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Chile 2020-2023 country up-date: the slow progress of geothermal development and future perspectives.

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ABSTRACT

Geothermal systems in the Chilean Andean Cordillera are mostly controlled by the different magmatic and tectonic processes related with the continuous subduction of the Nazca and Antarctic plates under the South American Plate. Due to this particular geological context, Chile has been considered as one of the more interesting geothermal prospects in the world. As consequence, in 2017 the first geothermal power plant of South America was installed by Geotérmica del Norte (GDN), a joint venture between the Italian Enel Green Power and the National Chilean Oil Company (ENAP). This geothermal plant named Cerro Pabellón is located in the north of Chile, and consist in two binary units of 24 MWe each were installed, providing a total of 48 MWe to the Chilean electricity matrix. During 2019-2022, a new binary unit was installed in the same geothermal system, with an additional power capacity of 33 MWe. Consequently, by the end of 2022, Cerro Pabellón is the only geothermal power plant in South America, providing a total of 81 MWe of clean and sustainable energy to the Chilean electricity system.

The reported 2020-2023 period of this work was dominated by of the Covid -19 pandemic, and thus, the exploration in other Chilean geothermal systems was very limited. In fact, only Transmark company developed new exploration campaigns with the aim of drilling production wells in the Adobera project (Southern Chile). Unfortunately, local opposition in 2022 delayed drilling program from its original plans.

Concerning direct use, from 2019 a modification to the Chilean geothermal law has been presented in parliament. The aim of this modification is to facilitate shallow geothermal development in Chile. To date, this new amendment to the law is under review, without a precise date for the final acceptance. Nevertheless, different pilot projects have been developed by the Andean Geothermal Center of Excellence (CEGA) funded by Regional Governments and the Ministry of Energy. These projects demonstrate the benefits of shallow geothermal for society and local communities to provide heating in public schools and greenhouses with territorial relevance, offering a clean alternative for energy autonomy in remote areas from urban centers. Most of the projects were developed in Southern Chile; however, since 2022 few projects are under development in the northern Chile to provide heating and cooling of public spaces.

In this Chile country up-date, an update of the different geothermal exploration, exploitation, applications and development activities, for the production of electrical energy, geothermal heat pumps and direct uses will be presented. Likewise, a social analysis about the opportunity of direct use of geothermal energy to face energy poverty, and future perspectives in Chile at the national and regional levels will be included. Finally, the main activities related to capacity building in the country will be summarized.

1. INTRODUCTION

After more than one century from the first pioneer exploration of geothermal energy in the Northern Chile, the first commercial geothermal power plant in South America, Cerro Pabellón, was finally installed by 2017. More than one century was necessary for crystallize those preliminary studies conducted at the beginning of XX century. As a long route, with probably more shadows than lights, can be defined the progression of the geothermal industry in Chile. A tortuous route with several barriers (technical, economic, social and political) that at the beginning of XXIth century showed a complete paradox. 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. The high geothermal anomaly existing in the Chilean Andean Cordillera has been presented in several papers and numerous congress (*e.g.* Aravena et al., 2016; Lahsen, 1986, 1988; Lahsen et al., 2015; Morata et al., 2020; Vieira & Hamza, 2019). And after the implementation by 2000 of the Chilean Geothermal Law (law 19.657) a dozen of private companies were installed in Chile with the aim of explore and develop the different geothermal fields already existing along the country (see Lahsen et al., 2015. Morata et al., 2020). Probably was a decade of intense geothermal exploration but, with time passing, several problems concerning the few geological background for some of these companies or, simply because the decrease of the

electricity price in the Chilean market (between other reasons), combined with unsuccessful geothermal exploration programs and the strong entry of solar energy in the electricity Chilean market, resulted in a progressive reduction of companies exploring for electricity generation using geothermal energy, generating in the Chilean geothermal industry a clear pessimistic scenario. 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 Cordillera. Today Cerro Pabellón is the only geothermal power plant running in Chile (and rest of South America). However, with respect to the report presented by Morata et al (2020) about the status of the Chilean geothermal country up-date, few advances are remarkable to highlights. By October 2019 a major social movement was observed in Chile, where during several weeks numerous social protests highlight the political and social agenda. After that, the year 2020 (and partially 2021) was clearly influenced by the pandemic situation related with the Covid 19. Most of the geothermal exploration activities were consequently frozen for more than one year, and therefore, this country up-date report will not present huge differences in comparison with the previously presented in the World Geothermal Congress 2020.

However, in spite of this slow development of the Chilean geothermal industry during these last three years, the projection for a Chilean electricity market 100% composed by renewable energies by 2050 is a light at the end of this tortuous tunnel. Moreover, the necessity approved by the society of removed coal-based thermal power plant imply the necessity of change this fossil fuel by renewable energies. This will be an extra opportunity for the development of the Chilean geothermal industry during the next decade.

2. GEOLOGY BACKGROUND

The Chilean particular geological context, controlled by continuous active subduction of the oceanic Nazca and Antarctic plates under the continental South American Plate, with active volcanism along most of this subduction zone, evidence one of the most favorable area for volcanic related-type geothermal systems. The differences in the velocity, morphology and dip of the subduction zone is the first order control of recent volcanism in this huge volcanic province, 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 Cordillera, where high-temperature spring areas and other surface manifestations are present (Figure 1).

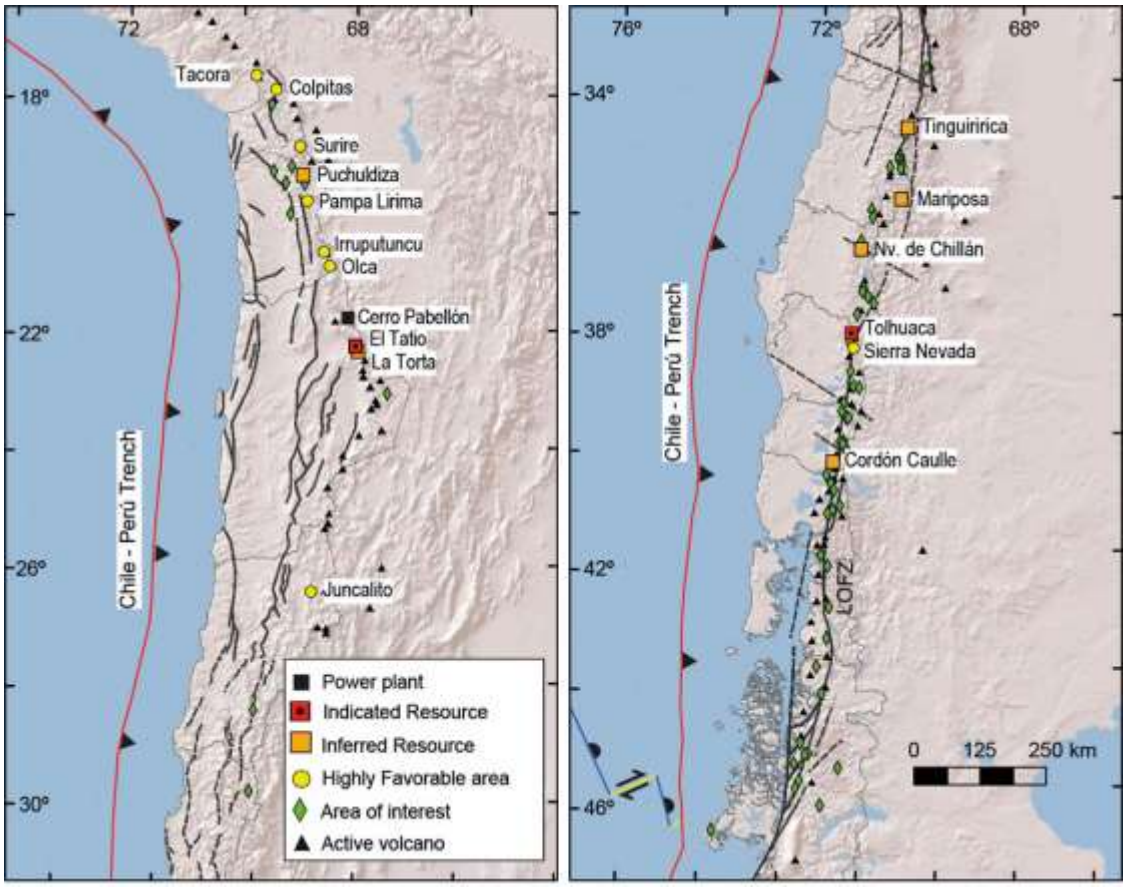

Figure 1: Active volcanism and location of the more developed geothermal fields in Northern, Central and Southern Chile (after Aravena et al., 2016). The Austral Volcanic Zone, generated by the active subduction of the Antarctic Plate under South American Plate is not showed.

The combination of active magmatism with various areas of high permeability and strongly fault-controlled (e.g. Sánchez-Alfaro *et al*.,2013; Tardani *et al*., 2016; Pérez-Flores *et al*., 2017; Roquer *et al*., 2017; Wrage *et al.*, 2017; Veloso *et al.*, 2019, Pérez-Estay et al., 2020), allows to classify the Chilean Andean Cordillera as a set of extended convective geothermal play-type provinces (following the Moeck's 2014 classification). The perfect alignment of permeable units (primary and/or secondary permeability), continuous heat source and preferential geodynamic orientation for fluid-flow along structures ultimate controls of both medium- and high-enthalpy geothermal systems.

On the contrary to the geological restrictions for high- to medium-enthalpy geothermal systems, direct use based on geothermal heat pumps could be installed in almost all Chile, increasing the possibility to use for heating and diverse productive sectors. Diverse pilot projects have been installed along the country by the Centro de Excelencia en Geotermia de los Andes (CEGA, Andean Geothermal Center of Excellence), as presented in this paper. These pilot projects, together other initiatives based on this technology, open the possibilities for direct use not only in Chile but also in the rest of Andean countries as a way also to increase and improve the social acceptance of geothermal energy in our country, supporting energy transition and decreasing energy poverty.

3. GEOTHERMAL RESOURCES AND POTENTIAL

As a natural consequence of its geological context, Chile has a vast untapped potential for renewable electricity, which can help limit carbon dioxide (CO_2) emissions and air pollution as well as reduce import dependency. In this way, Chile point to a full renewable based electricity grid by 2050 and geothermal energy could strongly participate on this ambitious main goal. Geothermal energy in Chile has a special legal status compared with other renewable energy source. Chile's Law 19,657 on Geothermal Energy Concessions (2000) established regulatory frameworks for geothermal exploration and exploitation, as well as standards for concession allocation and tenders. This law opened the opportunity to private companies for exploration and exploitation concessions along the country, mostly in the high Cordillera (see Morata et al., 2020 and references therein). Unfortunately, after a period of intense geothermal exploration ion the country, during the last 5-7 years the different companies closed their offices and only 3-4 companies are today supporting the geothermal industry in Chile.

Most of the high- and medium enthalpy geothermal systems are located in the Andean Cordillera, in areas in close relation with active volcanism (see Figure 1) and where the local tectonic regime is favorable for fluid-flow processes and generation of geothermal reservoirs. However, up to day we don't have a precise estimation about the geothermal potential in Chile. 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 lower 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 9 well-identified high enthalpy geothermal areas in the Chilean Andes, obtaining a total value of 659 ± 439 MWe among medium (6) and large (3) systems. Moreover, the same authors outline the existence of, at least, a set of 65 favorable geothermal areas proposed as the most likely future development targets. Finally, the report of "Mesa de Geotermia" (Geothermal Round Table) 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 document represents the most realistic quantification 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 2086 MWe could be in operation along Chile if economic barriers will be addressed. Interestingly, these estimations were made using only available data provided by the industry from those geothermal areas, where companies had any geological information. No data are available from geothermal areas southern 46° Lat S (see Figure 1) and several medium-enthalpy were not considered in this potential estimation. In this sense, preliminary calculations generated by the Andean Geothermal Center of Excellence (CEGA) suggest that a total of 112 MWe are today measured (taking into account the Cerro Pabellón, El Tatio and Tolhuaca geothermal systems, where production wells are available), between 700 to 2000 MWe will be the indicated resources based on data from Puchuldiza, Pampa Lirima, La Torta, Licancura, Tinguiririca, Mariposa, Nevados de Chillán and Cordón Caulle geothermal systems (geothermal systems with available well data). Additionally, an estimation between 16000 and 40000 MWe could be considered as "inferred" if different theoretical potential is applied. An up-date of this academic estimation about geothermal potential in Chile is currently in progress by CEGA and hopping to finish during 2023.

Recent data presented by the Chilean Geothermal Council (4-6 April 2022, GeoEnergy Europe -GGE2-: "Chile Market visit seminar") summarize the geothermal potential available in the four main geothermal projects in Chile (Table 1). More than MMUS$ 565 has been invested in geothermal exploration in the country after more than 10 years of exploration. In conclusion, we can affirm that there is a contradictory scenario related with the geothermal industry in Chile. The positive side was the first power plant (Cerro Pabellón) running by 2017 to produce green electricity to the country. Two binary units, high-enthalpy organic ranking cycle type (HE-ORC), 24 MWe each one, were installed. Besides, a new third HE-ORC with additional 33MWe was finally in operation by end of 2021. A total capacity of 81MWe are today installed in our country, a geothermal capacity that represent only a small proportion of the theoretical power capacity that, after the "Mesa de Geotermia" (Geothermal Round Table) presented in 2018 by the Chilean Ministry of Energy could be installed in Chile by 2050. However, the negative side is the uncertainty about the future of the geothermal energy in Chile, even if the potential is already available, and the needs for move to a 100% renewable electricity market by 2050 is a growing social demand of the Chilean society. Projects under development with exploitation concessions ~ 300 MWe, all located southern Santiago, are waiting for some signals from government the finally allow their correct development (Table 1).

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. In fact, by 2022, only one exploration concession is active (Peumayén, by Transmark Chile SPA) and eight exploitation concessions are existing in Chile (Table 2 and locations in figures 1 & 2). A really different scenario to the previously presented in the last two country up-date (Lahsen et al., 2015 and Morata et al., 2020).

Table 1. Main geothermal projects in Chile (data source: Chilean Geothermal Council 2022). See location of this projects in Figure 1.

Geothermal field	**Cerro Pabellón**	**Tinguiririca**	**Mariposa**	**Tolhuaca**
Developer Company	GDN	Energía Andina	EDC/Enerco	Transmark
Investment (MMUS$)	385	40	40	100
Potential (P90)	114 MWe	200 MWe	240 MWe	220 MWe
Development strategy	48 + 33 + 33	100 + (50 + 50)	100 + (50 + 50)	100 + (50 + 50)
Location	Ollagüe, II Región	Tinguiririca, VI Región	Laguna del Maule, VII Región	Volcán Tolhuaca, VIII-IX Regiones

Table 2. Summary of active geothermal concession in Chile

Concession	Company
Olca	Compañía Minera Doña Inés de Collahuasi SCM
Apacheta (Cerro Pabellón)	Geotérmica del Norte S.A.
El Tatio	Geotérmica del Norte S.A.
La Torta	Geotérmica del Norte S.A.
Tinguiririca	Energía Andina S.A.
Laguna del Maule	EDC/Enerco
Pellado	EDC/Enerco
Peumayén	Transmark Chile SPA

The main advances during these last years of the main geothermal companies already existing in Chile are summarized in the following:

- Olca: This geothermal concession is located in the proximity of the active Olca volcano, close to the Chile-Bolivia border. The concession is property by the mining company Compañía Minera Doña Inés de Collahuasi. No new information has been published from this field.
- Cerro Pabellón: This is the only developed geothermal field in Chile (and South America). This power plant, developed by GDN (Geotérmica del Norte, joint venture between Enel Green Power and ENPA, the Chilean National oil company), begun electricity production by 2017 with two twin binary units (HE-ORC) installed capacity of 48 Mwe (Cappetti et al., 2020). Additional 33 MWe were incorporated by 2021 using the same HE-ORC technology. This new HE-ORC unit was benefit for CapEX reduction thanks to all infrastructures already built up and to the availability of geothermal fluid. This new unit will lean on the existing gathering system with the additional pipeline for connecting the CP 2 well pad (+ 2 wells). A new paper published by Vidal et al. (2022) focussed on hydrothermal alteration, specifically clays, in rock samples from deep reservoir. The results suggest a high heterogeneity of the reservoir in term of alteration and complete an integrated conceptual model of the high enthalpy (>250ºC) reservoir.
- El Tatio and La Torta concessions (GDN) don't present any advances during the last years.
- Tinguiririca: located in the proximity of the Tinguiririca volcano, in central Chile, this geothermal field, property of Energía Andina company, don't present advances during the last years.
- Laguna del Maule and Pellado geothermal fields, both concessions in central Chile and property of the Philippine Energy Development Corporation (EDC)-Enerco don't report advances during the last period.

- Peumayén (Southern Chile), the ex-Tolhuaca concession and currently licensed to Transmark company with an inferred capacity of 70 MWe to be developed. During the last three years the company is exploring the Adobera field, a small area in the proximity of the Tolhuaca volcano, within the Peumayén concession (https://transmark-renewables.com/news/transmark-renewables-and-its-consortium-partners-agree-development-adobera-project) co-financing by KfW and with funding by the EU. A recent paper published by Pavez et al. (2022) using MT in the proximity of the Tolhuaca volcano highlight two resistive bodies (~200 Ωm) in the upper crust below the laterally displaced argillic alteration layer to the west beneath the extinct Tolhuaca, which would correspond to a shallow reservoir (~1000 m from the surface) and a deep reservoir (>1800 m from the surface) that had so far not been identified by previous resistivity models. The result of this study provides new insights into the complexity of the Tolhuaca geothermal system.

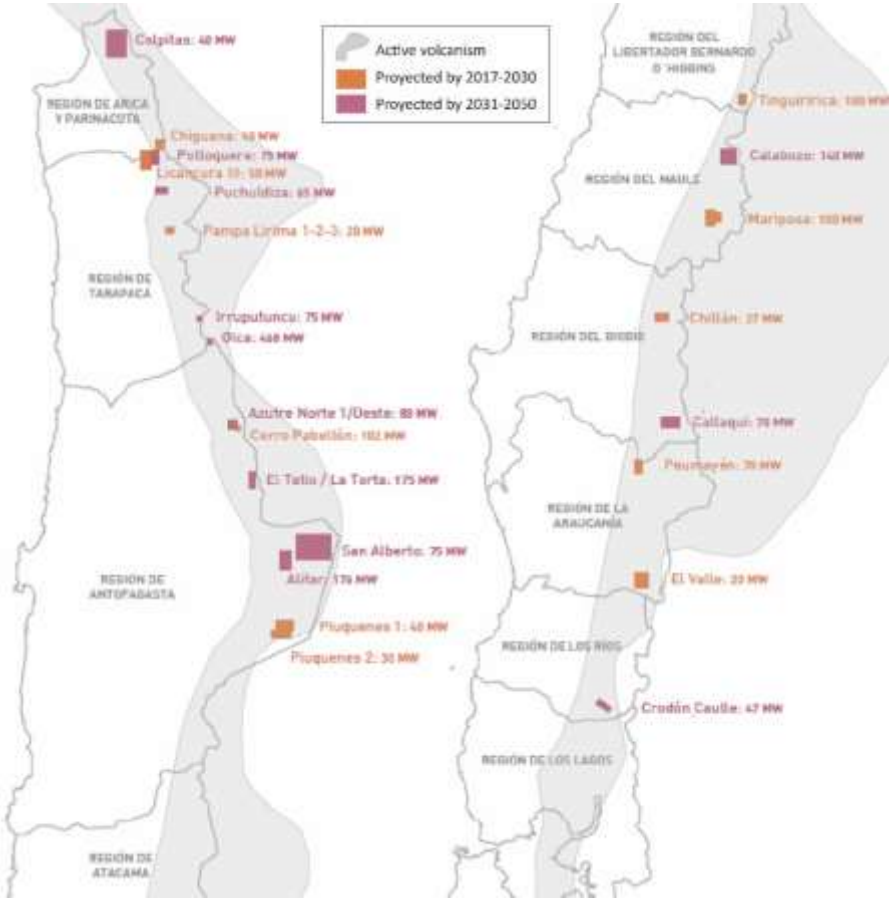

Figure 2: Geothermal areas with potential to be incorporated in the Chilean energy matrix in the period 2030-2050 (After Mesa de Geotermia report, 2018).

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 the country. Today the total electricity distribution is interconnected (Sistema Eléctrico Nacional -SEN) 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 by December 2022 is 33.318 MWe (http://generadoras.cl/generacion-electrica-en-chile). Renewables energies conform 62.0% of this total installed capacity (22.3% hydroelectricity, 24.1% solar, 13.0% wind, 2.3% biomass and 0.3% geothermal) meanwhile the other 38.0% correspond to fossil fuels based (13.0% coal, 15.1% natural gas and 9.8% oil). The vast majority of these non-renewables resources is imported from overseas. The Aysen System (SEA, by the Spanish Sistema Eléctrico de Aysén) has by December 2022 a total installed capacity of 69.8 MWe, composed by a 56.0% by diesel, 37.2% by hydropower, 4.2% solar and 2.6% wind power. Finally, the Magallanes region (the southernmost region in Chile) has a total installed capacity of 129.3 MWe, with a 75.2% from natural gas, 14.8% by diesel and 10.0 from wind power

It is remarkable 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 (Figure 3), a phenomena noticed by the international markets. By 2011 solar and wind energies were only 0.5% of the electricity grid being by end 2022 a 24.1% of the total capacity installed.

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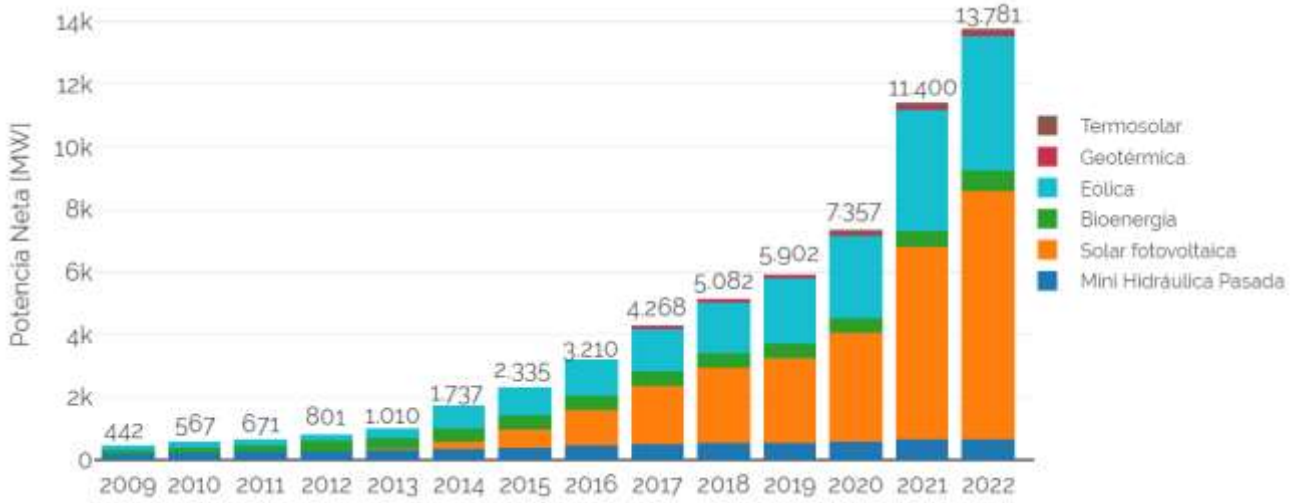

Figure 3: Evolution of non-conventional renewables energies (ERNC, by its Spanish acronym) in Chile during 2009 to 2022. Geothermal energy entry in 2017 with 48 MWe (Cerro Pabellón) and today adds a total of 81 MWe to the ERNC mix. Data and figure from the Chilean Renewable Agency ACERA, report December 2022 (https://acera.cl/).

The new scenario for the Chilean electricity grid 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 base load. By December 2022 coal-based installed capacity is of 4.332 MWe (and additional 5.031 MWe by natural gas and 3.270 MW by oil). If Chile aims to remove all thermal coal-based units by 2050 urgently need an energy policy promoting renewables energies that could be used as base load. In this category, geothermal energy must be a relevant actor. However, if government doesn't offer clear signals to the private sector, will be difficult the massive entry of geothermal energy in our market. 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 (Tranamil-Maripe et al., 2022).

With respect to direct use, a modification to the Chilean Geothermal Law is in the parliament from 2019. This modification aims to favor the development of shallow geothermal systems (< 400 m depth) for direct use (using geothermal heat pumps). Unfortunately after more than three years in the parliament this new law is in a stand by status. However, between the agenda of the Minister of Energy is planned to promote geothermal direct use and approved this new law that could be a legal framework for shallow geothermal (direct use only) development in Chile.

5. GEOTHERMAL UTILISATION

5.1 Electricity power installation and generation

By December 2022, the total geothermal capacity installed in Chile (Cerro Pabellón power plant) increased up to 81 MWe. Three HE-ORC conform this power plant operated by Geotermica del Norte (GDN), a joint venture between Enel Green Power (today owns of 84.6% of GDN) and the Chilean National oil company ENAP (with the 15.4% of GDN). The project is located in the Desert of Atacama, at about 100 km NE of Calama and at an elevation of 4500 m. Cappetti et al (2020) presented a complete summary of this power plant and its development. The first 24 MW unit was put in operation on March 31,2017 and the second unit on June 12, 2017. A total of 13 deep wells were drilled (9 production and 4 re-injection wells). By 2021 a new 33 MWe HE-ORC unit was installed. The new unit will lean on the existing gathering system with the additional pipeline for connecting the CP 2 well pad (+ 2 wells).

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 the country, whilst some of them are equipped with sophisticate touristic infrastructure others have a rather rustic display. The total heat capacity estimated for the main thermal springs arise up to 14.71 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 heating touristic cabins or the hotel installations are the Centro Termal Armada Liquiñe (Los Rios region) and the Puyuhuapi Lodge (Aysén region). Moreover, in Liquiñe

town, in the Hipólito-Muñoz thermal springs, a greenhouse heated using thermal water was installed by CEGA thanks to a grant from the Regional Government. This project was a pilot initiative with the aim to show to the communities the different added values from thermal water. Today this greenhouse is currently working and provides fresh vegetables during winter time (characterized by very low temperatures and occasionally presence of snow).

Table 3. Summary of the different geothermal direct use in Chile.

Geothermal Application	Installed capacity (MW)	Total energy produced (TJ/year)	Energy used (TJ/year)	Number of installations
Agriculture and food processing	1.45	10.46	7.32	5
Industrial process heat	0.00	0.00	0.00	0
Health, recreation and tourism	14.71	228.91	0.00	30
Heating and cooling for buildings	5.98	1.10	0.86	50
Other uses	1.25	0.00	0.00	4
Total values	**23.38**	**240.47**	**8.18**	**89**

Other applications of direct use were for agriculture and food processing and also heating of buildings (see Table 3). As reported in Morata et al (2020), most of these direct uses are managed by privates and, information on private investment for direct utilization projects is difficult to obtain and, consequently, data on Table 3 must be considered as minimum values.

For geothermal heat pumps, 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, Altos del MacKay in Coyhaique, Luis Cruz Martínez in Curacautin among others).

The Andean Geothermal Center of Excellence (CEGA), and granted by regional funds, has strongly promoted the direct use along the country. In this sense, by December 2022, different pilot projects are running from North to South of Chile, showing the benefits of this technology and how geothermal heat pumps can be used for remove wood stove from public class rooms (e.g. Coyhaique, Curacautín and Puerto Cisnes), for heating rural medical center (Lago Ranco) or promoting geothermal greenhouses in Southern Chile, where weather conditions during winter time do not allow the growing of fresh vegetables like tomato.

These pilot projects granted by Regional Government and the two projects granted by the Minister of Energy (public school in Curacautín and Puerto Cisnes) are clear evidence of the interest of the different public institutions for promoting direct use in Chile. These projects, together those promote by private sectors have provided the basis for a bigger development of geothermal heat pump systems in the near future. However, as documented previously, the delay to approve the proposed modification of the Chilean law for geothermal development (nº19.657) promoting the shallow geothermal (< 400 m depth) direct use in Chile favoring the quick installation and implementation of several direct use initiatives under a regulated scenario, don't favor the massive implementation of direct use in the country. In the new agenda from the Minister of Energy is clearly specified that this modification would be solved in a short time. A complete list of the different direct use projects executed or in operation by CEGA during the last years can be obtained in http://www.cega-uchile.cl/investigacion/

6. RESEARCH, SOCIAL ASPECTS AND HUMAN CAPACITY BUILDING

As reported in previous years, most of the research and human capacity building are centered in the Andean Geothermal Center of Excellence (CEGA, http://www.cega-uchile.cl/en/). This center was granted for 12 years by the Chilean National Science Foundation (ANID, Agencia Chilena de Investigación y Desarrollo), from 2011 to 2022 (see also Morata & Otero 2020). From January 2023 CEGA has no more granted by ANID but thanks to the different grants obtained by regional funds, CEGA will maintain its R+D+I activities at least up to 2025.

In order to address human capacity gaps about heat pumps systems, CEGA has offered an on line course about geothermal direct use and heat pumps technologies for the last three years. This virtual modality for teaching allows to include participans from different countries of South America. From 2020 to 2022 this course trained 70+ people from different background creating an international network with interest in direct use in the region.

26 Graduate and 54 post-graduate (29 MSc and 25 PhD) students were also formed (or continue developing their thesis) in CEGA during the period 2020-2022. Unfortunately, because the end of granted CEGA by ANID, direct fellowships for students will be not possible for the future.

During January 2023 was the final seminar of the German-Chilean BrineMine project (https://geothermics.agw.kit.edu/english/brinemine.php). This project pursues the approach of extracting raw materials from geothermal waters. With the help of membrane technology, the heat of the water is to be used to separate the mineral raw materials and the water from each other in a closed system by means of a technical process. The aim is to obtain not only minerals but also drinking water as an important resource. In this way, a raw material-efficient and sustainable alternative to conventional lithium mining is demonstrated (Goldberg et al., 2021), giving a new market opportunity to the Andean geothermal industry. In light of the criteria of environmental protection, this new opportunity to use geothermal water requires a strict and clear legal framework. As Olave and Vargas- Payera (2020) point out, the protection of water resources in geothermal activities is a pending challenges in Latin America and new potential uses of the energy has to fulfil this gap in advance to assure environmental protection.

During 2022, a new research project was funded for a three years period. This new project, granted by ANID and obtained by CEGA researchers, aims the study of water-energy-food nexus specially addressed from the point of view of resources to generate the necessary knowledge to understand its complexity in Central Chile, and that will provide a timely transfer of the existing connections to decision makers and society. The aim of this study will be to comprehend the recharge and connection of surface and ground water in Central Chile and unravel their relationship with energy and food production. This project will be in operation up to 2025 and the results expected to be obtained will provide valuable information for the energy transition in Central Chile and will be an instrument to evaluate the real possibility of greenhouse gas reduction. Food production not only needs water but also to increase its resilience to extreme events (frost, heavy rains, etc.), so the relationship between water availability, production per hectare, and geothermal energy (direct use) to stabilize crop conditions will be better constrained. Finally, CEGA also promoted the research line of Geothermal and Society, as a way to include communities in the different projects developed along the country. The presence of communities from the beginning of the different direct use implemented by CEGA has shown the best way to increase the positive social perception of geothermal energy in our country (see Vargas-Payera, 2018). At the same time, direct use projects and the introduction of geothermal heat pumps implies several challenges, not only economic and technical, but also cultural and social. The pilot projects from CEGA confirm that long-lasting adoption of GHP require changes in users' cultural practices, which in turn need follow up activities to accompany these processes of change after implementation, not being enough just investing until installation.

7. DISCUSSION AND CONCLUSIONS

After more than one century from the first geothermal explorations in Northern Chile, finally in 2017, Chile joined the selected club of countries generating electricity with at least one geothermal power plant. The Cerro Pabellón power plant in operations since November 2017, begun its operations with two HE-ORC units, 24 MWe each one, and expanding by 2022 to additional 33 MWe. In total, today Chile has 81 MWe capacity installed with geothermal energy, making Chile the only country in South America with geothermal energy installed in their electricity grid. However, as presented in this 2022 country up-date, 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. Following data from the Chilean Geothermal Council, at least 300 MWe are available to be developed in a short time period. But the general opinion, both from developers and academia, is the necessity in Chile of public policies aimed to guarantee the development of geothermal energy as a real, sustainable, and environmentally friendly way to produce electricity. If Chile aims to achieve a 100% renewable matrix by 2050, with the progressive decommission of coal-based thermoelectric power plants (around 4000 MWe currently installed) achieving carbon neutrality by 2050, geothermal energy must play a relevant role. This is critical for electric 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. Of course, solar energy in Northern Chile has geographical and climatic advantage conditions. However, also the presence of high- and medium-enthalpy geothermal systems along the country must be also considered as a logistic advantage for secure electricity matrix and provide energetic independence. Moreover, 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.

After the Chilean Geothermal Council, the current Chilean energy strategy is driven by the matrix decarbonization through public private agreement and other factors listed below:

- By 2050 Carbon Neutral Chile Energy Policy & Green H2 export policy;
- Chile was the first country in the region to subscribe the Paris Agreement;
- Responsible copper and traceability in export products / Option for Lithium;
- New thermal power plants only feasible with carbon capture schemes;
- 100% Renewable energy matrix no later than 2050 & efforts for achieving by 2030;
- Requirement for the electricity grid: Flexible Based Load.

According this institution, flexibility in the electricity system is a new or recent operational feature for the electrical system. With this new concept, technologies such as geothermal energy can contribute with flexible based renewable generation. On the other hand,

permanent drought in Central and Central-Southern Chile deteriorates hydraulic generation and, with this restriction, geothermal is one of the best options for the replacement of hydraulic operation providing a renewable matrix to the Chilean energetic matrix.

In terms of direct use projects, during these last years Chile evidence relatively good progress. Low-temperature geothermal systems are present along the entire country, in particular in the Central Valley, where most of the principal Chilean cities are located. The concentration of population and project in the Central Valley indicates the most promising areas for direct use with geothermal heat pumps. A recent paper published by Muñoz et al (2023) analyzes the Groundwater Heat Pump (GWHP) assessment in three cities in south central Chile (Talca, Temuco, and Osorno), considering the hydraulic parameters of the aquifer, its temperature, and the Thermal Affectation Zone (TAZ) generated around the reinjection well due to the reinjected water flow, and temperature difference due to thermal recovery. 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. However, if problems related with air pollution in various cities from central to southern Chile must be solved, Chile needs to promote geothermal district heating systems as in different European cities. These systems have high cost but also extremely high benefits. 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 the Geothermal Round Table 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. In addition, direct use of geothermal resources is beginning to be more researched and applied in the Chilean society.

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 Cordillera. Chile needs to maintain efforts for the continuity of R+D+I centers as CEGA. The only institution focused on the understanding of geothermal systems, promoting direct use, generating world-class research, maintaining a continuous capacity building and training programs and having very strong and positive impacts with the community. The good practices showed by CEGA in the work with communities and indigenous people are the best platform for the social acceptance of this technology. The development of the different pilot projects along the country that CEGA will implement in the next few years will also be a contribution to the development of geothermal energy in Chile and rest of the Andean countries.

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