After analyzing these phenomena, we are convinced of the deep origin of the steam and the infiltration of cold water into the upper strata of the ground, of a porous nature, as we have seen.

After a violent expulsion of water by cooling, also due to expansion, the dripping of this cold water into the well was enough to condense the still scarce steam, which escapes from the fissures at the bottom and walls. A column of water is thus formed, fast and sufficient to contain, with its hydrostatic pressure, the steam that, from that moment, stops coming out of the mouth of the drill pipe. But, in contact with the hot walls, also heated by the steam that is condensing, the water that enters eventually reaches boiling temperature and then begins to move due to the unfolding steam bubbles. Causing a tendency for the entire column to rise, accompanied by the ever-increasing thrust of the steam, which accumulates at the bottom. At one point, when the water reaches the height of the outer hole, a first overflow occurs and then a sudden decrease in weight of the column, contrasting the pressure of the steam, which then takes advantage and violently throws out, at great height, as we have seen, the little that remained. We are then in the same initial conditions, and the phenomenon of alternate emissions of steam and water continues, regulated - by the time that goes by between one phase and the other - according to the ratio of water and steam. With the continuation of drilling up to a certain point, with sufficient quantity of steam, the steam will mechanically drag the little water, when entering the borehole, thereby preventing its accumulation. Leaving without effect the cause of the regular interruptions of its flow. It is also worth mentioning that with the increase of steam, sufficient pressure is produced inside the borehole to expel the water from the fissures through which it makes its way, given the small load. I left El Tatio on September 23th recommending the continuation of the drilling started until reaching a depth of a hundred meters, giving the instructions for other wells in the area of Tocchi and Bertrand.

I also gave the necessary instructions so that temperature and pressure measurements could be reported to me, so I could calculate its volume. The first borehole was at that time 50 meters deep and showed the phenomena that I detailed above, but it was still far from representing a satisfactory volume.

The same measurement could not have been made with our Larderello methods given the abrupt variations in pressure, due, as I have mentioned, to the presence of water. A telegram that I received later, while I was still in Antofagasta waiting for the ship to take me home, announced an considerably increased flow and the continuity of the steam jet, which is why the driller requested to start drilling a second well. Very recent news informs us that this second well has reached a temperature of 80° C in the first 20 meters and leads us to hope for an imminent steam release.

But beyond the news on the presence of steam, whose existence I do not doubt at all, I hope to receive numerical data to make, at least, high-level estimates of the steam actually exploitable in certain conditions of temperature and pressure.

ESTIMATION OF AVAILABLE ENERGY

Given the impossibility of conducting an effective evaluation of the amount of steam available and practically exploitable, until drilling allows us to make flow measurements and also to collect new data on temperatures and chemical composition of the deep source steam (temperature, certainly above the 87 and 90° observed so far; composition, most likely similar to that already tested). We should focus on estimates suggested by the spectacular aspect of the phenomenon. Because of the extension of the active terrain which is at least five times that of Larderello. And, finally, from a general evaluation of the energy currently distributed in the heating of the Salado River waters, which come from the snows of the surrounding mountains, at a temperature close to zero degree. These waters are heated by the steam that rises from the deep volcanic magma, up to the 20° that they have at the mouth of the Hoyada. To these twenty degrees of heating of the 500 liters of stream of the Salado, correspond 10,000 calories and by the mechanical equivalence of the heat (425 kilograms per calorie), a theoretical power of 57,000 C.P.

On another occasion, when I had to turn my impressions of El Tatio into figures for a business person, I pointed out the possibility of installing a 50,000 kW power plant. I also stated, as I still maintain based on the aforementioned features, that such power is perfectly achievable. As long as the continuation of very well executed drilling works confirms the feasibility of obtaining steam under the desired conditions of temperature and chemical composition.

Signed, Engineer Ettore Tocchi
Castiglioncello, January 1923

Various authors, *Mesa de Geotermia: Rol de la geotermia en el desarrollo de la matriz energética chilena.* Santiago de Chile, Centro de Energía de la Universidad de Chile y Fundación Chile. Final report to the Ministry of Energy (July 2018)

Bona P. & Coviello M.F., *Valoración y gobernanza de los proyectos geotérmicos en América del Sur: Una propuesta metodológica.* Santiago de Chile, CEPAL (2016)

Bringhenti P., De Leva M., *Producción de energía eléctrica con fuerzas endógenas del Tatio (Antofagasta).* Santiago de Chile, Mining Bulletin of the Sociedad Nacional de Minería 581 pp. 502-509 (September 1948)

Cappetti, Guido, *Sviluppi tecnologici e strategie per la coltivazione dei campi geotermici: l'esempio di Larderello.* Pisa, Enel Generazione ed Energy Management - Produzione Geotermica (April 2006)

Cattaldi, Raffaele, *De la celebración del centenario de la industria geotermoeléctrica al desarrollo de la energía geotérmica en Italia en el siglo XXI.* Geotermia/Revista Mexicana de Geoenergía, Vol. 19 (July - December 2006)

Cattaldi R., Suárez M., *Our Geothermal Legacy: A Historic Overview.* Melbourne (Australia), paper adapted for the World Geothermal Congress 2015

Contini, Remo, *Missione in Cile.* Revista Larderello/Rassegna di Studi e di Attivitá Aziendali, n°3, (May-June 1960)

De la Paz Mellado, Verónica, *Energía geotérmica: principales usos; ejemplos de incentivos para su desarrollo.* Valparaíso, Asesoría Técnica Parlamentaria (December 2019)

Dickson, Mary H. y Fanelli, Mario, *Renewable energy.* Londres, Routledge (2011)

El Mercurio de Antofagasta, *Riqueza colosal.* Interview with Ettore Tocchi (edition November 3, 1921)

El Mercurio de Antofagasta, *Comunidad Preliminar del Tatio.* Sobre informe de Ettore Tocchi a la Comunidad Preliminar del Tatio (edition December 16, 1921)

Grebe, María E. e Hidalgo, Blas, *Simbolismo atacameño: un aporte etnológico a la comprensión de significados culturales.* Santiago de Chile, Revista Chilena de Antropología n°7, 75-97, Universidad de Chile (1988)

Huttrer, Gerald W., *Geothermal Power Generation in the World 2015-2020 Update Report.* Paper presented at the World Geothermal Congress 2020

Morata D., Aravena D., Lahsen A., Muñoz M y Valdenegro P., *Chile Update: The First South American Geothermal Power Plant After One Century of Exploration.* Paper presented at the World Geothermal Congress 2020

Recabarren Rojas, Juan F., *Episodios de la vida regional.* Antofagasta, Ediciones Universitarias Universidad Católica del Norte (2002)

Suárez Arriaga, Mario, *A Short Story of the Long Relationship Between The Human Race and Geothermal Phenomena.* Antalya (Turkey), World Geothermal Congress 2005

Tocchi, Ettore, *Il Tatio.* Castiglioncello (Livorno), Informe para Larderello S.p.A., Ufficio Geologico (January 1923)

Tuck, F.E.N., *The Utilisation of Thermal Steam at Larderello, Italy.* Report for the New Zealand Geological Survey (December 1944)

Unione Geotermica Italiana, *La Geotermia: Ieri, Oggi, Domani/Geothermal Energy: Yesterday, Today, Tomorrrow.* Pisa, Edizioni ETS (second edition, November 2007)


enel
PROCULTURA
FUNDACIÓN
Biblioteca Nacional
de Chile
Ministerio de las Culturas, las Artes y el Patrimonio
Gobierno de Chile
PROYECTO ACOGIDO
LEY DE
DONACIONES
CULTURALES