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Chile Up-Date: The First South American Geothermal Power Plant After One Century of Exploration

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ABSTRACT

The first formal geothermal exploration campaign in South America (one of the firsts in the world), was launched at the early beginning of the twentieth century in the high Andean Mountain Range of northern Chile. Since that romantic time, different methods to promote geothermal energy have been applied, most of them have failed to develop a generation plant. Moreover, in several world geothermal congresses organized on this XXI century, Chile (and the high Andean Mountain Range, in a more generic sense) has been presented as one of the biggest unexploited geothermal provinces in the world. Chile's geological conditions, placed on one of the most active subduction zones and with the highest concentration of active volcanoes, are evidence of the huge geothermal potential existing in the Chilean Andes. It wasn't until late 2017 that Chile crossed the expectation phase and finally entered the geothermal club. Cerro Pabellón, the first geothermal power plant in Chile (and South America) began its operation at the altitude of the high Andean Mountain Range (4500 m a.s.l.) through Geotérmica Del Norte (GDN), a joint venture between Enel Green Power and Empresa Nacional del Petróleo (ENAP). 48 MWe are currently in production, with a plan to expand its capacity with an additional 33 MWe during 2019. By 2020 Chile will have a total geothermal capacity installed of 81 MWe in the first South American power plant.

In addition to this breakthrough, during the last years, strong efforts were conducted to increase geothermal direct use in the country, for heating spaces, greenhouses, wine industry, and some other productive sectors. In this context, the remarkable role played by the Andean Geothermal Center of Excellence (CEGA) has been significant in this direct use revolution. This geothermal research center has been granted with different funds from public institutions aimed to develop pilot projects, which are the first local experiences of this technology in each region of the country. These projects have been co-designed with the final users: school communities, farmers, or indigenous villages.

Regarding government stakeholders, important advances were made during 2017 on the base of the "Geothermal round table", a public-private initiative supported by the Ministry of Energy and funded by the Global Bank. After one year of working sessions, the estimation of potential geothermal development by 2050 would range between 1300 MWe and 3800 MWe, with a total investment between US$ 9-25 billion. This adds to the compromise acquired by Chile in 2017 to reduce coal-based thermoelectric power plants until they disappear completely from the energy matrix by 2050. This commitment opens an extraordinary window, as defined in the "Energy roadmap" presented by the government, for the definitive development of geothermal energy in Chile and the rest of South American countries.

1. INTRODUCTION

The first formal geothermal exploration campaign in South America (one of the firsts in the world), was launched at the early beginning of the twentieth century in the high Andean Mountain Range of northern Chile. Since that romantic time, different methods to promote geothermal energy have been applied, most of them have failed to develop a generation plant. At the end of the 60s and early 70s, several production wells were drilled by the national geothermal company (closed operations in 2010?) in El Tatio-La Torta geothermal field. These initiatives were shut down in the mid-70s, initiating a time gap in Chilean geothermal exploration. Moreover, in several past world geothermal congresses and even on the last one hosted in Melbourne (Australia, 2015), Chile (and the Andean Mountain Range, in a more generic sense) was presented as one of the largest undeveloped and unexploited geothermal provinces in the world (see Bertani, 2015, 2016 and Lahsen *et al.*, 2015 and references therein). Chile's geological conditions, placed on one of the most active subduction zones, with the highest concentration of active volcanoes under the continental crust, allow to effectively remark the huge geothermal potential existing in the Andes. Nevertheless, it wasn't until late 2017 that Chile crossed from the expectation phase and finally entered the geothermal club. Cerro Pabellón, the first geothermal power plant in Chile (and South America) began its operation through Geotérmica del Norte (GDN), a joint venture between Enel Green Power and Empresa Nacional del Petróleo (ENAP) in the altitude (4500 m a.s.l.) of the High Andean Mountain. 48 MWe are currently in production, with a plan to expand its capacity with an additional 33 MWe during 2019-2020 (Cappetti *et al*., 2020). This first geothermal power plant installed in South America opens an optimistic window for the geothermal development in the single continent that in 2015 was still lacking electricity generation using geothermal energy. This new scenario for geothermal energy in Chile is the consequence of several economic and political efforts. In 2000, the Chilean government passed the "Chilean Geothermal Law (law 19.657)" allowing private developers to explore and exploit geothermal energy. During the first decade of the XXI century, up to 14 private companies were exploring for geothermal resources in the Chilean Andean Mountain Range (see Lahsen *et al*., 2015). However, a dramatic decrease in the electricity prices in Chile combined with unsuccessful geothermal exploration programs and the strong entry of solar energy in the Chilean electricity market, resulted in a progressive reduction of companies exploring for electricity generation using geothermal energy. In this context, a pessimistic feeling prevailed in Chile among geothermal energy advocates. In fact, between 2015 and 2017, geothermal exploration in Chile was reduced to the minimum

expression. Meanwhile, solar energy strongly increased moving Chile to a renewable scenario with a lower dependence on fossil fuels.

However, new changes in the Chilean energy policy promoted that, by the end of 2017, a new optimistic window for geothermal development could open. Along with the starting production of the first South American geothermal power plant (November 2017), Chile declared a new policy for energy generation, pointing to a 100% renewable matrix by 2050, moving progressively towards a coal-free country. This new scenario could imply an opportunity for the increase of geothermal energy in Chile because it must be an important player in the future 2050-electricity matrix dominated by renewable energies. The total electricity capacity installed in Chile increased up to 23.590 MWe during the last decade (Table 1), with almost 50% dominated by fossil fuels (12.723 MWe, coal, oil and natural gas). These energy resources are practically non-existent in our country, and thus, they have to be imported. Among these, close to 5.000 MWe rely on coal-burning in thermoelectric power plants. This capacity must be replaced by renewable sources before 2050, opening the opportunity for geothermal energy to occupy a leading role in the future 100% renewable matrix.

2. GEOLOGY BACKGROUND

It is well known that geothermal resources in Chile (and the rest of the Andean countries) are in a strong spatial and genetic relationship with the active volcanism. This volcanism is mainly controlled by the almost continuous subduction of the Nazca Plate under continental South American Plate, present since Jurassic times (see Lahsen *et al*., 2015 and references therein). The nature and distribution of recent volcanism in this huge volcanic province is mainly controlled by the dip and morphology of the Benioff zone, dividing the Chilean Andean Volcanic Zone in Northern, Central-South and Austral Volcanic Zones. This distribution of active volcanism also controls the two main Chilean geothermal-volcanic zones that were previously defined: the Northern Geothermal Zone (17ºS – 28ºS) and the Central-Southern Geothermal Zone (33ºS – 46ºS), both in the high Andean Mountain Range, where high-temperature spring areas and other surface manifestations are present (Figure 1).

The perfect combination of active magmatism along the Andean Mountain Range with various areas of high permeability (mostly fault-controlled), allows Mountain Range to classify the Chilean Andean Mountain Range as a set of extended convective geothermal play-type provinces (following the Moeck's 2014 classification). Together with this active magmatism, a strong structural control for geothermal activity has been recently proposed for both the Northern Geothermal Zone (Veloso *et al.*, 2019) and the Central-Southern Geothermal Zone (Sánchez-Alfaro *et al*.,2013; Tardani *et al*., 2016; Pérez-Flores *et al*., 2017; Roquer *et al*., 2017; Wrage *et al.*, 2017). The perfect alignment of continuous heat sources (related with volcanism and surficial magmatic bodies) with the intersection of main fault systems are the ultimate controls of both medium- as high-enthalpy geothermal systems.

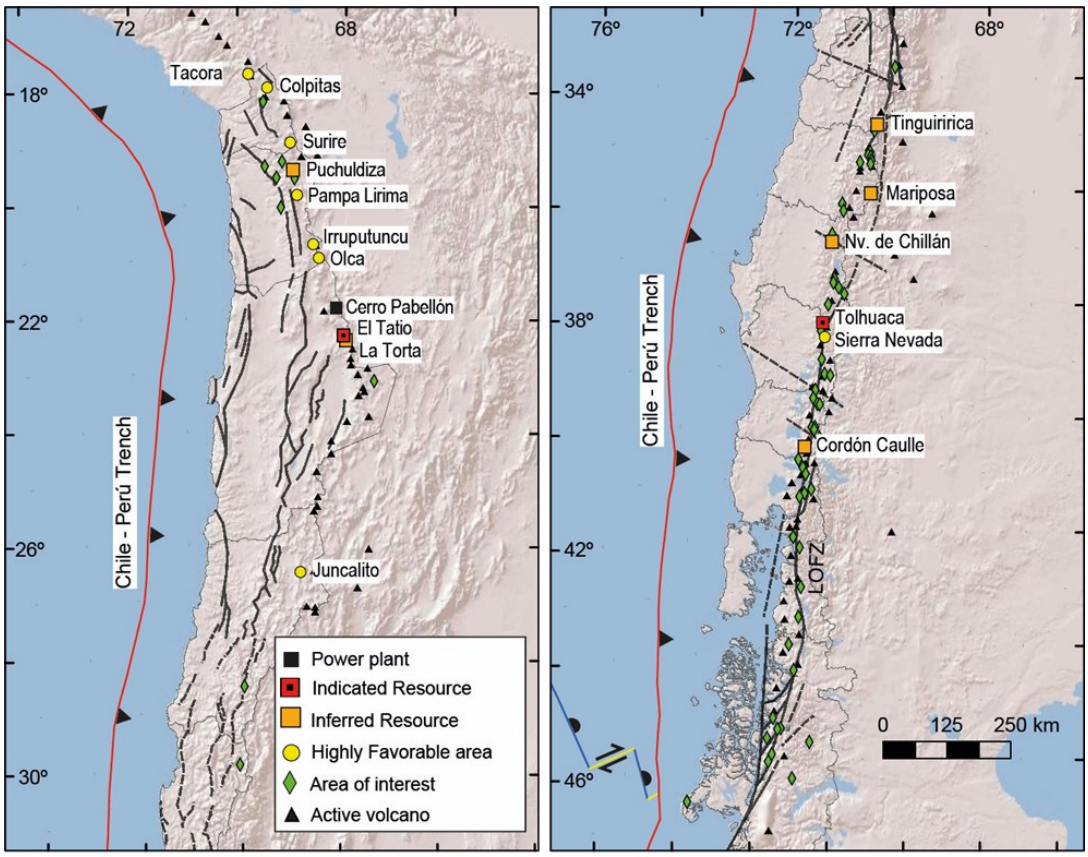

Figure 1: Active volcanism and location of the more developed geothermal fields (after Aravena et al., 2016).

On the contrary, low-temperature geothermal systems are present all along with the country. A new exploration strategy was proposed in Muñoz *et al* (2015), analyzing the heat favorability in sedimentary basins along the Central Valley (where most of the principal Chilean cities are located) and indicating the most promising areas for direct use with geothermal heat pumps. These estimations were based on comparison of soil thermal properties and hydrogeological parameters, showing the zonation of cities with the best heating systems and analyzing the main barriers for using this methodology (See Aravena et al., 2020).

3. GEOTHERMAL RESOURCES AND POTENTIAL

During the last five years, and after the WGC2015 Chilean country up-date, geothermal exploration has dramatically decreased, even though by November 2017 the first geothermal power plant was finally installed. In our reported document in 2015, fourteen private companies were actively exploring 74 geothermal concession areas. In addition, 8 areas were commissioned for exploitation, and 76 geothermal areas were waiting for the final acceptation from the Ministry of Energy for exploration (56 licenses) and exploitation (20 licenses). Different exploration activities were performed, with 12 exploration drill wells conducted and 6 production wells drilled (see Lahsen *et al*., 2015). It was a real "geothermal gold fever". However, this scenario radically changed in these last five years. By mid-2019, the Chilean geothermal activity was very limited and only two to three geothermal companies are active: Geotérmica del Norte (GDN), the joint venture company exploiting Cerro Pabellón power plant; Transmark, the Netherlands company exploring the Peumayén concession (ex Tolhuaca); and the Philippine Energy Development Corporation (EDC), which is currently in a stand-by period with Mariposas concession. These three companies conform, on the other hand, the Chilean Geothermal Council.

By march of 2018, only 9 exploration licenses are active with 12 exploitation areas in force. This new scenario is very different from previous ones reported along with the Chilean geothermal history. The reason for this decreasing activity is mainly due to economic barriers and not the absence of geothermal reservoirs. In fact, Lahsen (1986, 1988) estimated the presence of more than 300 geothermal areas associated with Quaternary volcanism, with a potential estimation in the order of 16,000 MWe for at least 50 years from geothermal fluids with temperatures above 150ºC, located at depths lesser than 3000 m. The Chilean Geothermal Council estimated in 2012-2013 that the potential of the 18 most developed and explored geothermal fields could range between 1000 and 2440 MWe. Aravena *et al*. (2016), based on reservoir temperature and volume (Heat in Place and decompression methods), assess geothermal power potential in nine well-identified high enthalpy geothermal areas in the Chilean Andes, obtaining a total value of 659 ± 439 MWe MW among medium (6) and large (3) systems. Moreover, these authors outline the existence of at least a set of 65 favorable geothermal areas proposed as the most likely future development targets. Finally, the "Mesa de Geotermia" (Geothermal Round Table) report was presented in 2018 by the Chilean Ministry of Energy, together with developers, private companies and the academia, and supported by the World Bank. This is the most realistic document about the geothermal potential, reservoir estimation, and cost for geothermal development in Chile. The main conclusions of this collaborative work outline a total of 599 MWe that could be incorporated to the electricity matrix by 2030, and an additional 1487 MWe during the period between 2030 and 2050 (Figure 2). Following these estimations (based on the real declared potential of the most developed and explored Chilean geothermal fields), a total of 2000 MWe could be in operation along Chile if economic barriers (mostly very low electricity price) were to be addressed.

Currently, the more promissory exploitation concessions are:

- Cerro Pabellón geothermal field (Northern Chile). This power plant, developed by GDN, comprises two twin binary units (ORC) with a total installed capacity of 48 MWe. It has been full running since November 2017, and it is planned to incorporate additional 33 MWe with the same ORC system, scheduled to start in the second half of 2019 (see Cappetti *et al*., 2020 for a complete and detailed summary of this project).
- Mariposas (central Chile), in exploration stage by EDC and an inferred capacity of 160 MWe.
- Peumayén (Southern Chile), the ex-Tolhuaca concession and currently licensed to Transmark company with an inferred capacity of 70 MWe to be developed.

To this day, all the previous concessions reported by Lahsen *et al*. (2015) are in a stand-by (or frozen) situation, waiting for better economic signals and/or the establishment of public policies aimed to guarantee electricity support. This would enhance the plan proposed for 2050 to transit to a coal-free economy.

4. CHILEAN ELECTRICITY MARKET

The Chilean electricity market is controlled by a few private companies, where the State only works as a regulatory entity. Different laws and institutions, mainly controlled by the Ministry of Energy, control the accomplishment of production, transmission, and distribution of electricity along with the country. During the last two years, the total electricity distribution has been finally interconnected, and only the Aysén and Magallanes regions (Southern Patagonia) remain disconnected from the national grid, with their own small local production.

The total installed capacity, according to data provided by the Ministry of Energy, is 23.590 MWe (Table 1), with 12.373 MWe being produced using fossil fuels (coal, natural gas, and oil). The vast majority of these resources is imported from overseas. Renewable energies account for the other 50% of the electricity matrix, which is dominated by hydropower and followed by the huge increase in solar energy production (photovoltaic). In fact, the extraordinary increase of the locally called non-conventional renewable energies (*Energías Renovables No Convencionales* or ERNC) including solar, wind, mini-hydro (< 20 MWe), biomass and geothermal, has been noticed by the international markets. By 2007 these ERNC accounted for just 2% of the matrix, while by 2019, it adds up to close to 20% of the total energy matrix. This extraordinary change has been motivated by the abrupt irruption of solar technologies at very low and competitive prices, favored by the extremely high solar radiation in the Atacama Desert (the aridest desert in the world). In 2014, only three solar electricity plants were installed, with a total capacity of 144 MWe. By 2019, the total installed capacity arises to 2.402 MWe, with the expectation to increase up to 4.000 MWe by 2020. Geothermal energy, with the first 48 MWe installed in Chile (and the rest of South America), accounts for only 0.2% of the total installed capacity. The projections of geothermal energy are to increase in an additional 33 MWe (with the expansion of Cerro Pabellón power plant) by the end of 2019, achieving an effective total installed capacity of 81 MWe. Regarding the beginning of the exploitation of the Peumayén geothermal field (ex-Tolhuaca), another 50 MWe could be operating by 2020, achieving a total installed capacity of 131 MWe.

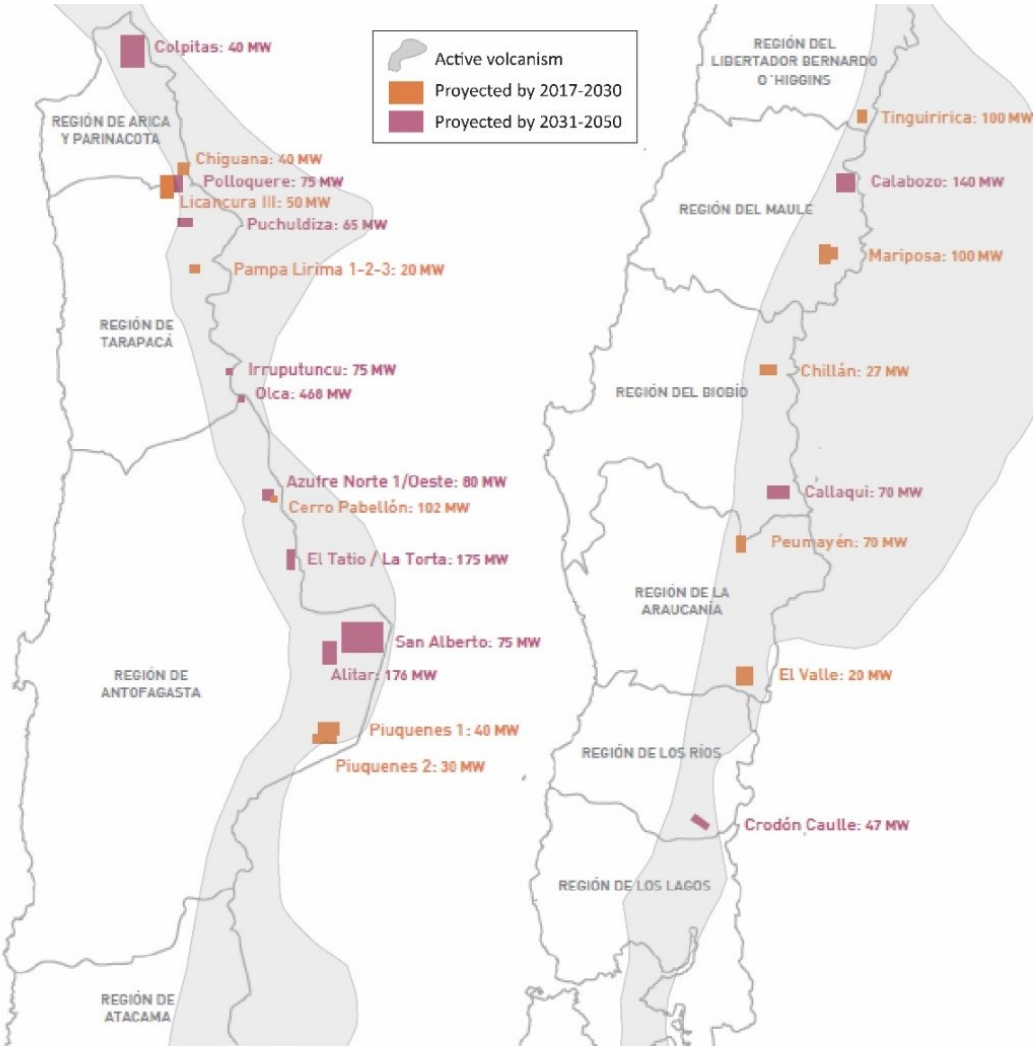

Figure 2: Geothermal areas with potential to be incorporated in the Chilean energy matrix in the period 2030-2050 (After Mesa de Geotermia report, 2018).

There are two other small electrical distributions systems in Chile; the Aysén and Magallanes systems in the southern extreme of the country. The first one has an installed capacity of 59 MWe (hydropower 35.6%, thermal power 57.6% and wind power 6.8%), while the Magallanes System has an installed capacity of 121 MWe, (natural gas 82.6%, diesel 14.9% and 3.5% wind power).

However, future developments could favor the increase of geothermal energy in the Chilean market. Chile aims to be a neutral coal economy by 2050, with an electricity matrix composed 100% by renewable energies. Considering the climate change phenomenon, the unpredictable global scenario of the near future will force the Chilean state to implement public policies aimed to assure electricity independence. In a coal-free matrix, proposed for 2050, geothermal energy could ensure the necessary energy baseload. Moreover, the possibility of implement hybrid (solar & geothermal) power plants in Northern Chile could also open a new opportunity for the final input of geothermal energy in Chile.

5. GEOTHERMAL UTILISATION

5.1 Electricity power installation and generation

In November 2017, the first geothermal power plant in Chile initiated its operations: the Cerro Pabellón power plant (Figure 3), a two binary units system with a total installed capacity of 48 MWe (Table 2).

A total of 13 wells were drilled during the exploration and development phases. These drilling works took place in the Pampa Apacheta graben, at 4.500 m.a.s.l. and 120 km away of the Calama city, in the Antofagasta Region of northern Chile. At present, 6 production and 4 reinjection wells are connected in the power plant (Cappetti *et al*., 2020). This power plant has the capacity to provide electricity to an equivalent of 165.000 houses, saving CO_2 emissions for a total of 166.000 tons/year.

The Cerro Pabellón geothermal field, located in a extensional NW-SE oriented graben (Rivera *et al*., 2020), could be defined as a blind geothermal system characterized by a thick clay cap and almost zero surface thermal manifestations (Maza *et al.*, 2018; Taussi *et al*., 2019; Cappetti *et al.*, 2020; Morata *et al*., 2020).

Table 1. Present and planned production of Chilean electricity. Data source: Ministry of Energy (Chile) except for geothermal energy, with data provided directly from companies (Geotérmica del Norte for Cerro Pabellón and Transmark for Peumayén geothermal fields)

	Geothermal		Fossil Fuels		Hydro		Nuclear		Other Renewables (solar+wind+biomass)		Total	
	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr
In operation in December 2019	48	400	12.373	41.209	6.698	23.144	0	0	4.471	11.074	23.590	75.827
Under construction in December 2019	33	270	688		1.062		0	0	1.243		3.026	270
Funds committed, but not yet under construction in December 2019	50	394	5.920		1.220		0	0	22.190		29.380	394
Estimated total projected use by 2020	131	670	13.464	24.327	7.520	38.267	0	0	7.478	18.403	28.593	81.667

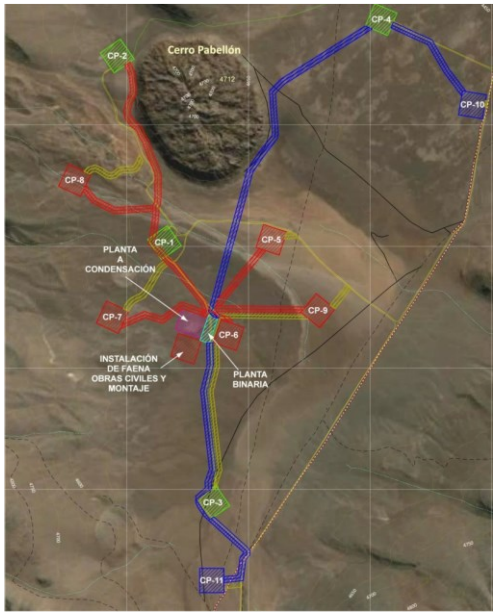



Figure 3: Aerial view of the Cerro Pabellón geothermal power plant with the location of production and reinjection wells and pipelines settings. The graben is sealed by the 50-70 ky old dacitic Cerro Pabellón dome. Photographs source: Geotérmica del Norte (GDN).

Table 2. Utilization of geothermal energy for electric power generation as of 31 December 2019

Locality	Power Plant Name	Year Com-missioned	No. of Units	Status[1)]	Type of Unit[2)]	Total Installed Capacity MWe[3)]	Total Running Capacity MWe[4)]	Annual Energy Produced 2019 GWh/yr	Total under Constr. or Planned MWe
Chile, II Region, 120 km NO Cala	Cerro Pabellón 1&2	2017	2		B	48	48	400	33
Total			2			48	48	400	33

Legend: (1) N = Not operating (temporary), R = Retired. Otherwise leave blank if presently operating.

(2) 1F = Single Flash; 2F = Double Flash; 3F = Triple Flash; D = Dry Steam. B = Binary (Ranking Cycle); H = Hybrid (explain); O = other (please specify).

(3) Electrical installed capacity in 2019

(4) Electrical capacity actually up and running in 2019.

5.2 Direct use

As in the rest of Andean countries, Chilean geothermal resources have been traditionally used for recreational and touristic purposes. A plethora of thermal spring resorts and Spas are distributed along with the country, whilst some of them are equipped with sophisticate touristic infrastructure others to have a rather rustic display. The total heat capacity estimated for the main thermal springs arises up to 14.68 MWt, which equals an annual energy use of 228.91 TJ/yr (Table 3). The majority of these thermal springs use geothermal energy only for bathing and swimming. The only two cases known for using geothermal energy for touristic heating cabins or the hotel installations are the Centro Termal Armada Liquiñe (Los Rios region) and the Puyuhuapi Lodge (Aysén region).

In most cases, the thermal water is collected from natural hot springs and then piped to buildings and pools. Only very few spas have shallow wells drilled to extract the hot water underneath. Generally, information on private investment for direct utilization projects is difficult to obtain and, consequently, data on Table 3 must be considered as minimum values.

On the other hand, the use of geothermal heat pumps in Chile began in 1996. Since then, a notable increase in installed heat pumps with respect to the 8.6 MWt reported in the WGC2015 has been achieved (Table 4). During 2015, and supported with funds from the World Bank, the Ministry of Energy licensed a study to establish the present-day status of geothermal heat pumps in Chile. This study identified 29 projects using geothermal heat pumps (Harfagard *et al.*, 2016), mostly in the Metropolitan and Bío-Bío regions, with a total power capacity of 6.9 MWt. A notable increase in private companies offering heat pump services is highlighted in this study. Moreover, CEGA has followed the survey of the different geothermal heat pumps systems installed in the country. Our results suggest that, to this day, at least 8 MWt are installed in different regions of Chile. We are convinced that this reported value must also be considered as a minimum because several institutions/companies (with installed heat pumps) did not answer our questioner when the report was being developed. Water source (well or lake water) and horizontal closed-loop systems are the predominant heat caption methods, but some vertical, closed-loop, as well as one pond loop systems, were also reported. It is remarkable that the new heat pump systems are being installed in edifications with different purposes. Such buildings, for instance, are the two public hospitals in the cities of Rancagua and Talca. Also, educational institutions have included this technology for space heating purposes (Liceo San Javier in Puerto Montt, Voipir de Ñancul in Villarrica and Altos del MacKay in Coyhaique, among others). Finally, different industrial uses in aquaculture, greenhouses, and wine industry have included the use of geothermal heat pumps, mainly due to its high efficiency. All these new public and private installations have provided the basis for a bigger development of geothermal heat pump systems in the near future.

Another important change with respect to the 2015 report is the newly proposed modification of the Chilean law for geothermal development (nº19.657). The new law aims to promote geothermal direct use in Chile, reducing (or even removing) some administrative barriers favoring the quick installation and implementation of several direct use initiatives under a regulated scenario. This new law is expected to be in discussion in the Chilean parliament during the second semester of 2019. Moreover, additional funds from the World Bank and the Development Interamerican Bank (*Banco Interamericano del Desarrollo* or BID) were provided. These funds aimed to mitigate the geothermal risk, promoting the geothermal direct use in Chile.

From 2016 to 2018, two pilot projects with geothermal heat pumps were developed by CEGA. These two initiatives, located in Southern Chile (Aysén), aimed to show the benefits of geothermal direct use. In addition, these projects have shown how the use of geothermal heat pumps could improve the life quality of different communities. One of these pilot projects is a geothermal greenhouse in Puerto Aysén, where the extreme weather conditions did not allow for crops to grow during the winter season. With the new system, the greenhouse operators are able to grow and harvest crops year-round. The other project is a heating system for a public school in Coyhaique, which has been qualified as one of the most polluted cities in South America, due to wood burning-based heating systems in the vast majority of houses. Both projects were internationally recognized by the GeoLac organization (http://www.cega-uchile.cl/noticias/latinoamerica-premia-al-cega-por-calefaccion-geotermica-en-liceo-patagonico/).

Table 3. Utilization of geothermal energy for direct heat as of 31 December 2019 (other than heat pumps).

[1] I = Industrial process heat; H = Individual space heating (other than heat pumps)
C = Air conditioning (cooling); D = District heating (other than heat pumps)
A = Agricultural drying (grain, fruit, vegetables); B = Bathing and swimming (including balneology)
F = Fish farming; G = Greenhouse and soil heating
K = Animal farming; O = Other (please specify by footnote)
S = Snow melting

[2] Enthalpy information is given only if there is steam or two-phase flow

[3] Capacity (MWt) = Max. flow rate (kg/s)[inlet temp. (°C) - outlet temp. (°C)] x 0.004184 (MW = 10^6 W)
or = Max. flow rate (kg/s)[inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg)] x 0.001

[4] Energy use (TJ/yr) = Ave. flow rate (kg/s) x [inlet temp. (°C) - outlet temp. (°C)] x 0.1319 (TJ = 10^{12} J)
or = Ave. flow rate (kg/s) x [inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg)] x 0.03154

[5] Capacity factor = [Annual Energy Use (TJ/yr)/Capacity (MWt)] x 0.03171
Note: the capacity factor must be less than or equal to 1.00 and is usually less, since projects do not operate at 100% of capacity all year.

Note: please report all numbers to three significant figures.

Locality	Type[1]	Maximum Utilization					Capacity[3]	Annual Utilization		
		Flow Rate	Temperature (°C)		Enthalpy[2] (kJ/kg)			Ave. Flow	Energy[4]	Capacity
		(kg/s)	Inlet	Outlet	Inlet	Outlet	(MWt)	(kg/s)	(TJ/yr)	Factor[5]
Mamiña	B	2,7	51	28			0,26	1,90	5,76	0,70
Pica	B	2,3	34	26			0,08	1,60	1,69	0,70
Socos	B	3,2	30	22			0,11	2,56	2,70	0,80
Colina	B	7,3	50	24			0,79	5,62	19,27	0,77
Cauquenes	B	2,8	45	30			0,18	1,80	3,56	0,64
El Flaco	B	7	76	45			0,91	3,60	14,72	0,51
Panimavida	B	1,8	32	25			0,05	1,40	1,29	0,78
Chillán	B	15,2	65	45			1,27	7,80	20,58	0,51
Tolhuaca	B	4,6	61	45			0,31	2,70	5,70	0,59
Manzanar	B	6,9	48	35			0,38	1,90	3,26	0,28
Huife	B	8,2	52	40			0,41	2,10	3,32	0,26
Minetué	B	2,6	41	30			0,12	1,30	1,89	0,50
San Luis	B	0,8	40	28			0,04	0,60	0,95	0,75
Palguín	B	2,9	39	28			0,13	1,80	2,61	0,62
Geométricas	B	10	77	40			1,55	5,00	24,40	0,50
Vergara	B	0,5	40	35			0,01	0,50	0,33	1,00
Cofré	B	0,5	41	30			0,02	0,50	0,73	1,00
Rincon	B	1	38	30			0,03	1,00	1,06	1,00
Coñaripe	B	6,5	64	40			0,65	1,30	4,12	0,20
Rayen Co	B	2	62	40			0,18	1,20	3,48	0,60
Liquiñe	B	13,6	46	35			0,63	3,20	4,64	0,24
Armada	H-B	2	73	40			0,28	1,00	4,35	0,50
Hipólito Muñoz	B	10	78	40			1,59	7,00	35,09	0,70
Quilalelfu	B	0,2	66	35			0,03	0,20	0,82	1,00
Puyehue	B	5	70	45			0,52	3,40	11,21	0,68
Aguas calientes	B	4,5	65	45			0,38	2,80	7,39	0,62
El Amarillo	B	4,2	55	40			0,26	2,00	3,96	0,48
Puyuhuapi	B-H-O	13,6	68	45			1,31	4,20	12,74	0,31
Others	B						2,20		27,30	
TOTAL							14,68		228,91	

Table 4. Geothermal (ground – source) heat pumps as of 31 December 2019.

This table should report thermal energy used (i.e. energy removed from the ground or water) and report separately heat rejected to the ground or water in the cooling mode. Cooling rejected to the ground in the cooling mode as this reduces the effect of global warming.

1) Report the average ground temperature for ground-coupled units or average well water or lake water temperature for water-source heat pumps

2) Report type of installation as follows: V = vertical ground coupled (TJ = 10^{12} J)
H = horizontal ground coupled
W = water source (well or lake water)
O = others (please describe)

3) Report the COP = (output thermal energy/input energy of compressor) for your climate - typically 3 to 4

4) Report the equivalent full load operating hours per year, or = capacity factor x 8760

5) Thermal energy (TJ/yr) = flow rate in loop (kg/s) x [(inlet temp. (°C) - outlet temp. (°C)] x 0.1319
or = rated output energy (kJ/hr) x [(COP - 1)/COP] x equivalent full load hours/yr

6) Cooling energy = rated output energy (kJ/hr) x [(EER - 1)/EER] x equivalent full load hours/yr

Note: please report all numbers to three significant figures
Due to room limitation, locality can be by regions within the country.

Locality	Ground or Water Temp. (°C)[1]	Typical Heat Pump Rating or Capacity (kW)	Number of Units	Type[2]	*COP[3]	*Heating Equivalent Full Load Hr/Year[4]	Thermal Energy Used[5] (TJ/yr)	Cooling Energy[6] (TJ/yr)	Source
Invernadero CET, Puerto Aysén	11	22	1	H	3,0	1755,1	0,14	-	1
Escuela Altos del Mackay, Coyhaique	10	22	2	W	3,4	550,0	0,10	-	1
Secador de leña e invernadero, Coyhaique	9	22	1	W	3,4	3788,0	0,30	-	1
Hospital de Talca	16	1024	4	W	-	-	0,10	-	2
Sunny ridge, Melipilla	17	22	1	Pond Loop	-	-	0,00	-	2
Colegio Llifén	13	19,2	1	W	-	2190,0	0,00	-	2
Jardin Coyhaique	10	22	1	Basquet loop	-	-	0,00	-	2
Invernadero Lampa	15	50	1	W	3,3	-	0,00	-	2
Escuela Voipir de Ñancul	-	-	-	W	-	-	-	-	2
Piscicultura Hendrix genetics, Pucon	-	580 460	-	W	-	-	0,06	-	3
Piscicultura Sealand, Challahue, Calbuco	-	350 310	-	W	-	-	0,03	-	3
Lo Pinto, Colina	17	12,8	2	W	-	-	0,00	-	3
San Fernando	17	19,2	1	W	-	-	0,00	-	3
Refugio Altos de trancura, Pucon	12	12,8	2	W	-	-	0,00	-	3
Talca proyecto habitacional	16	24	1	W	-	-	0,00	-	3
El silo	-	19,2	1	W	-	-	0,00	-	3
Constructora ABN, Puerto Varas	-	40	-		-	-	0,00	-	3
Ensenada de camanchaca, Puerto Varas	-	58	-		-	-	0,01	-	3
El tepual norte, Puerto Montt	-	27	-		-	-	0,00	-	3
San Carlos	16	18	-		-	-	0,00	-	3
San Javiér, Puerto Montt	-		-		-	-	0,00	-	3
Geomarket, Arauco	-	700	-		-	-	0,07	-	3
Viña Maquis	-		-	W	-	-	0,00	-	3
Hospital de Rancagua	16		-	W	-	-	0,00	-	3
Médico en Pirque	-	12	1		-	-	0,00	-	3
Colegio Osorno	14		-		-	-	0,00	-	3
Secador Santa Juana	-	4	-	H	4,0	-	0,00	-	4
Hogar hermanita de los pobres, Concepción	-	100	-	H	4,0	-	0,01	-	4
Hotel Quelen, Lago Lanalhue, Cañete	-	40	-	H	5,0	-	0,00	-	4
Viveros bosques Arauco, Viveros Laraquete	-	10	-	H	4,5	-	0,00	-	4
Particular, Chillán	-	5	-	H	5,0	-	0,00	-	4
Piscina temperada, Chiguayante	-	8	-	H	4,0	-	0,00	-	4
Particular 2, Lomas San Sebastián, Concepción	-	5	-	H	4,0	-	0,00	-	4
Unifrutti , San Felipe	16	20	-	H	3,5	-	0,00	-	4
Casa familia Silva, Condominio Las Canteras siti	-	18	-	H	3,4	-	0,00	-	4
Casa familia Salazar, Polo de Chicureo II, sitio 46	-	16	-	H	3,6	-	0,00	-	4
Condominio Las Tortolas, Pirque	-	12	-	H	4,6	-	0,00	-	4
Forestal Arauco vivero Horcones, Laraquete, ruta	-	700	-	W	4,6	-	0,07	-	4
Casas La Reina, La Reina, Santiago	16	216	-	V	3,1	-	0,02	-	4
Centro logístico, San Miguel, Santiago	16	75	-	V	3,1	-	0,01	-	4
Arauco: Horcones, Los Horcones s/n, Arauco	-	700	-	H	4,5	-	0,07	-	4
Casas Habitacionales Los Angeles, Colina,	16	14	-	H	4,1	-	0,00	-	4
Casino Dreams Valdivia	-		-	W	-	-	0,00	-	5
ACHS Los Angeles	-		-	W	-	-	0,00	-	5
PDI Puerto Montt	-		-	W	-	-	0,00	-	5
Casa Von Murr, Santiago	-		-	H	-	-	0,00	-	5
Condominio Frankfurt, Temuco	13		-	W	-	-	0,53	-	5
INACAP Puerto Montt	-		-	W	-	-	0,00	-	5
Colegio Aleman, Puerto Varas	-		-	W	-	-	0,00	-	5
Anasac Lautaro	-		-	H	-	-	0,00	-	5
Caja Los Andes, Maipu	-		-	V	-	-	0,00	-	5
Caja Los Andes, Viña del Mar	-		-	H	-	-	0,00	-	6
Teatro del Lago (Frutillar)	-		-	W	-	-	0,00	-	5
Santiago College, Los Trapenses	-		-	W	-	-	0,00	-	5
ACHS Curicó	-		-	W	-	-	0,00	-	5
Jumbo Osorno	-		-	W	-	-	0,00	-	5
Hospital Umayor, Temuco	-		-	W	-	-	0,00	-	5
Casa Scherson, Valdivia	-		-	H	-	-	0,00	-	5
Casino Dreams Temuco	-		-	W	-	-	0,00	-	5
Casa Guzman-Clarke, Valdivia	-		-	W	-	-	0,00	-	5
Others		2150					0,40	-	6
TOTAL		**7939,2**					**1,95**		

1 Project carried out by CEGA
2 Project visited by CEGA
3 Pers comm.
4 Energy Ministry, Chile
5 EEChile catalog
6 Lahsen et al., 2015 (CEGA)

* In projects with no data available, a COP of 4 and heating load of 3600 H/year is assumed

Table 5. Summary table of geothermal direct heat uses as of 21 December 2019

1) Installed Capacity (thermal power) (MWt) = Max. flow rate (kg/s) x [inlet temp. (°C) - outlet temp. (°C)] x 0.004184
or = Max. flow rate (kg/s) x [inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg)] x 0.001
2) Annual Energy Use (TJ/yr) = Ave. flow rate (kg/s) x [inlet temp. (°C) - outlet temp. (°C)] x 0.131 (TJ = 10^{12} J)
or = Ave. flow rate (kg/s) x [inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg) x 0.03154
3) Capacity Factor = [Annual Energy Use (TJ/yr)/Capacity (MWt)] x 0.03171 (MW = 10^{6} W
since projects do not operate at 100% capacity all year
4) Other than heat pumps
5) Includes drying or dehydration of grains, fruits and vegetables
6) Excludes agricultural drying and dehydration
7) Includes balneology

Use	Installed Capacity[1)] (MWt)	Annual Energy Use[2)] (TJ/yr = 10^{12} J/yr)	Capacity Factor[3)]
Individual Space Heating[4)]			
District Heating [4)]			
Air Conditioning (Cooling)			
Greenhouse Heating			
Fish Farming			
Animal Farming			
Agricultural Drying[5)]			
Industrial Process Heat[6)]			
Snow Melting			
Bathing and Swimming[7)]	14,7	228,9	
Other Uses (specify)			
Subtotal	14,7	228,9	
Geothermal Heat Pumps	7,9	2,0	
TOTAL	22,6	230,9	0

Finally, Table 6 summarized the total wells drilled for the electrical, direct, and combined use of geothermal resources in Chile.

Table 6. Wells drilled for the electrical, direct and combined use of geothermal resources from January 1, 2015, to December 31, 2019 (excluding heat pump wells). Source of data: Geotérmica del Norte (GDN)

Purpose	Wellhead Temperature	Number of Wells Drilled				Total Depth (km)
		Electric Power	Direct Use	Combined	Other (specify)	
Exploration[1)]	(all)					
Production	>150° C	7				13,7
	150-100° C					
	<100° C					
Injection	(all)	3				8,1
Total		**10**				**21,8**

(1) Include thermal gradient wells, but not ones less than 100 m deep.

6. PERSONNEL

Professional personnel involved in geothermal activities is summarized in Table 7. After the maximum period of geothermal exploration in Chile (first half of the last decade), the number of companies actively exploring geothermal concessions in Chile has been radically reduced from 14 in 2015 to 3 in 2019. Consequently, the number of professional personnel working in geothermal activities in Chile is limited to few people in the three already existing companies (GDN, Transmark and EDC) and professionals in public services (SERNAGEOMIN –the National Geological Survey- and Ministry of Energy) and academy (the Andean Geothermal Center of Excellence –CEGA-). Personnel in the geothermal industry decreased from 44 in 2014 to 30 in 2019, with the majority being professionals working in Enel Green Power-Geotérmica del Norte. On the contrary, people working in the

academy (CEGA), increased from 14 in 2014 to 45 by 2019. Moreover, CEGA is currently the only research center focused in geothermal energy (both for electricity production as for direct use) and the main human resources training center in the country (and probably in the rest of South American countries). CEGA develops interdisciplinary research, development, and innovation in geothermal resources (see Morata and Otero, 2020) and has implemented the analytical facilities needed for solid, liquid and gases geothermal analyses together with geophysical surveys.

Table 7. Allocation of professional personnel to geothermal activities (restricted to personnel with University degrees).

Year	Professional Person-Years of Effort						Total
	(1)	(2)	(3)	(4)	(5)	(6)	
2015	3	5	44	0	0	25	77
2016	3	3	47	0	1	23	77
2017	3	3	46	1	1	29	83
2018	3	3	47	1	3	16	73
2019	3	3	45	0	9	30	90
Total							

(1) Government; (2) Public utilities; (3) Universities; (4) Paid Foreign Consultants; (5) Contributed Through Foreign Aid Programs; (6) Private Industry. For CEGA, only professionals and researchers are considered; Ph.D. and MSc students (around 40/year) were not considered

7. INVESTMENT

During the last five years, the departure of geothermal companies from Chile has resulted in the frozen investment in exploration campaigns. However, the construction of the Cerro Pabellón power plant was a major investment that ended in 2017. The Ministry of Energy received international funds for promoting geothermal energy (BID and World Bank). On the other hand, CEGA continues its funding by the Chilean National Science Foundation (CONICYT) throughout its FONDAP program, with a budget of US$ 1.4 million/year. In general terms and compared with the reported in Lahsen *et al.* (2015), where investment rose to around US$52 million, the total calculated investment by the period 2015-2019 achieved US$ 350 million, mostly influenced by the construction and development of the Cerro Pabellón power plant.

Table 8. Total investments in geothermal in (2019) US$

Period	Research & Development Incl.	Field Development Including Production	Utilization		Funding Type	
			Direct	Electrical	Private	Public
	Million US$	Million US$	Million US$	Million US$	%	%
1995-1999	0	0	0	0		
2000-2004	0	0	0	0		
2005-2009	55,05	0	0	55	100	
2010-2014	51,607	0,5	0	40	100	(*)
2015-2019	12,01	340,47	0,77	340,5	100	(*)
	A total amount of US$ 13.7 is the CEGA budget for research (2011-2020), supported 100%					
	by FONDAP-CONICYT (the Chilean National Science Foundation)					

8. DISCUSSION AND CONCLUSIONS

By 2017, Chile has been incorporated to the selected club of countries generating electricity with at least one geothermal power plant. The Cerro Pabellón power plant, in operations since November 2017, provides the first 48 MWe in South America, showing the electricity generation with geothermal energy is completely possible in the Andean countries. Moreover, with the projected additional 33 MWe expansion of this geothermal field, the total geothermal capacity installed in Chile will rise to 81 MWe by 2020. This expansion stage is very important, considering it is the first and only South American geothermal power plant.

However, the future scenario for geothermal expansion in Chile is not clear due to electricity market limitations. Electricity generation in Chile is provided by private companies, and in the present-day scenario with very-low electricity prices (mostly due to the sudden entry of solar energy in the electricity matrix), geothermal energy stands as non-competitive in an economic system dominated by the market. It is evident that Chile needs public policies aimed to guarantee the development of geothermal energy as a real, sustainable, and environmentally friendly way to produce electricity. Chile aims to achieve a 100% renewable matrix by 2050, removing progressively all coal-based thermoelectric power plants (around 4000 MWe currently installed). This is critical for electrical engineering design because a reliable energy matrix needs to have a secured amount of production that does not depend on climate factors. In this context, geothermal energy (with its superior net capacity factor) is the most suitable alternative to supply a 100% renewable matrix with the required percentage of MWe that cannot be affected by climate phenomena. Also, considering the existing climate change scenario, geothermal energy arises as a powerful alternative to harvest the earth's natural engine with a minimum environmental impact.

Several barriers (geological, social, economic and legal) were identified by Sánchez-Alfaro et al. (2015), showing the necessity for a more leading role of the State in the Chilean geothermal development, considering its huge potential. Estimations given by

geothermal developers suggest that by 2030, a total of 599 MWe could be operating. That figure could be increased in additional 1.487 MWe by 2050. This assessment is very positive, although a change in the Chilean energy policy is required. Several modifications are necessary, along with extensive community work with indigenous groups (Vargas-Payera, 2018). These major challenges for Chile are completely addressable in the next few years, but a real interest from the state is mandatory. Several geothermal fields are ready to enter in exploitation phase if economic barriers were to be removed. In addition, direct use of geothermal resources is beginning to be more researched and applied in the Chilean society. Problems related to air pollution in various cities from central to southern Chile could be solved by using geothermal district heating systems.

Finally, increasing the investment and funding in research, innovation, and development, is the only way for the Chilean geothermal industry to unlock the huge geothermal potential that already exists in the Andean Mountain Range.

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