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The Andean Geothermal Centre of Excellence (CEGA): Ten Years of Research, Training and Geothermal Development in Chile

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ABSTRACT

The Andean Geothermal Centre of Excellence (CEGA, for its Spanish acronyms) begun its operations by December 2010, product of the interest of a group of scientists that applied to a state fund to create a research centre that could address a critical topic that had been neglected by local scientific production and the State planning of energy development, despite of having the world's largest untapped geothermal potential. CEGA was awarded the FONDAP Fund, the Chilean national programme for excellence research centres in priority areas, one of the most competitive programmes of the Chilean National Science Foundation (CONICYT). These FONDAP programmes support excellence centres for a period of five years, renewable for other additional five years only after positive international evaluation. CEGA is hosted in the Department of Geology of the Universidad de Chile, the principal institution, and includes researchers from the Pontificia Universidad Católica de Chile (the associated institution), Universidad Austral de Chile and National Geological Survey. CEGA is working in five main strategic lines: high-level research, training, networking, outreach and applied scientific goals. Research goals were focused on the establishment of a comprehensive geological model for the Andean geothermal systems, addressing different case studies (natural laboratories) existing in northern, central and southern Chile. Five main research lines were established for allowing our main goals: (1) heat sources; (2) fluid and isotopic geochemistry; (3) heat-fluid-rock interaction, (4) structural geology & geophysics and (5) reservoir architecture and modelling. Each research line has been working on specific scientific questions but also in interdisciplinary projects, both for high- and low-enthalpy systems. Strategic integrative projects for high-enthalpy systems were proposed for Northern and Southern Chile. And for low-enthalpy systems, integrative projects between all research lines were developed with the aim to promote direct-use in our society.

After the ten years granted by CONICYT, CEGA consolidated as an internationally well-reputed research centre. The establishment of world-class analytical facilities was another major highlight of these ten years. Almost fifty professionals worked in the centre, and more than two hundred undergraduates and postgraduates (MSc and PhD level) developed their theses in our centre. CEGA positioned as one of the most relevant centres for training and capacity building in the region. Numerous ISI papers and presentations in national and international congress turned CEGA into a prestigious centre for high impact science generation. CEGA also contributes to the improvement of the geothermal industry in Chile and the rest of the Andean countries, and a special programme was created for the development of direct-use projects in different places in central and southern Chile. Outreach activities were also relevant during these ten years and positioned CEGA as a reference for dissemination and work with society and indigenous communities.

Unfortunately, the continuity of CEGA beyond November 2020, the last month granted by FONDAP, might not be possible, as industry investment in science is rare in Chile and the geothermal industry specifically is minuscule in Chile. Without the State support, all these high impact initiatives might be dramatically interrupted, in accordance with the history of geothermal development of the country where during the last century initiatives flourish and vanish lacking a public policy that allows them to keep the momentum going.

1. INTRODUCTION

The Chilean National Science Foundation (CONICYT, for the Spanish abbreviation of Comisión Nacional de Investigación Científica y Tecnológica) has three main goals: (a) funding scientific and technological programmes, (b) award grants for PhD and MSc students, and (c) promote the scientific and technological culture in Chile. One of the most competitive programmes create by CONICYT is the Fund for Research Centres in Priority Areas (FONDAP, as per the Spanish abbreviation of Fondo de Financiamiento de Centros de Investigación en Áreas Prioritaria). Since its establishment in 1997, FONDAP programme has financed 15 centres in very different areas, such as mathematics, oceanography, astronomy, sustainable agriculture and aquaculture, climate change, sustainable urban development, natural disasters, solar energy, indigenous people and geothermics. Granted FONDAP Centres of Excellence can operate for a period of 10 years (5 + 5 years), with a budget of around US$1.4 million/year, and a yearly evaluation by international reviewers. FONDAP centres need to generate high–impact scientific research of excellence, based on the articulation of multidisciplinary groups of researchers who can demonstrate their productivity in areas where basic national science has reached a high level of development. Other goals of the FONDAP centres are the formation of advanced human capital, the establishment of national and international cooperation networks, and the dissemination of research results to the scientific community and the society.

In 2009, a group of geologists from the Universidad de Chile presented the proposal of the Andean Geothermal Centre of Excellence (CEGA) to the FONDAP call for competition, in order to create a research centre to address geothermal research, a critical topic that had been neglected by local scientific production and the State planning of energy development, despite of having

the world's largest untapped geothermal potential (Lahsen *et al.*, 2005). After an international evaluation, out of more than 30 proposals presented that year, in November 2010 the FONDAP council announced that only two proposals were awarded, being CEGA one of the two selected centres. Consequently, the Andean Geothermal Centre of Excellence (CEGA) begun its activities in December 2010. In November 2015, and after the first five years supported by FONDAP, we presented a continuity plan for the period 2016-2020. This second round, after international evaluation, was finally approved granting economic support up to November 2020.

2. THE ANDEAN GEOTHERMAL CENTRE OF EXCELLENCE (CEGA)

The Andean Geothermal Centre of Excellence (CEGA, http://www.cega-uchile.cl/en/) is a FONDAP-CONICYT project that began operations in December 2010. CEGA comprises a team of researchers from the Faculty of Physical and Mathematical Sciences at the Universidad de Chile (UCH, Principal Institution), with scientists from the Pontificia Universidad Católica de Chile (PUC, Associated Institution) and other national and international institutions. CEGA works to generate and improve geothermal knowledge in Chile, and it is located at the Department of Geology at the School of Physical and Mathematical Sciences of the Universidad de Chile. The centre's mission is to develop geothermal energy as a sustainable, environmentally friendly and economically competitive resource in order to contribute to the energy requirements in Chile and the Andean countries. CEGA's main goals for its second period (2016-2020) are:

- Establish a comprehensive geological model for the Andean geothermal systems.
- Form highly trained professionals in basic and applied research in geothermal energy.
- Promote national and international networking with other world-class research centres.
- Increase public awareness and promote geothermal as renewable, clean and alternative energy.
- Incorporate applied sciences and engineering.

Researchers from various disciplines including, geology, geophysics, computer sciences, civil, mechanical, electrical and hydraulic engineering, together with chemists, journalists, social scientists and technicians form part of the scientific team of CEGA. A total of 44 people (plus a variable number of undergraduate and postgraduate students, in the order of 40-50) integrate this research centre focused in geothermal energy (Table 1), the only of its kind in Chile and South America.

Table 1: Evolution of the CEGA staff (undergraduate and postgraduate students are not included) in the period 2016-2020.

	2016	2017	2018	2019	2020
P. I. Researchers	5	5	5	5	
Associated Researchers	18	15	14	14	
Other Researchers	8	11	16	16	
Post-doctoral researchers	7	7	5	4	
Technicians	3	3	3	3	
Journalists	2	2	2	3	
Administration	2	2	2	2	
Graphic designer	0	0	1	1	
Total	**44**	**45**	**48**	**48**	

The organisation of the Centre for the period 2016-2020 was based on CEGA's five main action lines: research, training, networking, outreach and applied sciences & engineering. CEGA's organisation can be summarised in the follow organigram:

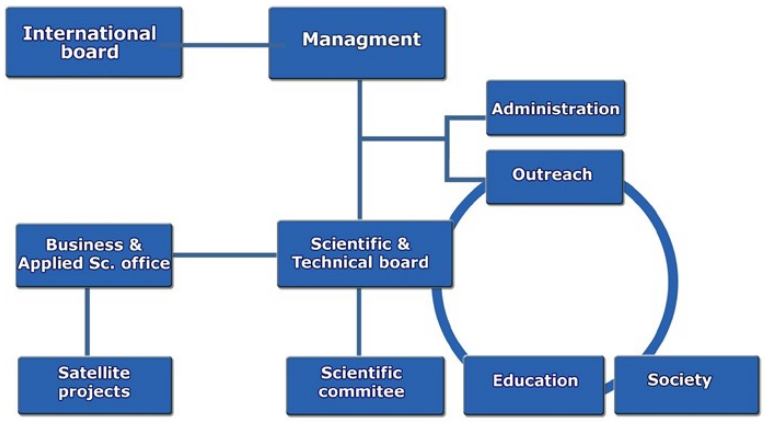

Figure 1: CEGA's organisation for the period of 2016-2020.

The main responsibilities of the different fields defined in the organisation scheme are:

- Management: headed by the Director and Deputy Director
- Administration: responsible for the economy of the Centre, economic report, administration.

- International Board: composed of four outstanding national, international researchers and specialists in renewables energies, with the mission to advise the centre and recommend best international practices.
- Scientific and Technical Board: composed by the principal researchers (scientific committee) and a representative of the outreach office. The main responsibilities of the board are the continuous follow-up of the centre (at least one meeting/month), supervising research, training, outreach and applied for scientific advances.
- Outreach office: responsible for geothermal promotion with target audiences, internal communications, and media management.
- Business and applied sciences: responsible for the management of external projects and relationships with industry, acting as a bridge between academy and industry analysing and preparing research + development + innovation proposals and initiatives.
- Satellite projects: depending on the scientific and technical board, responsible for the execution of specific projects by means of internal or external funding.

2.1 Research at CEGA

The Andean mountain range is a unique and exceptional natural laboratory for geothermal research and with this purpose in mind five main research lines were defined: (1) heat sources; (2) fluid and isotopic geochemistry; (3) heat-fluid-rock interaction, (4) structural geology & geophysics and (5) reservoir architecture and modelling.

- Heat Sources. This scientific line aims to understand the heat source nature of different geothermal systems and the mechanisms of heat transfer to the environment, as well as its influence on the circulation of hydrothermal fluids. Main research questions are: How long magma-derived heat sources can survive to sustain geothermal systems? How mechanisms of heat and mass transfer to the country rocks operate?
- Fluid and Isotopic Geochemistry. This research line aims to characterise the elemental and isotopic geochemistry of fluids from active and fossil geothermal systems in Chile, and to develop and operate in-house, state-of-the-art analytical facilities.
- Heat-Fluid-Rock Interaction. This research line studies the effects of hot fluids that reside or flow through an area of rock that becomes highly altered as a result. The main objectives of this research line are to better constrain the Physico-chemical conditions of high- to low-temperature fluid-rock interaction in geothermal fields, by investigating the stability of alteration minerals together with the kinetic constraints of reactions (e.g. varying fluid conditions, duration of heating, the effect of rock strain, etc.).
- Structural Controls and Geophysics. This research line aims to delineate the late Cenozoic three-dimensional geometry and strain fields, elucidate relations between faults, stratigraphic features, and thermal aquifers, and constrain stress orientations. The comprehensive structural and tectonic analysis of the Andean Cordillera is critical for a complete understanding of geothermal reservoirs. Using structural and geophysical observations and interpretations, this line defines geothermal reservoir models that will result in improved exploration guidelines for new sources of geothermal energy in Chile and the Andean Cordillera.
- Reservoir architecture and Modelling. The main goal of this research line is to obtain a 3-D understanding of the reservoir architecture in terms of permeability (primary and secondary -fracture controlled-) and fluid dynamic in a regional context with the aim to establish the potential aquifer systems. One of the most important elements of geothermal energy systems is the presence of suitable aquifers in contact with geothermal heat sources. Consequently, establishing the nature of rocks that could be acting as reservoirs in geothermal systems will be one of the main scientific goals to develop.

Each of the five research lines addressed specific scientific problems to answer the main scientific questions to understand Andean geothermal systems. In parallel, the synergy between research lines is promoted by the direction, and our strategy for synergy was based on solving first-order problems in active high-enthalpy geothermal systems and promoted collaborative, inter-research lines, research programmes on direct use. For high-enthalpy systems, we focused our research in the northern geothermal cluster (where Cerro Pabellón, El Tatio and La Torta geothermal fields are the most relevant sites) and for southern Chile, we focalised our synergetic efforts in those high to medium geothermal systems strongly controlled by the Liquiñe-Ofqui Fault System (LOFS) and the Andean Traverse Fault (ATF). Questions related to the heat source, structural control, nature of fluids, residence time and influence of depth host-rocks (for allowing or avoiding permeability) are major topics which were researched on together.

Our advances in the five research lines (heat sources, structural geology & geophysics, fluid and isotopic geochemistry, heat-fluid-rock interaction and reservoir architecture and modelling) together with our unit of "satellite projects" and outreach and communication were presented during 2018 in 64 papers (published or under revision, from which 62 are ISI) and 135 presentations to national and international congresses. The average impact of the reported 2018 ISI papers was 3.283, very close to the top 10% (impact > 3.514) reflecting the high quality of our published papers. Fifty-two of the total 62 ISI papers rank as Q1. A summary of the scientific productivity during the period 2016-2020 is given in Table 2.

Table 2: Scientific productivity of CEGA during the period 2016-2020 (number of undergraduate and postgraduate students are cumulative with time)

	Year 2016	Year 2017	Year 2018	Year 2019	Year 2020
Number of ISI papers	80	66	62		
The average impact of publications	2.871	3.091	3.283		
Presentation to Congress	79	72	135		
Number of new post-docs	5 (+6)	1(+7)	2(+8)	1(+9)	
Number of PhD students	23	31	20	20	
Number of MSc students	44	39	41	41	

Number of undergraduate students	43	39	49	54	

(Number of ISI papers and congress during 2019 would only be available at the end of the year)

2.2 Human Resources and Capacity Building at CEGA

Training is a key issue for CEGA. The centre builds capacities and trains advanced human capital at CEGA both the undergraduate and postgraduate level. At the undergraduate level, the centre organises three courses directly related with geothermal: "Principles of Geothermics", "Alteration in Geothermal systems" and "Advances topics on geofluids", all in the curricula of the Department of Geology at the Universidad de Chile. Moreover, the course "Principles of Geothermics" is also part of the Minor in Renewable Energies of the Universidad de Chile. This course was extremely popular among students, with 85 students participating during one semester, almost double of what was initially expected. Students attending this course come from different backgrounds: geology, geophysics, and mechanical, industrial, electrical engineering, among others; reflecting the multidisciplinary concept of geothermal energy.

The team wrote a Spanish language textbook of teachers involved in this Minor (Vargas *et al.*, 2019). This textbook will be published in 2019 by the Editorial Universitaria of the Universidad de Chile and will be the first attempt to present in a single text the different renewables energies and how they could be exploited. CEGA researchers are also involved in current undergraduate programmes in Geology (UCH) and Geophysics (UCH) and are the responsibility of the Major in Geosciences (PUC), an innovative experience with a sustainable increase of students during the last years. Also, the outreach unit at CEGA delivers an undergraduate course on science communication and culture, to introduce students to the importance of disseminating their work and research in different audiences and giving them tools that facilitate this task. Numerous undergraduate students also develop their initial research projects at CEGA, both from the Department of Geology (UCH) and from the Department of Structural Engineering (PUC). These students during one semester develop short research that can also include fieldwork finishing with a small report. This first contact with research has been very successful, and several of these students follow their research activities in CEGA with undergraduate memoir or even postgraduate theses. At the postgraduate level, CEGA researchers participate actively in different Master and PhD programmes supervising student theses.

The number of students working at CEGA during 2018 was around eighty (24 undergraduate, 36 Master of Science and 16 PhD). CEGA supports all these student tuition fees, and in most cases, analytical costs are also supported by CEGA or by projects generated by CEGA researchers. For the MSc students, almost all of them have CEGA fellowships (academic fees and salary). PhD students are also partially supported by CEGA.

2.3 Geothermal Development and Innovation at CEGA

Collaboration with geothermal developers was limited to Enel Green Power, the only active geothermal company working in Chile during 2018. However, the centre continues working in strategic proposals with Transmark and EDC, the other two companies installed in Chile with active exploitation fields[1]. In this sense, CEGA is in continuous contact with the Chilean Geothermal Council sharing our academic experience for the final development of geothermal energy in Chile (and rest of Andean countries). CEGA also maintains continuity in work with national and international stakeholders and, in particular, with the Minister of Energy and the regional divisions of this Minister. CEGA has now a remarkable presence in some regions of southern Chile. Some regional projects were obtained, and a continuous interest for the regional authorities in developing more direct use projects has been observed. Aysen, Los Ríos and La Araucanía are three regions were CEGA is present with regional direct use projects. During 2018 CEGA was also intensely working with the national oil company (ENAP) and the Regional Government of Magallanes with the idea of using abandoned oil and gas depth wells for district heating or, even for electricity generation. This is an ongoing programme seeking funding, waiting for results during 2019.

For direct use, CEGA created its own geothermal direct use pilot projects to show to the communities by experience how life quality improved with this technology, along with a media campaign and media training of our spokespersons that took geothermal out of the shadows and turned it into the energies 'new black'. The centre started this work in Aysén Region, at the Chilean Patagonia, creating the first geothermal projects in the region including a greenhouse in a local prison centre, geothermal heating system at a public school and a geothermal wood dryer. These projects seek to change the culture of heating in southern Chilean cities (which have extremely bad air quality problems during wintertime, Aysén capital is the most polluted city of America (Molina *et al.*, 2017) for a more sustainable, and CO_2 free, comfortable and safe heating technology. Two of these projects were internationally recognised in GeoLac 2018 and 2019 with the prize for the best social impact project of the region (Figure 2).

CEGA has created and developed a consolidated multidisciplinary and inter-research lines research team on direct use. We follow one of the core strategies for the period 2016-2020: the development of a continuous research and training programme in geothermal direct use. Effectively, we have now a solid team integrated by young researchers, including geologist, geophysics, mechanical engineering, and social sciences and communications experts. This group works under the supervision of CEGA's Director, and we continued working on already existing projects and developed new ones for the next years. Thanks to this "direct-use team", CEGA has consolidated as an international reference for promoting direct geothermal use in local industries and organised communities.

We have developed a direct-use strategy promoting this concept not only to the scientific community but also to authorities (Minister, Regional Governments) and communities. Main targets concerning direct use are focused on the following topics:

[1] Information on current geothermal exploration and exploitation concessions in Chile at https://www.sernageomin.cl/catastro-de-concesiones-geotermicas/ last accessed 28 July 2019

- Analyses on the feasibility and direct-use potential in some of the main cities of central and southern Chile (also the most air polluted in America) showing favourability maps for heat pump implementations.
- Introduction of geothermal heat pumps for agriculture (green-houses) and other productive applications.
- Heating of educational building in Southern Chile, promoting the upgrade from wood burning heaters to geothermal heat pumps, with the consequent improvement in students' and teachers' quality of life.
- Collaborative work with stakeholders aimed to change direct use regulation in Chile.
- Development of an innovative programme for using abandoned oil and gas deep wells in Magallanes (Southern Chile) for direct use and, even, if geological conditions are favourable, electricity production.
- Changes in the communication strategies introducing new methodologies for better dissemination of direct use (see Point 5 of this chapter) and creating a novel methodology for better communication of geothermal concepts to indigenous communities.



Figure 2: GeoLac 2019 award for the first geothermal heating system at a public school in Patagonia.

2.4 Work with Communities and Indigenous People

There is consensus in that social acceptance is a crucial factor for the development of any energy project (Cataldi, 1999). Taking into account this social aspect, since 2016 CEGA includes a Geothermics and Society area to study and increase the level of social acceptance of geothermal energy and both incorporate local needs and work on community technology appropriation for the pilot direct use projects the centre develops. Regarding this topic, in 2018, CEGA trained 200 indigenous and local leaders through eight workshops developed in Chilean territories with high geothermal potential. These activities were carried out in coordination with the Ministry of Energy in order to decrease information gaps, enhance local engagement and undertake information asymmetries. Geothermics and Society area in coordination with CEGA's outreach office developed special informative material for those activities (Ministerio de Energía, 2018). CEGA's work with communities has been very intense (Figure 3). A collaborative programme with the Minister of Energy during 2018 allowed the creation of regional seminars along with the country with different indigenous communities. In these seminars, our specialists worked with indigenous leaders, attending their inquiries about geothermal and explaining the different benefits and impacts of geothermal energy, both for electricity generation and direct use. This itinerant programme will end in the first semester of 2019.



Figure 3: Different views of CEGA work with community and schools.

2.5 Outreach and Dissemination

As defined in our original proposal, CEGA's outreach goal is to increase public awareness and promote geothermal as renewable, clean and alternative energy within different non-expert audiences that we have identified as priority publics: decision-makers, school students & teachers, local communities next to areas of geothermal interest, and science-interested young professionals.

CEGA is to date a national and international reference in the positioning of geothermal in the public agenda. Our centre is a source of consultation to advise organisations on how to communicate geothermal energy to different audiences better and also, science in general. Our outreach strategy achieves excellent records, with over 60 appearances in the media annually, and a sum of 6000 followers in our social media (Facebook, Instagram, Twitter, YouTube). CEGA's outreach unit has been awarded three national competitive projects for geothermal dissemination (Explora CONICYT Assessment and Dissemination Projects of Science and Technology), one of which was awarded the 2016 Annual Prize for Innovation in Science Education from the Young Science Foundation. The CEGA outreach unit also organises seminars and actively participates in science fairs, and exhibitions delivering short courses on science communication and generate dissemination materials on various platforms such as digital applications, books, animated videos, infographics, pop-up experiences and more (Figure 4).

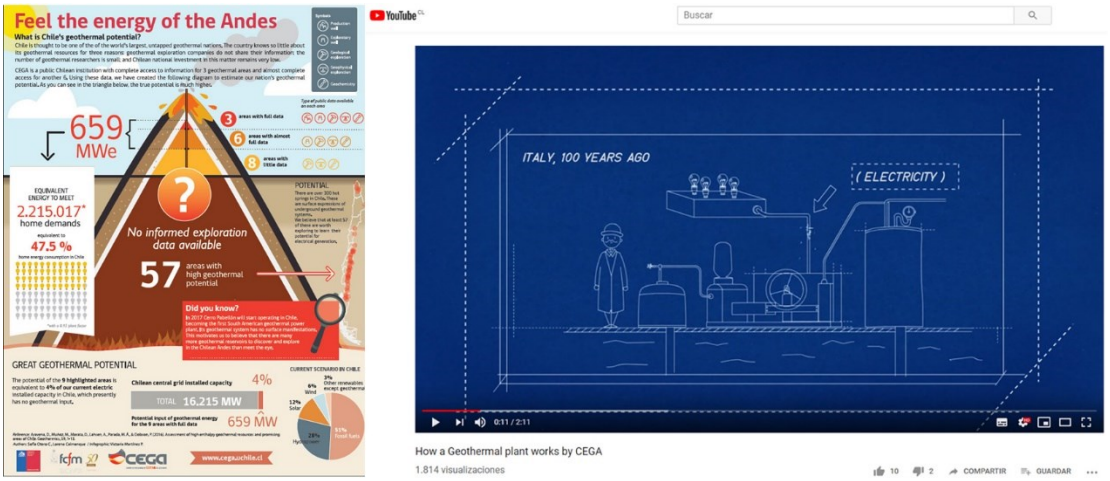

Figure 4: Some outreach products generated by CEGA. All CEGA products are licensed under Creative Commons and are available for download at request. More information at http://www.cega-uchile.cl/

3. CONCLUSION

After the ten years granted by CONICYT, CEGA consolidated as an internationally well-reputed research centre. The establishment of world-class analytical facilities was another major highlight of the decade. Almost fifty professionals worked in the centre, and

more than two hundred undergraduates and postgraduates (MSc and PhD level) developed their theses in our centre. CEGA was consequently constituted in one of the most relevant centres for training and capacity building in the region. Numerous ISI papers and presentations in national and international congress turned CEGA into a prestigious centre of high impact science generation.

CEGA also contributes to the improvement of the geothermal industry in Chile and the rest of the Andean countries, and a special programme was created for the development of direct use projects in different places in central and southern Chile. Outreach activities were also relevant during these ten years and positioned CEGA as a referent for dissemination and work with society and indigenous communities. After nine years of existence, we can state that CEGA is a relevant actor for geothermal development both at national and international level. We developed an intense programme on activities with different stakeholders at both national (Ministers, public institutions, Regional Governments) and regional level (Latin America) and beyond.

Probably one of the biggest achievements of CEGA is to finally play a key role in the development of geothermal research and training in the Andean countries. As defined in our mission, our main goal is to improve the geological knowledge of the Andean geothermal systems and the training and capacity building for new professionals needed in our countries to develop this low CO_2 emission, base-load and autochthonous, clean, renewable energy source. Our results obtained along these previous years allow us to define and establish some comprehensive geological models for the different observed Andean geothermal systems. We can now conclude that there is not a "unique" Andean geothermal system. Notably, differences have been observed between geothermal systems in Norther Chile with respect to those from central and/or Southern Chile. And, of course, notable differences between high-enthalpy vs low-enthalpy systems, addressing different case studies (natural laboratories) existing in northern, central and southern Chile.

Unfortunately, the continuity of CEGA beyond November 2020, the last month granted by FONDAP, might not be possible, as industry investment in science is rare in our country and geothermal industry specifically is minuscule in Chile, without the State support all these high impact initiatives might be dramatically interrupted, in accordance with the history of geothermal development of the country where during the last century initiatives flourish and vanish lacking a public policy that allows them to keep a momentum.

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