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Geothermal Energy in South America: A Case Study for Northern Chile

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Abstract: Chile represents one of the largest undeveloped geothermal areas of the world. Chile forms part of the Pacific Ring of Fire, a belt of volcanoes and earthquake epicentres. This belt contains numerous explored and virgin territories for geothermal energy production. The geothermal potential of Chile exceeds 12,000 MWe. The electricity demand in Chile has grown by 125% between 2000 and 2023. The per capita electricity consumption reached 4237 kWh in 2023. The low-carbon electricity generation continues to grow, reaching 3174 kWh per capita in 2024. The Chilean Government has stressed the importance of renewable energy supplies (mostly solar and geothermal, while also looking at further developing hydro energy). Contrary to other countries in the world, as e.g., New Zealand and Iceland, where geothermal energy is widely exploited, South America in general, and Chile in particular, remain in a preliminary development phase despite the abundant resources and the growing electricity demand. The aim of this paper is to illustrate the development of the geothermal energy in Chile, while showing the economical results of a test case of a Geothermal Power Plant of 50 MWe developed in the North of Chile.

Keywords: geothermal energy; Chile; geothermal power plant; economical assessment

1. Introduction

1.1. Geothermal Energy

Geothermal energy is the heat enclosed within the body of the earth. Geothermal temperature anomalies occur where molten magma comes closer to the surface. This process typically happens at the boundaries between the tectonic plates which make up the surface of the earth like the Pacific basin or 'ring of fire' [1]. In such regions, the temperature gradient within the rock may be 100 °C/km or more. In some cases, water can travel through fractured rock and carry the heat back to the surface. The clearest signs of a potentially exploitable geothermal resource are hot springs and geysers. The water of reservoirs at a depth of 2 km or more below the surface, could reach temperatures of 120–350 °C. These reservoirs are ideally suited for power generation [2–4]. The geothermal generating capacity has grown slowly, and so far 23 countries have exploited geothermal resources in order to produce energy. The largest user is the USA with around 3800 MWe, then countries such as the Philippines with 1935 MWe, Italy with 950 MWe and Mexico with 960 MWe. Indonesia is rated at 2360 MWe, and Japan at ~650 MWe [5]. Geothermal energy presents many benefits, with the continuous availability and the reliability of the energy as major factors. Contrary to other sources of renewable energy, such as solar or wind energy, geothermal energy can generate power in a stable way. Geothermal plants in the United States, New Zealand and Iceland are available to operate around 95% of the time. In addition, geothermal resources can provide energy for 25 or even 35 years [6–9]. Another important benefit is the price stability. For any other power plant, the cost of the energy will be influenced by the cost of the energy resource utilised. For example, many power plants use solid or liquid fuels and the production cost is very variable, albeit very low due to the present low costs of fossil fuels. The price of geothermal energy will hardly change over the time and geothermal energy will have a better performance than other types of energies. In addition, this energy produces minimal environmental impacts and emissions. Table 1 tentatively compares different power generation technologies.

Table 1. Comparison of Power Technologies.

Technology	Average Hours Available Out of 24 h/day	Dispatchability	Availability During Peak Hours	Expected Capacity Factor (%) *
Coal	24	Yes	Yes	71
Nuclear	24	No	Yes	90
Geothermal	24	No	Yes	86–95
Wind	8–9	No	No	25–40
Solar	6–7	No	Yes	25–35
Solar, with thermal energy storage	24	Yes	Yes	70–75
Natural Gas Turbine	24	Yes	Yes	30–35
Hydropower	24	Yes	Yes	30–35
Biomass	24	Yes	Yes	83

* Annual % of production.

1.2. Geothermal Potential in South America

The population in South America is expected to grow by up to 72% by 2035. The main energy source is hydroelectric energy. Although this energy is renewable and clean, its future and further capacity increase is not evident, since most of the readily available resources have been included already. South America has abundant stores of geothermal energy that are still unexploited. These resources are the result of the convergence of the South American tectonic plate and the Nazca plate that has given rise to the Andes Mountain chain [10,11].

Introductory studies carried out in 1999, estimated a potential for electricity generation from geothermal resources between 3979 and 8610 MWe [12]. Nevertheless, subsequent studies implemented in Chile, have estimated a geothermal potential of 16,000 MWe for the next 50 years [13–16]. The South American tectonic plate is bordered by the Nazca and Antarctic plates. These three plates meet at the Chile triple junction. Geothermal resources are the results of earthquakes and volcanic activity produced by the friction and pressure between the plates. Volcanic activity and shallow magma chambers produce heat sources, while the faults and fissures through which water flows is a consequence of earthquakes. The Andes chain, itself a consequence of the convergence of the plates, starts in the north of Venezuela and terminates in Patagonia.

1.2.1. Colombia and Ecuador

Ecuador has an electricity generation potential based on geothermal resources of 534 Mwe [17]. In 2009, one exploratory well was drilled in the Tufiños-Chiles area. In addition, feasibility studies have been carried out in the Chacana and Chachimbiro prospects in the northeast. The studies finished with the definition of two exploration well locations. The use of geothermal resources in Colombia and Ecuador is limited only to recreational purposes, but their Governments have tried to encourage the development of geothermal resources through a joint study in the area of Chiles, Tufiño and Cerro Negro.

1.2.2. Bolivia

Bolivia presents more than 70 areas with geothermal manifestations [18]. The initial assessments and geothermal exploration started in 1970 [19]. Pre-feasibility studies were carried out in the Salar de Empexa and Laguna Colorada fields between 1978 and 1980. After the feasibility studies, new wells were drilled expecting the installation of a 4–10 MWe plant. Nevertheless, this was not developed. The most advanced project in Bolivia is Laguna Colorada project [19]. This is located close to the Chilean border, in the Cordillera Occidental thus reaching an elevation of 4900 m. The project is carried out by state company Empresa Nacional de Electricidad (ENDE). Six wells have been drilled in 2000 with a depth of 1500 m. The potential of the area is around 120 MWe for 20 years with the option for an additional 300 MWe thereafter. Haraldsson [20] states that the aim of this project is the installation of a 100 MWe power plant and the construction of a single circuit 230 kV transmission line with a length of 170 km to connect the plant with the national grid.

1.2.3. Peru

As ThinkGeoEnergy argues [21], Peru has a potential of geothermal energy which reaches 3000 MWe. This potential is concentrated in the areas of Tutupaca, Calacoa, Maure, Laguna Salinas, Chachani, Chivay, Puquiao, Parinacochas, Orcopampa, Catahuasi, Coropuna, Caylloma and Mazo Cruz. The use of geothermal resources in the country is still limited to recreational purposes. Nevertheless, the Peruvian Government has strongly encouraged the development of geothermal resources as an energy source in the country. The Energy Development Corporation of the Philippines and Hot Rock are working in a joint venture for exploration and development of the Chocopata and Quellaapacheta concessions.

1.3. Geothermal Activity in Chile

The cost of the energy in Chile is closely linked with the variation of fossil fuel prices. This is a consequence of Chile having to import almost 75% of its energy requirements. The Chilean Government has worked on different measures for developing new and less expensive sources of energy. Geothermal energy appears as a possible new source of energy, which is still undeveloped in Chile.

The country has a high potential of geothermal resources, reaching 16,000 MWe for the next 50 years, but located at a depth less than 3000 m. with temperatures exceeding 150 °C. Geothermal resources in Chile are a consequence of the active volcanism. The two main volcanic areas in Chile are the Northern Volcanic Zone and the Central-Southern Volcanic Zone. In these zones, different concessions have been identified and granted to different companies in the country (Figure 1). The most important geothermal concessions in the Northern of Chile are Apacheta, Puchuldiza, El Tatio, while in the Central- Southern of Chile locations of Nevados de Chillán and Cordón Caulle are examined.

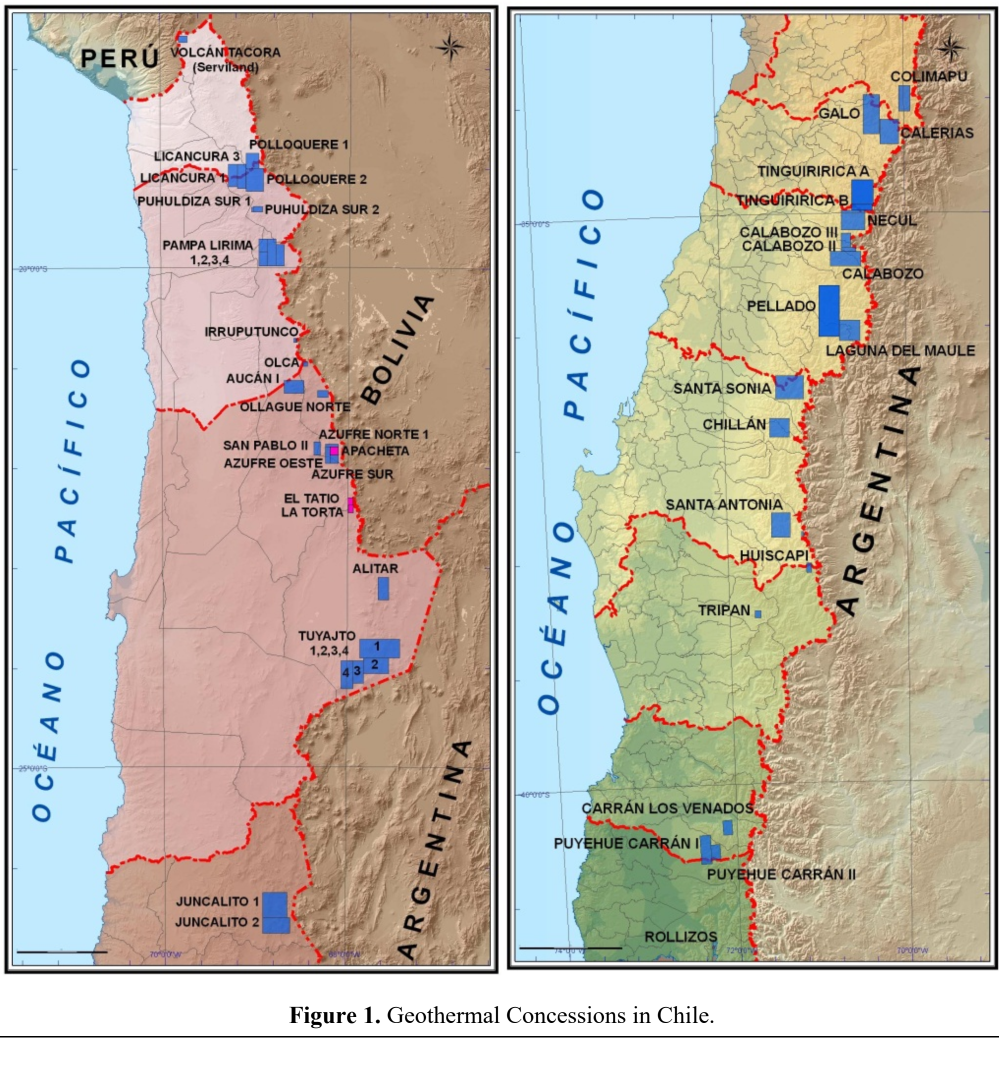

Figure 1. Geothermal Concessions in Chile.

Cerro Pabellon is the most advanced geothermal project in the north of the country. The project is located in the Antofagasta Region, in northern Chile, at an elevation of 4500 m. This is developed by ENAP, the Chilean state oil company, and the Italian state company Ente Nazionale per l'Energia Elettrica (ENEL). In 2012, the environmental impact study was approved for the construction and operation of a 40 MWe plant plus a 10 MWe binary group. In addition, the environmental approval for the transmission line was obtained in 2013. The construction of a first plant started in 2014 (20 MWe), and became operational in 2016.

1.3.1. Geothermal Legislation in Chile

In 2000, the Chilean Government promulgated the Geothermal Law, which defines the general basis in order to develop the geothermal energy in the country. This establishes that the exploration phase has duration of two years, and this phase could be extended for two more years after completing 25% of the commitment budget. After that period, the exploitation phase should start: the company has the right to exploit the field and sell the energy produced.

As a result of the need of increasing renewable energy sources in Chile in order to produce more clean energy and decrease the energy cost in the country, the Chilean Government promulgated several laws aiming to increase the implementation of renewable energies in Chile. These laws also have the purpose of decreasing the dependence of Chile towards hydroelectric energy and fossil fuels. This diversification of the energy matrix of Chile would allow the country to reduce the variability of the cost of energy.

1.3.2. Challenges for Developing Geothermal Projects in Chile

The electricity market in Chile has two main independent systems, the Northern Interconnected Power Grid System (SING) and the Central Interconnected Power Grid System (SIC). According to the National Energy Commission of Chile (CNE), the SING has about 28% of the installed capacity of the country and SIC about 71%. SING supplies the northernmost regions of Chile with an installed capacity of 3602 MWe. The generation companies utilise diesel, fuel and coal as source of energy for generation of electricity. SIC supplies 90% of the population of Chile and it has an installed capacity of 9120 MWe. The main sources of energy for generation of electricity are hydraulic energy (53.46%) and fossil fuels (46.34%).

Despite the Government "Energy Agenda", aiming to considerably reduce the cost of the energy, there are still many challenges and barriers that have to be resolved. Contrary to other countries in the world, as New Zealand and Iceland where geothermal energy is widely exploited, Chile remains in a very preliminary phase despite the abundant resources, the correct legal framework and the growing electricity demand. Despite these advantages, many barriers have stopped the development of the geothermal potential. Geothermal projects have an exploratory phase which includes a high exploratory risk. This risk is unfamiliar for banks and other sources of funding. As a consequence, obtaining funds for developing exploration geothermal projects is very difficult. In addition, these types of projects are very capital intensive, requiring internal and external funding. Moreover, Chile did not propose any financial incentives for developing unconventional renewable energy projects in place, unlike other countries which have implemented measures of the price tariffs, tax credits or access to state funds.

Chile also presents barriers related to its geographical setting. Chile is the southernmost country of America and the geothermal resources are located in places with difficult access, at elevations between 4500 to 4900 m in very dry environments. These aspects increase the cost for moving rigs and equipment to the places in order to develop the projects. In addition, cooling water for the power block needs to be pumped over long distances.

As the geothermal industry is still undeveloped in Chile, additional barriers include the lack of skilled professionals like geologists, drilling engineers, reservoir engineers with a high know-how in geothermal projects. Although it is possible to hire foreign professionals with expertise in geothermal projects, this increases the cost of the projects.

Geothermal resources are also located close to native communities, making the granting of exploration, exploitation and environmental approvals more difficult: the Tatio project, located in northern Chile has a high potential, but a nearby well was stopped as a consequence of problems with the communities. Chile still lacks a suitable legal framework that establishes the obligations of the institutions, financial policies, relationships with the communities and real incentives for developing unconventional renewable energy projects in the country.

2. Uncertainties in Assessing a Geothermal Project in Northern Chile

Cerro Pabellon will be the first geothermal project in South America to complete an initial deep well exploration stage and reach a development stage. Four exploratory and appraisal wells were drilled thus confirming the existence of a reservoir at a depth of about 2000 m below ground level. However, in spite of the initial success, validating and developing geothermal resources through test drilling is capital intensive and the small number of wells and the general lack of previous experiences in the geological environment of the Andes Mountains make it specially risky. The main uncertainties are associated with the exploration risk and the well performance forecast.

2.1. Exploration Risk

According to the information published in the Environmental Impact Study by the project's operator Geotermica del Norte [22], later confirmed by Vidal et al. [4], four exploration and appraisal deep wells were drilled in Cerro Pabellon project (CP-1 to CP-4. Three of the 4 wells (CP-1, 2 and 4) reported finding a unit of fractured volcanic rocks (Hydrological Unit 3), that shows the presence of a liquid-dominated reservoir with a maximum-measured temperature of 260 °C [23]. These results confirm the prospect previously suggested by a geophysical model based on a 3-dimensional magneto-telluric survey acquired over the prospective area. The fourth well (CP-3) fell too short into the seal zone and did not reach the reservoir unit.

In the proposed development plan, those two wells with the highest temperature and transmissibility will be completed as producers and connected to the plant; the shorter well and one of the appraisal wells (well CP-3, with low reservoir's transmissivity) are reported to be converted into injector wells [24].

A study carried out by the International Financial Corporation (IFC) of World Bank Group (2013) [25] reports the results of 2613 wells throughout 57 fields in 14 countries showing that the exploration phase has a significant range of well success rate (63% of fields with well success rates of more than 50% and 42% of the fields exceeds 70%). Cerro Pabellon results impliy a 67% chance of success during the exploration-appraisal phase of the project (two out of three wells that tested the reservoir), which is in line with the IFC findings. The variation of success rates during different project phases is illustrated in Figure 2.

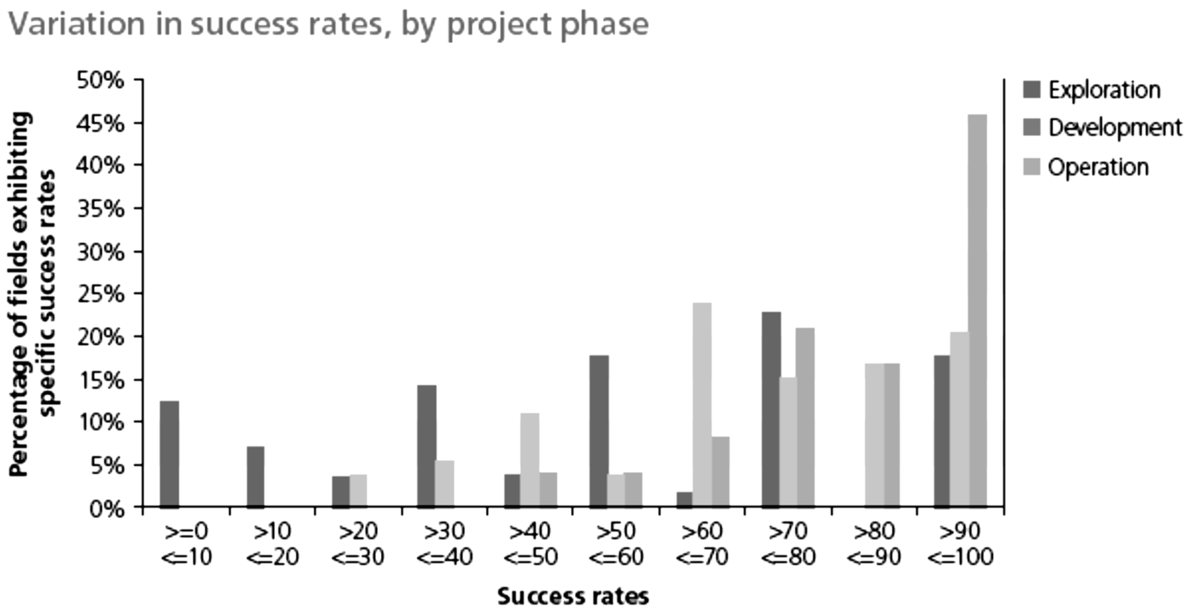

Figure 2. Variation in success rates by phase of development [25].

The total area covered by the geothermal concession is 81 km^2. According to the project map [22], the area tested by the exploration wells and where the initial development wells that will feed a 50 MWe plant are being proposed encompass around 10 km^2. Therefore, in this stage, resources from only 13% of the geothermal concessions have been tested and will be developed.

2.2. Well Performance Forecast

Since the most common reservoirs in geothermal systems are volcanic rocks that usually have very low matrix permeability, most high temperature geothermal fields are highly naturally fractured systems. The existence, size and distribution of these fractures, determine the capacity and, to a large extent, the definitive productivity of a geothermal reservoir. Fractures in geothermal reservoirs can be highly heterogenous and may vary in scale from micro-cracks to fractures extending over meters or more [26]. Wells that do not encounter these fractures may have a too low permeability and, therefore, a too low productivity to be considered commercial. Nevertheless, when the result is an unsuccessful production well, it may be used as an injection well [25], recovering some of the associated financial losses.

In Cerro Pabellon, the three deep wells found fractured volcanic rocks as reservoir, detected as zones with partial to total losses of circulation. Injectivity tests showed transmissivity between 17 and 67 m^2/d in the two best wells (CP-1 and 2). The third well (CP-4), having a low transmissivity, will be converted into an injection well.

A geothermal well is considered successful when the productivity is above a certain threshold, which in many cases could be 3 MWe. Based on the injectivity tests, in Cerro Pabellon productivity has been estimated in a range of 5–10 MWe per well.

Lateral continuity of the fracture system detected by the wells will be an important factor of uncertainty as drilling progresses. Therefore, a dry or uneconomic well risk factor should be considered in the development phase of the field. The earlier mentioned IFC report states that 75% of the fields reached more than 60% of success development (Figure 2).

3. Economic Evaluation of a Geothermal Project in Northern Chile

3.1. Considerations Concerning Potential and Capacity

There will be a significant uncertainty on the real performance and costs of a geothermal project in Chile. In addition, there is a lack of good geothermal economical models that allow companies to assess their projects. The economic model that was developed in this study was based on information of international geothermal projects that was tailored to the Chilean reality. In the economic assessment of a geothermal project in Chile, a well success rate of 65% is utilised in the exploration phase and 75% in the development phase. Regarding the gross capacity of the wells, a wide range is possible. Based on the IFC study, the average well capacity is 6.8 MWe. In addition, the study shows the correlation between the well depth and the average capacity. Geothermal wells in Chile have a depth between 1300 and 2000 m. According to this study, the average well capacity for that depth will reach 6.5 MWe (Figure 3). The economic assessment utilises a gross capacity of 6.0 MWe per well.

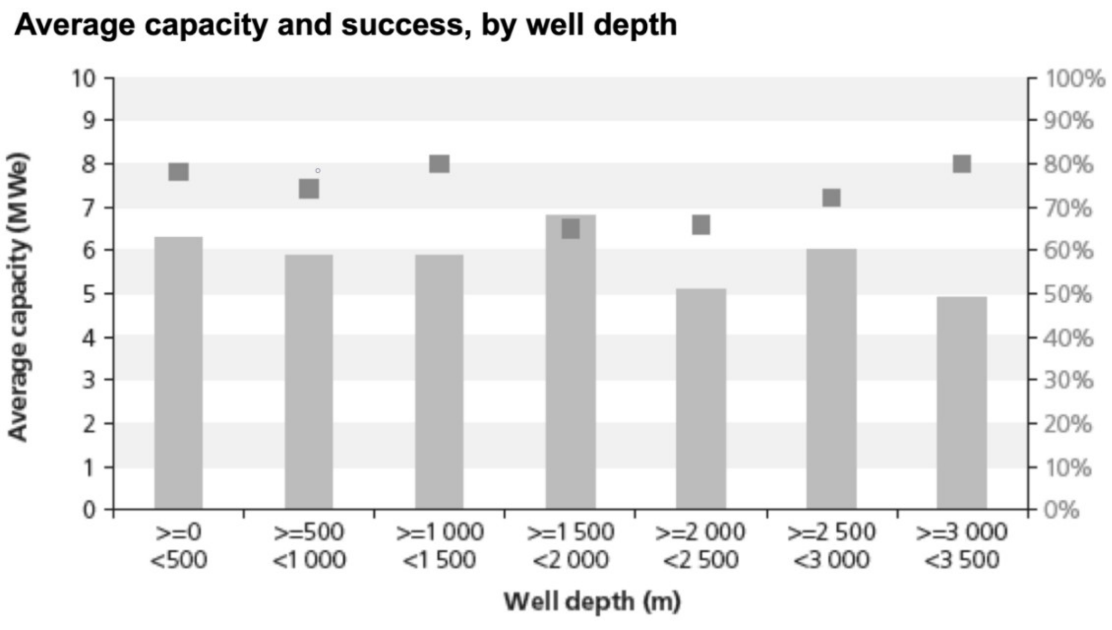

Figure 3. Average Well Capacity (MWe) and success by depth of development wells, indicated by ■.

3.2. Prices and NCRE Bonus

The energy produced by the geothermal project will be sold through a Power Purchase Agreement (PPA) to the mining companies in the North of Chile in order to supply their energy demand. The estimated price is 105 \$/MWh. This price is based on the average of similar PPA values negotiated by other companies. This price also includes the Non-Conventional Renewable Energy, NCRE Bonus, which is paid by the final client and represents an incentive granted by the Government of Chile in order to encourage the development of unconventional sources of energy in the country. The NCRE financial incentive encourages the development of non-conventional renewable energy in the country. This financial incentive or bonus applies to Geothermal Energy.

The economic assessment considers a PPA for 20 years and the continuity of the price for the following years (Table 2).

Table 2. PPA Price and NCRE from 2015–2025.

	2015	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
Base Price ($/MWh)	102	101	100	99	97	95	94	94	94	94	94
NCRE Bonus ($/MWh)	3	4	5	6	8	10	11	11	11	11	11
PPA FINAL PRICE (US$/MWh)	105	105	105	105	105	105	105	105	105	105	105

3.3. Investments and Economic Results

Abbreviations used in the economic analysis are detailed in the Supplementary Information.

The net capacity of the power plant is assumed to be 50 MWe, using condensation turbines. The total investment per MWe, which includes exploration, development and plant contracting, reaches 7.70 MUS$/MWe (Table 3).

Table 3. Key Performance Indicators.

Key Performance Indicators	**Power Plant Capacity**
Gross Capacity (MW)	57.21
Net Capacity (MW)	50
OPEX/MW (MUS$)	0.08
Total Capex/MW(MUS$/MW)	7.70
Exploration	0.88
Development drilling	2.58
EPC	2.10
T-Line	0.88
Campsite	0.54
Civil Works & Others	0.43
Miscellaneous	0.29

The development drilling investments consider the wells that have to be drilled in order to replace the natural decline of the production of the wells (an average decline of 2% per year was considered).

Based on all the assumptions mentioned above, the project was modelled for 40 years of operation. The economic assessment of the project shows an NPV of −21,163 MUS$ for a PPA Price of 105 US$MWe and a NPV of 9918 for a PPA Price of 120 US$/MWe. The results show that the project is very sensitive to price (Table 4). The investment NPV/WPV ratio is a financial ratio between the net present value of the investment and the net present value of the project. This ratio allows investors to measure the real performance of the total investment of the project compared with the value created by these investments.

Table 4. Economical Results (Discount Rate 10%).

	PPA Price			
Economical Results	105 (US$/MWh)	110 (US$/MWh)	115 (US$/MWh)	120 (US$/MWh)
NPV(MUS$)	−21,163	−10,777	−430	9918
IRR	9.2%	9.7%	9.9%	10.7%
Investment NPV/NPV	−11.0%	−5.6%	−0.2%	5.1%
Payback	13 years, 1 month	12 years, 8 months	12 years, 4 months	12 years, 1 month

3.4. Economies of Scale

Even more important than price, it is the economies of scale in a geothermal power plant. For the same price, a power plant could be more profitable only because it has a higher capacity. This is a consequence of two effects: exploration phase and power plant investments. All the projects have to invest in the exploration phase, which in addition presents risk. Exploration investment has economies of scale since that the total investment utilised will be the same for the different power plant capacities. Likewise, the investment in the power plant presents economies of scale since the total cost will not increase in the same proportion as the capacity of the plant. The results show that a power plant capacity of 50 MWe is very inefficient in CAPEX per MWe utilised compared to a power plant of 75 MWe or 100 MWe (Table 5).

Related to the economic value of the project, it is possible to observe that this increases its value substantially when its power plant capacity growth. For the same price, it is possible to reach an additional value of 38,000 MUS$ by just increasing the capacity of the plant. For a price of 105 US$/MWh a power plant with a capacity of 50 MWe is not profitable; nevertheless, a power plant with a capacity of 75 MWe or 105 MWe are profitable (Figure 4).

Table 5. Scale Economies based on different Power Plant Capacities.

Key Performance Indicators	Power Plant Capacity		
Gross Capacity (MW)	57.21	84.43	114.22
Net Capacity (MW)	50	75	100
OPEX/MW (MUS$)	0.08	0.05	0.04
Total Capex/MW(MUS$/MW)	7.70	7.16	7.12
Exploration	0.88	0.59	0.44
Development drilling	2.58	262	2.56
EPC	2.10	2.20	2.32
T-Line	0.88	0.81	0.78
Campsite	0.54	0.36	0.35
Others	0.43	0.29	0.36
Miscellaneous	0.29	0.29	0.29

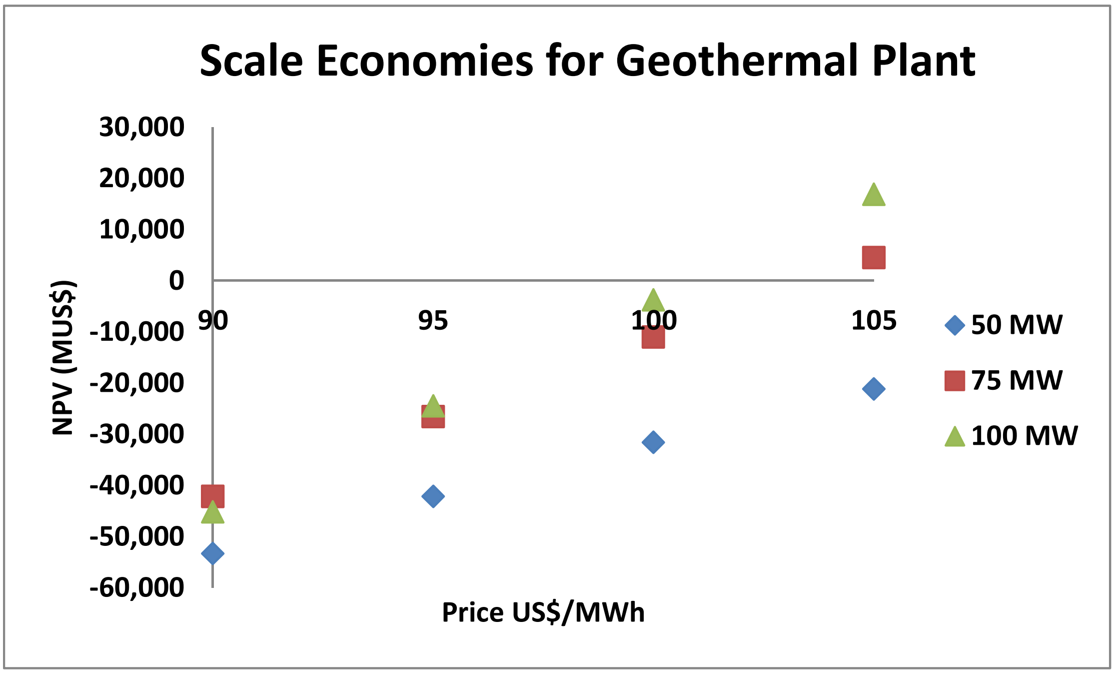

Figure 4. Economy of Scale of a Geothermal Project.

3.5. Environmental Benefits

Although the geothermally pumped water contains high levels of salt and other minerals, the impact is negligible, since the water is directly pumped back to the geothermal reservoir. No cases of water contamination were reported from geothermal sites.

Although cooling requires between 6.5 and 10 m^3 H_2O/MWh, mostly cold geothermal fluid is used and stored in a reservoir.

Air emissions, possibly H_2S, NH_3, CH_4 and B, are commonly contained by reinjecting the geothermal fluids into the well. Occasional emissions can be contained, mostly by alkaline scrubbing. The land use, as an important assessment factor, is limited to ~5 ha/MWe. This is comparable to the land use of concentrated solar power plants.

The emission of Greenhouse Gases (CO_2, CH_4, NH_3) is limited and significantly below common fossil fuel power generation plants. On average, CO_2 emission of geothermal plants is below 0.1 kg $CO_{2\text{-equivalent}}$/kWh, significantly below ~0.15 to 0.5 kg $CO_{2\text{-equivalent}}$/kWh when using natural gas, or 0.7 to 1.8 kg $CO_{2\text{-equivalent}}$/kWh when using coal.

Clearly, the environmental impacts of a geothermal power plant are limited and can be easily contained.

4. Conclusions

Geothermal resources could play a very important role in the energy matrix of Chile. Chile is facing a high cost of energy, which could affect the growth of the country. Chile has been annually growing at an average rate of 5.2% but the cost of the energy has increased between 25% and 30%.

Based on the economical assessment of a geothermal power plant in the North of Chile, it is possible to develop a geothermal project if this reaches the right capacity with a competitive price. Nevertheless, the economical results are still not widely profitable in order to incentivize private companies for investing in a geothermal project. If the Government of Chile wants to develop the geothermal industry in the country, it has to implement the adequate incentives.

As a consequence of the development of a geothermal industry in Chile, the total costs and investments will decrease thus allowing the companies to achieve the expected profitability for continuing investing in geothermal projects in the country.

Author Contributions

D.A., J.B. and Y.D.: conceptualization, methodology, software; D.A., Y.D., M.Y. and J.Z.: data curation, writing—original draft preparation; J.B. and Y.D.: visualization, investigation; J.B. and Y.D.: supervision; D.A., Y.D. and M.Y.: software, validation; all authors: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data will be made available on request to the corresponding authors.

Conflicts of Interest

The authors declare no conflict of interest.

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