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Article

Geothermal Potential Evaluation for Northern Chile and Suggestions for New Energy Plans

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Abstract: Chile is a country rich in natural resources, and it is the world's largest producer and exporter of copper. Mining is the main industry and is an essential part of the Chilean economy, but the country has limited indigenous fossil fuels—over 90% of the country's fossil fuels must be imported. The electricity market in Chile comprises two main independent systems: the Northern Interconnected Power Grid (SING) and the Central Interconnected Power Grid (SIC). Currently, the primary Chilean energy source is imported fossil fuels, whereas hydropower represents the main indigenous source. Other renewables such as wind, solar, biomass and geothermics are as yet poorly developed. Specifically, geothermal energy has not been exploited in Chile, but among all renewables it has the greatest potential. The transition from thermal power plants to renewable energy power plants is an important target for the Chilean Government in order to reduce dependence on imported fossil fuels. In this framework, the proposed study presents an evaluation of the geothermal potential for northern Chile in terms of power generation. The El Tatio, Surire, Puchuldiza, Orriputunco-Olca and Apacheta geothermal fields are considered for the analysis. The estimated electrical power is approximately 1300 MWe, and the energy supply is 10,200 GWh/year. This means that more than 30% of the SING energy could be provided from geothermal energy, reducing the dependence on imported fossil fuels, saving 8 Mton/year of CO_2 and supplying the mining industry, which is Chile's primary energy user.

Keywords: renewable energy; geothermics; strategic energy planning; sustainable development; Chile

1. Introduction

Chile is a republic located in South America bordered by the Andes Mountains and the Pacific Ocean. The country is partitioned into 15 administrative regions. Chile is rich in natural resources such as copper, timber, nitrates, precious metals and molybdenum. It is the world's largest producer and exporter of copper and mining is the primary Chilean industry and an essential component of the Chilean economy. Although Chile has an abundance of copper and other mining resources, it has limited indigenous fossil fuels and over 90% of its fossil fuels needs must be met by imports [1].

In 2012, Chile's energy demand was approximately 60,000 GWh and it is projected to increase by 4.9% annually reaching a consumption of 136,000 GWh/year by 2030 [1,2]. The installed capacity for electric generation is 17,500 MWe, producing approximately 65,600 GWh/year [3]. Of the total installed capacity 62% corresponds to fossil-fuelled power plants, 34% to hydropower plants and only 4% to renewable resources [3]. The majority of the total electricity is consumed by the mining and industry sectors. The electricity market in Chile is comprised of two main independent systems:

SING—the Northern Interconnected Power Grid;
SIC—the Central Interconnected Power Grid.

SING has an installed capacity of approximately 3800 MWe, 100% of which is generated by imported fossil fuel. SIC has an installed capacity of 13,500 MWe, 53% of which is generated by imported fossil fuels, 42% by hydroelectric power and the remaining 4% by renewable resources [3].

Therefore, Chile is heavily dependent on imported fossil fuels and hydropower represent the main indigenous energy source of the country. Other renewable resources such as wind, solar, biomass and geothermal energy are poorly developed, but several corporations, such as the Centre for Renewable Energy (CER), have been working to ensure the optimal participation of renewable energies in Chile's energy matrix to contribute to the sustainable development of the country [4].

In 2011, The Global Energy Network Institute (GENI) suggested that a strategic energy plan for Chile was necessary to ensure both energy autonomy of the country and the transition from thermal power plants to renewable energy power plants [4]. This passage from conventional energy to renewable sources is indispensable both to reduce the amount of greenhouse gases emitted into the atmosphere and to reduce the dependence on imported fossil fuels. Under such circumstances, renewable energy resources in Chile should become more relevant. Geothermal energy is not yet exploited here, but among all renewable resources it has the greatest development potential. Although no geothermal power plants have been installed to date, a vigorous geothermal exploration program is under way [5]. A preliminary evaluation of northern Chile's geothermal power potential is approximately 2000 MWe, whereas the country's central-southern region is estimated to be between 1000 and 1500 MWe [6,7]. This makes Chile one of the most attractive countries for the utilisation of geothermal energy.

The purpose of this work is to review the geothermal potential evaluation for northern Chile in terms of power generation, considering the conventional geothermal resources of Surire, Puchuldiza, Apacheta, El Tatio and Irriputunco-Olca. This evaluation could provide useful information for the development of a new strategic energy plan applicable to the SING. Northern Chile has been chosen for the analysis because more data are available than for the central and southern regions, and because of the country's large energy reliance on imported fossil fuels.

2. Regional Setting of the Study Area

Northern Chile has a relatively homogeneous geological setting, consisting of Lower Miocene–Pleistocene ignimbrite deposits and andesitic–rhyolitic volcanic products overlying Middle Cretaceous–Upper Miocene volcano-sedimentary formations [8–13]. The latter hosts the main hydrothermal reservoirs that predominantly consist of andesitic lava and pyroclastic flows, conglomerates, breccias, sandstones, siltstones, limestones, marls and evaporites [10,14]. The main hydrothermal systems are located within the NS-, NW-trending grabens [8,10,15] on the western side of the Pliocene–Holocene Central Andean Volcanic Zone.

For each studied system (Figure 1), a brief geographical/geological setting with relative descriptions of the geothermal manifestations at the surface is reported. The geothermal fields of Colpitas and Larima are also described, but it was not possible to evaluate their geothermal potential due to a lack of public data.

Figure 1. Geothermal areas of northern Chile. The red box shows the studied area.

2.1. Colpitas

The Colpitas geothermal field is located in the northernmost part of Chile, in the Arica and Parinacota region, with an elevation from 4000 to 5200 m above sea level (a.s.l.). Geologically, the area is characterised by volcanic rocks and volcanoclastic deposits and volcano-sedimentary sequences ranging from Miocene to Holocene [16]. The stratigraphy is mainly comprised of the Lupica Formation (Upper Oligocene-Miocene), corresponding to the *basement* of the basin. It is constituted by rhyolitic ash flow tuffs, andesitic lavas and subvolcanic plugs as well as epiclastic sandstones. The Lupica Formation underlies, in the western part of the study area, the Huaylas Formation (Upper Miocene). The Huaylas Formation is mainly formed by lacustrine epiclastic sandstones and gravels, with interbedded ash layers and is itself overlain by the Lauca Ignimbrite (Upper Pliocene).The potential reservoir is likely located within Cenozoic volcanoclastic rocks. The thermal springs, located in the northern and southern part of the Colpitas field, have temperatures that range from 28 to 55 °C with a total flow <10 L/s [16]. The North Thermal springs are interpreted as being the most representative of deeply derived thermal waters [16]. Stable isotope composition indicate that thermal spring waters have been subject to evaporation, or more likely, varying amounts of mixing with groundwater brine that underlines the salt deposits in the basin [16]. Na/K ratio of the North Thermal Springs gives the hottest equilibration temperatures of approximately 235 °C. Many of the springs have moderate bubbling of what is likely to be CO_2 and H_2S gas [16]. Recently, a slimhole well was drilled to prove the existence of a geothermal reservoir and to evaluate the potential of the field [3,16].

2.2. Surire

The Surire hydrothermal system is located at an altitude of 4000–4300 m a.s.l., in the southeast part of the Salar de Surire. Many volcanoes rise above 5500 m around the salar, some lavas have flowed into it and are now partially buried by sediments. The volcanoes are dacitic and andesitic; the dacities generally occur as domes and the andesities form stratovolcanoes. In 1972, as many as 133 thermal discharges occurred in an approximately 15 km^2 area [15]. Presently, most of the bubbling pools and thermal springs are located along the southern border of the salar and have temperatures between 20 and 80 °C [15]. The Database of Geothermal Resources in Latin America & the Caribbean [17] indicated a potential temperature of the geothermal reservoir of 110–234 °C and an electric power output of 50–60 MWe.

2.3. Puchuldiza

The Puchuldiza-Tuja hydrothermal system is located at an altitude of approximately 4100–4200 m a.s.l. and is 27 km SW of the active Isluga volcano that is characterised by permanent fumarolic activity [18]. The hydrothermal area of Puchuldiza is limited both to the north and south by several Plio-Pleistocene stratovolcanoes reaching altitudes higher than 5000 m. A Pleistocene-Holocene fracture system characterized by northeast-southwest faults affected the Plio-Pleistocene volcanoes and produced, in part, the surficial hydrothermal activity. The fluid discharges within the Puchuldiza area are controlled by the Churicollo, Puchuldiza and Tuja faults. Several thermal springs with low gas emissions surround the main emission areas [19]. The geothermal reservoir is hosted in the Utayane Ignimbrite and the Puchuldiza Formation. The permeability of the volcanic formations is due to cooling joints and tectonic fractures [6]. Geothermometry evaluations suggest that the fluid reservoir has a relatively high equilibrium temperature, up to 270 °C [18]. The Database of Geothermal Resources in Latin America & the Caribbean [17] indicated a potential electric power output of 190 MWe.

2.4. Lirima

The Lirima geothermal field is located at an altitude of 3900 m a.s.l., 25 km SW of the Sillajguay volcanic chain. The geology of the area is characterized by Mesozoic basement rocks constituted by clastic-carbonate sequences, volcanic and sedimentary rocks of Oligocene-Miocene and middle Miocene to Pleistocene volcanic edifices [20]. In the Lirima area have been recognized bubbling pools, along the western side of the field, and three main sites with thermal springs [21]. The thermal springs are characterized by temperatures between 38 °C and 80 °C, high Cl and B concentration, $\delta^{18}O$ enrichment, and relatively low Mg concentration; consistent with deep circulation from a geothermal reservoir, and low mixing degree. Minimum temperatures from water and gas geothermometers range from 200 to 200 °C.

2.5. Apacheta

Apacheta is located 105 km NE of Calama City and 55 km NW of the El Tatio hydrothermal system. A 180 m deep well (PAE-1) drilled by the Chilean National Mining Company (CODELCO) in 1998 produced steam measured at 88 °C [22]. Fluid discharges emitting superheated steam (up to 118 °C) [22] with high flow rates are found along the eastern flank of the 5150 m high Apacheta volcano. Currently, in the Apacheta geothermal field, a project (Cerro Pabellón) is underway for power production from geothermal resources. Project feasibility studies began in 2005, then four wells were drilled from 2009 to 2010, whose depths reached between 1300 and 2000 m. The results of the production and injection tests showed the presence of a liquid-dominated reservoir with a maximum-measured temperature of 260 °C. ENEL Green Power has planned the drilling of 13 wells to operate a 50 MWe power plant. This project represents the first commercial-scale geothermal plant in the country [7].

2.6. Irriputunco-Olca

The Irriputuncu-Olca field is characterised by the presence of the Irriputuncu and Olca Volcanos, located in the Chilean Altipiano at 4000–5000 m a.s.l., and in the vicinity of the copper mine. Irriputuncu is an active dacitic stratovolcano, with fumaroles at the top crater and one acid-sulphate hot spring at the base of the volcano. Two slim boreholes (800 and 1430 m in depth) measured a bottom hole temperature close to 150 °C and 195 °C (at 3350 and 3000 m a.s.l., respectively) [23]. Time domain electromagnetic (TEM) and Magnetotelluric (MT) data suggests the presence of a potentially deeper reservoir at approximately 220 °C [23]. Olca is an andesitic volcano, of which the TEM-MT data exhibit two conductive layers intercalated with resistive zones. The possible thickness of the reservoir is 2000–3000 m and for the surface area there are three estimates, conservative (7.5 km^2), likely (15 km^2) and optimistic (45 km^2) [23]. Preliminary results, assuming up to 10 MWe/km^2 and a reservoir temperature of 230–300 ℃, suggest a potential for electric generation between 75 and 450 MWe [23].

2.7. El Tatio

El Tatio is located 100 km E of Calama City at an altitude of 4300 m a.s.l. Several thermal springs, fumaroles, geysers and boiling and mud pools are present. Hydrogeological models [24,25] indicate that meteoric waters infiltrate in recharge areas 15 km E of the field. The main hydrothermal reservoir is confined within the permeable Puripicar Formation and the Salado Member. An important secondary aquifer occurs in the Tucle Dacite subunit that is capped by the impermeable Tatio Ignimbrite [24]. In Figure 2, the simplified geological profile and circulation conceptual model are shown. The potential geothermal reservoir is hosted in the Puripicar Formation and Salado Member, although a temperature of approximately 170 ℃ was recorded in the permeable levels hosted in the Grupo volcanic de Tucle [6].

In Figure 3, a profile of the El Tatio Graben is shown. It crosses through the wells numbered 1, 4, 9 and 7, from NW to SE. In the boreholes, three permeable zones were detected. The permeability essentially originated by tectonic fracturing or rapid cooling of the volcanic bodies [9]. The temperatures of the three permeable zones ranged from 170, 230 to 260 ℃, moving from the Grupo volcanico de Tucle to Puripicar Formation and Salado Member, respectively [9].

Figure 2. Simplified geological map of the El Tatio geothermal field, geological profile and circulation conceptual model. The dashed box represents the area in Figure 3 (modified from [9]).

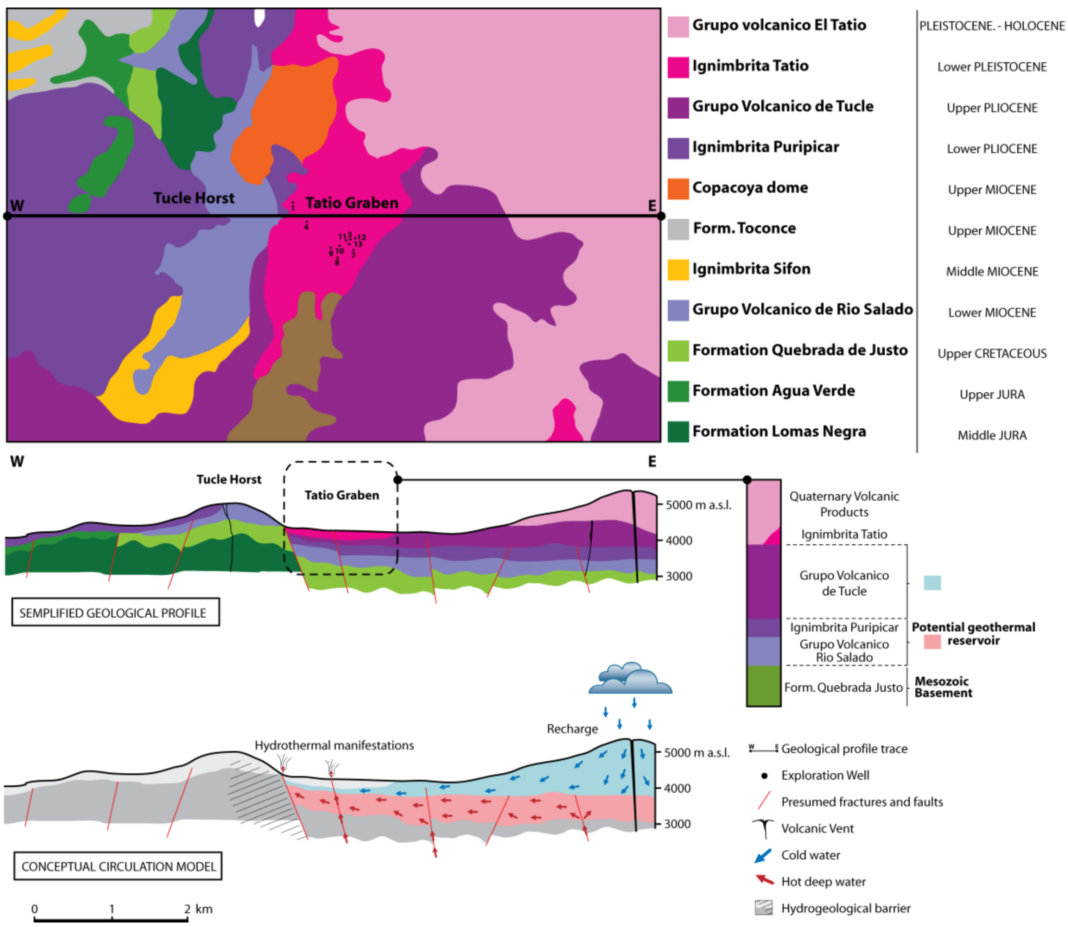
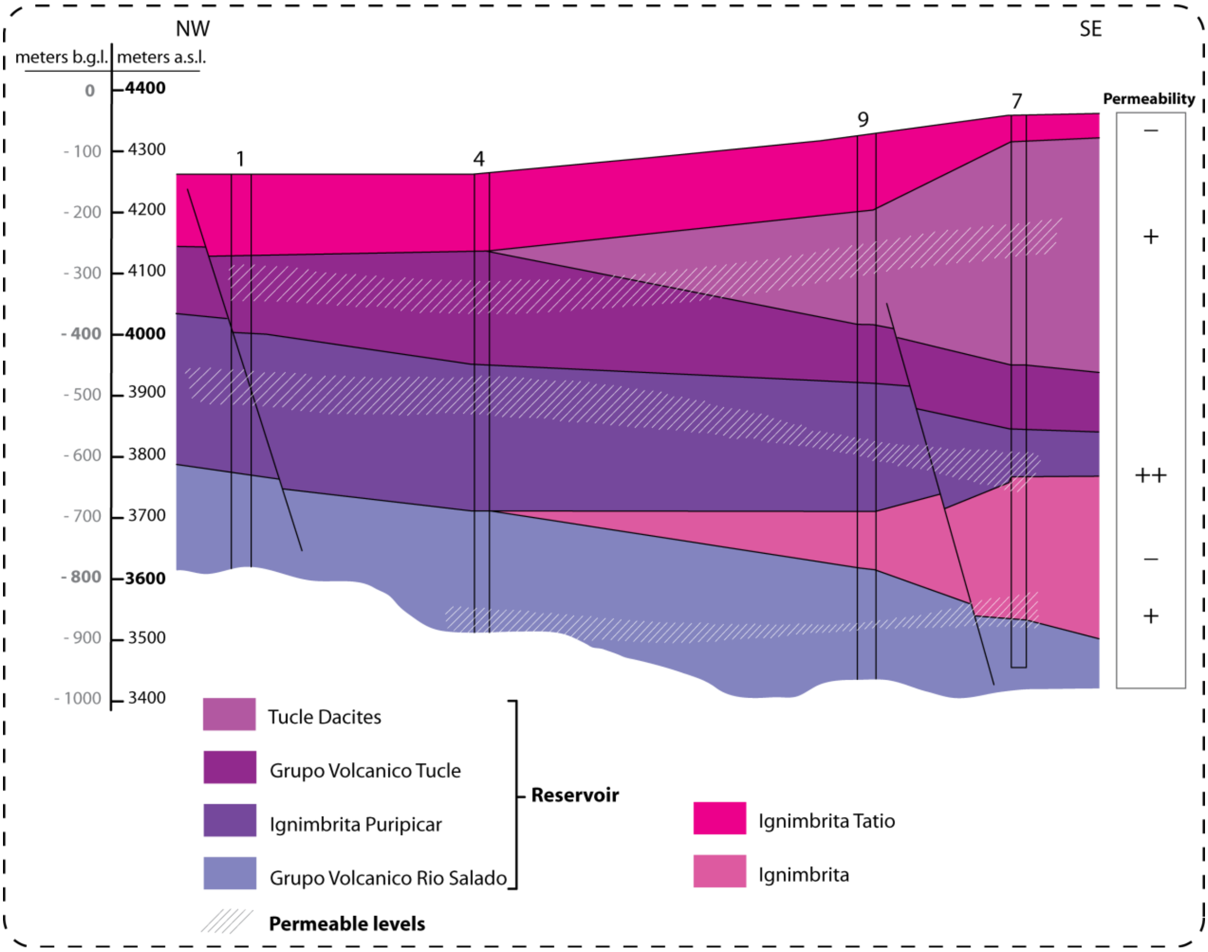


Figure 3. The geological profile from NW-SE of the El Tatio graben through the boreholes numbered 1, 4, 9 and 7 (modified from [9]). For further details see text in the previous page; paragraph relative to El-Tatio.



2.8. Geothermal Exploration in Chile

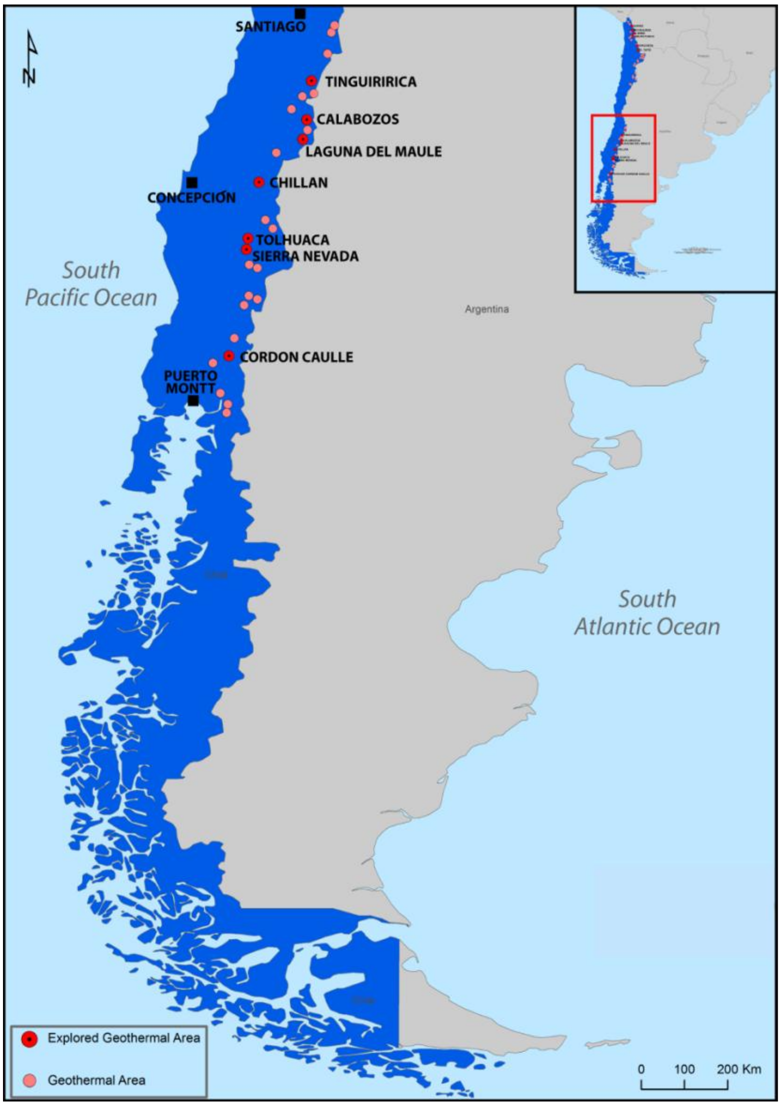
Initial geothermal exploration in the Central Andean Volcanic Zone took place in late 1960s in response to increasing Chilean energy demands. At El Tatio, a pre-feasibility investigation, funded in 1967 by the Corporation for the Promotion of Development and the United Nations Development Program (CORFO/UNDP), was followed by geological, geophysical and geochemical surveys from 1968 to 1980. Six 600 m deep exploration wells, drilled between 1969 and 1971, encountered temperatures up to 250 °C. Seven production wells drilled in 1973 and 1974 disclosed three discrete reservoirs with temperatures up to 260 °C. Three of these wells produced an average of 14.7 kg/s (adequate for 6 MW each); two other wells produced less, but could still be capable of 5 MW each. An electric power output of 100 MWe for the El Tatio geothermal field was estimated [26]. At Puchuldiza, geological, geochemical and geophysical studies were performed by CORFO/UNDP (from 1968 to 1974) and by Japan International Cooperation Agency (JICA) (from 1978 to 1980) to evaluate the geothermal potential. Six wells were drilled in 1976 and a depth of 1200 m was reached. Temperatures up to 175 °C were measured at depth of 900 m [27,28].

In the Surire zone, geological and geochemical [15,29] investigations were performed by CORFO between 1972 and 1979. Reservoir temperatures up to 230 °C were estimated by geothermometric calculations based on the water chemistry of the thermal discharges [29]. Geological and geochemical studies were conducted but no wells were drilled.

Geothermal exploration in the Central Andean Volcanic Zone was abandoned in 1982 because of both the remote location of the hydrothermal systems and economic factors. After almost three decades, private and governmental companies have planned to conduct a new phase of geothermal exploration in the systems investigated between 1969 and 1982 as well as in other areas of northern Chile. New slim holes will be drilled at Puchuldiza, Polloquere, Pampa Lirima, Colpitas and Juncalito by Energía Andina, which plans to have a geothermal plant working by 2015 [30].

In central-southern Chile, the geothermal activity is related to the Pocuro fault system (33°–34°S) and to the Liquiñe-Ofqui Fault Zone (39°–46°S). Several slimholes have been drilled in Tinguiririca, Calabozos, Laguna del Maule, Chillán and Tolhuaca with a potential output estimated at 3–10 MW per well (Figure 4). At Tolhuaca, two holes have been drilled up to depths of 1200 m and a 50 MW geothermal power plant is planned to start production in 2013. The potential is estimated at 600 MWe to 950 MWe in this area [31]. Currently, 79 exploration and 7 exploitation concessions have been given to Chilean and foreign companies [3].

Figure 4. Geothermal areas of southern Chile.



3. Methodology

In the selected potential geothermal fields, the minimum and maximum electric energy supply (E_{su}) was evaluated considering an operation time (OT) of 8000 h/year. To evaluate the E_{su} it was necessary to estimate both heat (Q) and electric power (W_e).

The recoverable Q of examined geothermal reservoir was computed using the following equation:

$$Q = m \cdot C_w \cdot (T - T_0) \tag{1}$$

where m is the mass flow rate of the geothermal system (kg/s), C_w (J/kg·K) is the specific heat capacity of the fluids contained in the geothermal reservoir, T is the reservoir temperature (K) and T_0 is the reinjection temperature. The minimum reservoir temperature T^- and the maximum reservoir temperature T^+ were used to compute the minimum (Q^-) and maximum (Q^+) heat, respectively.

The production rate m of the examined geothermal system is obtained by multiplying the volume of the geothermal reservoir V (km^3) and the specific productivity (m_w) [32] derived from the flow well tests. The W_e was estimated using the following equation:

$$W_e = Q \cdot \eta \tag{2}$$

where the η represents the efficiency of the selected power plant. The electric power was computed considering both conventional and binary cycle power plants as ORC (Organic Rankine Cycle). For conventional and binary plants, a η of 20% was considered, whereas the value of η, relative to geothermal binary power plants, was computed following the methodology proposed by Di Pippo [33]. Generally, the ideal cycle for a binary plant is the Carnot Cycle, but this assumption is inappropriate and can result in misleading conclusions [33–36]. Carnot's ideal cycle produces the highest efficiency with respect to any other cycle operating between a heat source and a sink, but the Carnot Cycle is applicable only to reversible processes. This property means that all heat transfer and work processes must be thermodynamically perfect and these conditions are impossible for a real cycle. A more useful model is the triangular (or trilateral) cycle, which considers the heating medium not as an isothermal source but rather as a fluid that cools as it transfers heat to the cycle working fluid [33]. Therefore, the efficiency (η) was computed considering a triangular cycle and following the equation:

$$\eta_{TR} = (T_H - T_C)/(T_H + T_C) \tag{3}$$

where T_H and T_C represent the heat source and the fixed condensing temperature, respectively. In this work, a T_C of 50 °C was considered. In order to convert from the ideal cycle to the practical it is necessary to apply a relative efficiency [33]. Real binary plants have demonstrated relative efficiencies of about 55% ± 10% [33]. Thus, one may estimate the efficiency of a binary plant using the approximate formula:

$$\eta_{b[TR]} = 0.55(T_H - T_C)/(T_H + T_C) \tag{4}$$

Therefore, the minimum and maximum *electric energy supply* (E_{el}) was evaluated for the selected geothermal systems based on 8000 working hours per year. The total E_{su} from the selected geothermal systems was evaluated. Moreover, the CO_2 emissions saving was computed considering the substitution for the estimated E_{su} of the crude oil with geothermal energy.

The relationship between CO_2 emissions and the different energy resources, such as coal, crude oil, natural gas and geothermal energy, is shown in Table 1.

Table 1. CO_2 emissions for kWh by coal, petroleum, natural gas and geothermal energy [37,38].

CO_2 Emissions (g/kWh)	Coal	Petroleum	Natural Gas	Geothermal Energy
	949	892	598	122
References	[37]	[37]	[37]	[38]

4. Results and Discussion

For the analysis, the geothermal systems of El Tatio, Surire, Puchuldiza, Irriputunco-Olca and Apacheta were considered. A satisfactory dataset is available only for the El Tatio geothermal field, whereas for the other systems partial data are present. The specific productivity (m_w) is available only for the El Tatio geothermal field where the Q and W_e were computed, whereas for the others systems, data for W_e were sourced from previous specific literature [17,22,23]. For the El Tatio geothermal system, the boreholes numbered 7, 10 and 11 provide the main information in terms of specific productivity m_w (kg/s), minimum and maximum temperature and type of fluid (Table 2). This geothermal system is water-dominated. The recorded m_w ranges from 37 to 77 kg/s, the temperatures range from 170 to 260 °C and the C_w was considered to have a value of 0.0042 J/kg K. The minimum temperatures are recorded in the Tucle Formation, whereas the highest temperatures are in the Puripicar and Rio Salado Formation.

Table 2. Available data for the El Tatio geothermal field.

Well	m_w (kg/s)	C_w (J/kgK)	T^- (°C)	T^+ (°C)	K
7	77	0.0042	170	260	273.15
10	37	0.0042	170	260	273.15
11	74	0.0042	170	260	273.15
Reference	[1]	-	[1]	[1]	-

The estimated minimum and maximum heat (Q^-, Q^+) ranges from 1482 to 2752 MW_{th}, for a reservoir volume of approximately 15 km^3 (Table 3). The electric power (W_e^-, W_e^+) was estimated for both conventional [c] and binary geothermal power plants [b]. For temperatures up to 170 °C, an efficiency ($\eta_{b[TR]}$) for a geothermal binary plant of 0.09 was computed considering the Equation (4). The minimum estimated electric power ($W_{e\ [b]}^-$) is 45 MW_e, whereas the maximum electric power ($W_{e\ [c]}^+$), which was computed considering a conventional plant with an efficiency (η_c) of 0.2, is 174 MW_e. The relative energy supply ($E_{su[b]}$, $E_{su[c]}$) for an operation time of 8000 h/year, is 362 and 1391 GWh/year for binary and conventional plants, respectively.

For the other geothermal systems (*i.e.*, Surire, Puchuldiza, Irriputuncu-Olca and Apacheta), the energy supply has been evaluated for the electric power values provided by scientific literature [17,22,23]. The Database of Geothermal Resources in Latin America & the Caribbean [17] indicated an electric power output of 50–60 and 190 MWe for Surire and Puchuldiza, respectively. Reyes *et al.*, in 2011 [23], estimated the electric power for the Irriputunco-Olca system to be 75–450 MWe, and Urzuà *et al.*, in 2002 [22], evaluated the electric power for the Apacheta geothermal field to be 400 MWe. The computed energy supply (E_{su}) for the systems listed above is reported in Table 4. For the evaluation, an operation time of 8000 h/year was considered. The values range from 400 to 3600 GWh/year. The maximum estimated value of the total energy supply for northern Chile is approximately 10,200 GWh/h whereas the minimum total energy supply is around 3000 GWh/year.

The total CO_2 emissions corresponding to 10,200 GWh/h are 1.2 Mton/year. The CO_2 emissions would be approximately 9 Mton/year for the same energy amount if sourced from petroleum only.

Northern Chile has large geothermal potential. The evaluations performed for the El Tatio, Surire, Puchuldiza, Irriputunco-Olca and Apacheta geothermal fields show that the geothermal energy could provide approximately 10,200 GWh/year, with an installed capacity of approximately 1300 MWe. Currently, the SING has an installed capacity of 3800 MWe, approximately 100% of which is generated by imported fossil fuel. Geothermal electric power could replace more than 30% of the SING installed capacity, decreasing the reliance on foreign fossil fuel providers. Furthermore, substituting 1300 MWe of fossil fuel for geothermal energy means a CO_2 emissions savings of approximately 8 Mton per year.

The geothermal potential of northern Chile could be greater than 1300 MWe for two main reasons: (1) it was not possible to evaluate some explored areas because of the lack of public data (especially Larima and Colpita); (2) there are many unexplored areas characterised by medium temperatures that could be exploited using binary systems such as ORC and/or Kalina cycles.

The proposed approach is reasonable for regional estimates of efficiency and power output and cannot replace detailed heat balance analyses needed for plant design.

Table 3. Evaluations of the thermal and electric power for the El Tatio geothermal field. The letters [*b*] and [*c*] means binary cycle and conventional, respectively.

EL Tatio	m * (kg/s)	C_w (J/kg K)	T^- (°C)	T^+ (°C)	T_0 (°C)	K	V (km^3)	Q^- (MW$_{th}$)	Q^+ (MW$_{th}$)	$\eta_{b[TR]}$	η_c	W_e^- [*b*] (MW$_e$)	W_e^+ [*c*] (MW$_e$)
-	63	0.0042	170	260	40	273.15	15	1482	2752	0.09	0.2	45	174

* Arithmetic mean computed starting from Q_w values listed in Table 2.

5. Conclusions

Chile is rich in natural resources such as copper, timber, nitrates, precious metals and molybdenum. Although Chile has an abundance of copper and mining resources, it has limited indigenous fossil fuels, and over 90% of the fossil fuels must be imported. The SING has an installed capacity of 3800 MWe, 100% of which is generated by imported fossil fuel.

As suggested by the Global Energy Network Institute (GENI) in 2011, a strategic energy plan for Chile is necessary to ensure the transition from traditional power plants to renewable energy power plants. This transition is necessary both to reduce the amount of greenhouse gases into the atmosphere and to reduce the country's dependence on imported fossil fuels. The development of geothermal energy represents a useful tool for achieving this objective.

Table 4. Evaluations of the thermal and electric power for the northern Chile.

Geothermal System	Elevation	A (km^2)	H (km)	m (kg/s)	Hydrothermal Manifestations	Geological Features	T^- (℃)	T^+ (℃)	Reservoir	W_e^- (MW_e)	W_e^+ (MW_e)	OT (h/y)	E_{su}^- [b] (GWh/y)	E_{su}^+ [c] (GWh/y)	Reference
El Tatio	4,300	30	0.5	63	Geysers, thermal springs, fumaroles, bubbling pools, mud pools, hydrothermal alteration. $T \sim 86$ ℃	N-S graben filled by Miocene to Pleistocene ignimbrites and andesitic volcanoes.	170	260	Liquid Dominated	45	174	8,000	362	1391	Table 2; [29]
Surire	4,000	45	-	-	Fumaroles, thermal springs, hydrothermal alteration, bubbling pools. 20 ℃ < T < 80 ℃	Plio-Pleistocene dacitic volcanoes.	110	234	-	50	60	8,000	400	480	[17,30]
Puchuldiza	4,100	50	-	-	Thermal springs, fumaroles, mud pools, hydrothermal alteration, bubbling pools. 20 ℃ < T < 90 ℃	Volcano-tectonic depression surrounded by Plio-Pleistocene volcanoes.	175	200	-	50	190	8,000	400	1,520	[17,30,39]
Irriputunco (OLCA)	4,000	15	2–3	-	Thermal springs, fumaroles. $T > 100$ ℃	Stratovolcano within a NE-SW trending chain of volcanoes constructed within the collapse scarp of a Holocene debris avalanche.	230	300	-	75	450	8,000	600	3,600	[23,30]
Apacheta	4,500	25	-	-	Fumaroles. $T \sim 118$ ℃	Plio-Pleistocene volcanic complex located within a NW trending graben.	200	325	Liquid Dominated	150	400	8,000	1,200	3,200	[22,30,39]
Colpitas	4,000	-	-	-	Thermal springs and bubbling pools, hydrothermal alteration. 28 ℃ < T < 55 ℃	Volcanic rocks, volcanoclastic deposits and volcano-sedimentary sequences from Miocene to Holocene.	135	235	-	-	-	-	-	-	[16]

Table 4. *Cont.*

Geothermal System	Elevation	A (km^2)	H (km)	m (kg/s)	Hydrothermal Manifestations	Geological Features	T^- (℃)	T^+ (℃)	Reservoir	W_e^- (MW$_e$)	W_e^+ (MW$_e$)	OT (h/y)	E_{su}^{-} [b] (GWh/y)	E_{su}^{+} [c] (GWh/y)	Reference
Lirima	4,000	-	-	-	Geysers, thermal springs, fumaroles, bubbling pools, hydrothermal alteration. 20 ℃ < T < 80 ℃	Upper tertiary sedimentary and volcanic rocks.	169	211	-	-	-	-	-	-	[17,20,30]
TOT	-	-	-	-	-	-	-	-	-	370	1,274	-	2,962	10,191	-
CO_2 emissions (Mton/year)	-	-	-	-	-	-	-	-	-	-	-	-	0.4	1.2	-

The black dashes indicate No Data availability.

In this paper a new evaluation of northern Chile's geothermal potential was performed, focusing on the El Tatio, Surire, Puchuldiza, Orriputunco-Olca and Apacheta geothermal fields. Thermal electric power and electric energy supply were calculated, although a satisfactory dataset is available only for El Tatio. The total estimated electric power for northern Chile is approximately 1300 MWe with an energy supply of 10,191 GWh/year. This means that more than 30% of SING's energy could substitute fossil fuel for geothermal energy, saving approximately 8 Mton of CO_2 per year. Geothermal energy development could be a useful resource for the mining and industry sectors, which represent Chile's primary energy users. It is important to note that dedicated field analysis for overcoming natural barriers, such as altitude, climate, water scarcity and distances from urban centres, will be necessary to accelerate Chilean geothermal development.

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Conflicts of Interest

The author declares no conflict of interest.

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