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The Integration between Solar Energy and Mining in Chile

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Abstract

The Atacama Desert has both one of the best solar resources in the world, as well as huge mineral deposits that include copper, iron, nitrates, and lithium. In the past these resources were exploited in a non-sustainable way, which led to the burning of the scarce forests that existed and the overexploitation of water resources.

Pioneering work was done there in water desalination, the determination of solar spectra and solar constant and the utilization of solar energy in some mining processes. Today, renewable energy, and especially solar, has lowered the cost of electricity provided to the mining sector, and has also been directly applied in three cases for obtaining process heat to aid copper electrowinning production.

In this paper we present both the past, present and future of the relationship between solar energy and mining in Chile. Special emphasis is given to what is known today and further research topics that must be addressed to properly use this vast resource.

Keywords: *solar energy, process heat, solar desalination, solar electricity production, Atacama desert.*

1. Introduction

Energy and water have always been one of the largest constraints for any sort of activity in the Atacama Desert. This vast expanse of extreme aridity that lies between the Pacific Ocean and the high Andean plateau (the Altiplano region), has nearly zero average rainfall, and only a few oases and places where groundwater is found. The high Andes receive both snowfall and rainfall (concentrated mainly in the summer monsoon season); so water seeps underground to lower altitudes, but along the way picks up significant amounts of salts, boron, arsenic and other contaminants.

The first documented use of solar energy in Chile is a solar desalination plant built by the Swedish engineer Charles Wilson around 1872. It was a basin still system, with a total surface of around 5.000 m² that produced around 20.000 liters of fresh water a day from brackish water pumped from desert wells. This supplied water needs both for the miners and draft animals (mules specially) that worked at the nearby *Caracoles* silver mine district (**Fig. 1**).

This project was first widely reported by Dr. Maria Telkes and later by Prof. Julio Hirschmann (Hirschmann 1961) from Universidad Federico Santa María (Chile). It was a landmark project, and only a few years ago Historian Nelson Arellano (Arellano 2011) found original documentation and discovered that in the period from the late XIXth Century until the early XXth Century, *three* solar desalination plants were built and operated for long periods. This is quite reasonable, since solar desalination was much less expensive than coal fired desalination plants of the period, so the good results of the Wilson plant were replicated.

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The next person who did pioneering work in northern Chile was Dr. Charles G. Abbot (Abbot, 1918). This eminent researcher in the field of solar energy and solar radiation built (with the help of the Smithsonian Institution) a network of several solar observatories in different parts of the world. One of the places chosen was *Montezuma,* a mountain nearby Calama and the copper mine in Chuquicamata. This observatory operated from around 1920 until the mid 1950's, conducting systematic measurements of direct solar radiation, solar spectra and studies in the determination of the solar constant and its variability. The measurements made are quite accurate according to modern measurements and the observations of great value.

After the Second World War the low price of fossil fuels discouraged most research on the use of solar energy. A big exception was the use of solar evaporation for nitrate production.

Nitrates are produced from a mixture of naturally occurring salts called *Caliche.* Originally these salts were dissolved in hot water, and then crystallized by fractions (containing different specific salts) as the brine cooled. Since nitrates are highly soluble, this was a simple method of separating nitrate from the other salts. However huge amounts of fuel are needed for an industrial operation. And during the late XIXth Century the natural forest existing in a place called *Pampa del Tamarugal* (The flatlands of Tamarugo's, a tree species), was almost totally wiped out.

Starting in the mid 1950's the ancient method was replaced by solar evaporation of the brines and partial precipitation of the different salt fractions. This is still widely used for the production of nitrates and iodine salts, as well as the large scale production of lithium carbonate from the Atacama Salt Flats.

2. Recent uses of Solar Energy in the Mining Industry

The first oil crisis of 1973 brought renewed interest in the use of solar energy in northern Chile. Several projects went into operation. These include the following:

- A flat plate hot water system that provided up to 40 m³ of hot water a day for the showers of each shift in the El Salvador copper mine. It started operation in 1980 and is still in use (with upgrades and periodic maintenance). This project was designed by Universidad Federico Santa María (**Fig. 2**).
- Copper concentrate was dried using solar energy (250.000 Tons/year) from around 1980 to the year 2000. This simple system was later replaced by drying using mechanical presses. The new method is faster and there's less concentrate loss. There was loss in the old system due to wind blowing some of the concentrate when it was picked up from the drying ponds.
- A passive heating system for a house at the industrial water source in the high Andes in El Salvador. In operation since 1982 (**Fig. 3**).

There were other projects of varying success, but interest waned in the 1990's due to lower fuel prices. Since the early years of the XXIth century rising fuel prices, as well as environmental concerns has sparked renewed interest in the use of solar energy for the mining sector in Chile.

Today, we can divide the uses of energy for mining in Chile in the following areas:

- **Electricity production:** mining accounts for over 25% of total Chilean electrical demand. And the Energy Ministry calculates that 60% of *new* electricity demand will come from the mining sector. Electricity is used mainly in ore milling and processing, as well as conveyor belts, pumps, motors, fans and a host of other equipment.
- **Water production:** mining requires large amounts of water for leaching, flotation and evaporation processes. Water is a scarce resource and already several mines have to desalinate large amounts of seawater and then pump this up to the mines.
- **Process heat:** from an overall view, process heat is not a very large requirement, but it can be a significant amount in the plants that produce copper cathodes by the electrowinning process or the electrorefining process. Each plant requires a thermal power between 5 to 20 MW. There are over 15 plants in Chile and also plants in several other countries. Today there are two solar plants in operation

and several in the planning stages.

- **Transport:** this is a very significant energy demanding sector but, for the moment, the production of fuel for this requirement is not yet feasible.

In the following paragraphs we'll give a brief outline on how renewable energy in general, and solar energy in particular, has already had a large (and growing) impact in the Chilean energy matrix and the mining sector in particular.

3. Solar Energy and Electricity Production in Chile

Up until 2009 the conventional view in Chile was that solar energy was too expensive compared to "conventional" energy sources. Only wind power had a very modest penetration. Electrical production was concentrated in very few companies (three of them controlled over 85% of the market) and prices were very high. Contracts were over US$120/MWh and spot prices exceeded US$160/MWh.

The established companies wanted more of the same. However citizens strongly opposed large scale projects (such as very large coal fired plants or large dams) and several conventional projects were successfully blocked. At the same time several important developments took place:

- Better resource assessment proved that northern Chile had an exceptional solar resource and large scale energy needs.
- The price of solar systems, PV in particular, swiftly dropped, powering a surge in large scale projects.
- New companies decided to invest in this emerging market in Chile.

After only six years the electrical energy panorama in Chile has drastically changed. The present day situation is that over 11% of electrical energy in Chile is produced from nonconventional renewable sources (all renewables excepting large hydro), Electrical production has increased 2,9% between 2014 and 2015, but nonconventional renewables have increased 17,8% (CIFES Report). In Table 1 we show the evolution of renewable capacity generation between 2012 and 2015.

Tab. 1: Non Conventional Renewable Capacity (MW) in Chile Between 2012-2015[1]

	2012 Q1	2013 Q1	2014 Q1	2015 Q1	2015 Q2
Wind	205	205	335	836	901
Solar	0	3,6	6,7	362	741
Biomass	270	394	394	416	417
Mini Hydro	246	278	320	350	390
Geothermal	0	0	0	0	0

The incorporation of large blocks of renewable energy in the matrix, especially in the northern part of the grid, has had a very large impact in prices. Spot prices have dropped from around US$160/MWh in 2010 to less than US$60/MWh today. This is because renewables have displaced diesel fired generation at peak hours. Also overall prices have dropped. Another very important effect is that the Energy Ministry has called for renewable energy blocks to supply the electrical energy matrix, and suppliers have come forth with long term prices of around US$60/MWh.

New solar plants are being installed very quickly, and solar will tend to displace wind as the largest generator in not more than two or three years. One large CSP plant (110 MW with molten salt storage) is being built by Abengoa near Calama. It will come online early 2017. Another 3 or 4 CSP plants are under development or consideration.

So in only three or four years, the electrical energy matrix in Chile has changed significantly. The incorporation of renewables has:

[1] Table data obtained from CIFES reports 2012-2015

- Proceeded at a much faster pace than originally envisioned.
- Renewables have helped lower the price of spot energy, as they have (mostly) displaced diesel systems for peak power demand. And they have also helped lower the average energy price, since due to the excellent solar conditions in Chile, solar can be competitive today with any other energy source, including coal.
- Already provide a significant, and rapidly increasing, amount of electrical energy for the mining sector.

We must also comment that the *average* year round capacity factor of the solar plants already in operation is over 23%. This is computed comparing the nominal power of each plant, and thus the nominal yearly output with the actual energy injected to the grid on a yearly basis. Thus it takes into account of all effects, including soiling, outages, resource variability and so on. By comparison, German solar power plants have an average yearly capacity factor of less than 9%. One axis tracking plants in Chile reach capacity factors of over 30% on a yearly basis.

This panorama also has some problems. They can be summarized as follows:

- There are significant transmission capacity problems. These have resulted in that in many places there are projects that have problems injecting the power they produce. Spot prices have dropped to very low prices in these area.
- In many places there are more projects than what existing power lines can accommodate. This has led to a rethinking of the whole power grid and the interconnection of the Northern and Central power grids which should be accomplished in less than five years.

4. Solar Energy use in Process Heat in the Mining Industry

4.1. Present situation

One of the processes that use significant amounts of thermal energy is copper production by *electrowinning.* This applies mainly to copper oxide ores. The process is as follows:

- Copper ore is extracted from the mine and crushed at the mill to a diameter of around 20-30 mm. This is then conveyed to form large *leaching piles.* These typically are around 10 to 15 m high, 30 meters wide and several hundred meters in length. Under the piles there's an impermeable membrane to prevent the leaching solution from seeping into the ground.
- The leaching piles are irrigated with an acidic solution (water plus sulfuric acid). As this solution seeps through the pile, it picks up copper ore. After seeping it has a copper concentration of around 4 [g/lt].
- The solution is then piped to a *solvent extraction plant.* There, using organic solvents, a fraction is extracted with copper concentration is increased to around 20 to 27 [g/lt]. The rest, with low copper concentration is again pumped to the leaching piles.
- The high copper concentrate solution is first pumped to a special plant that removes the organic solvents, and then is pumped to the *electrowinning* production facility. In it the solution (which must be at a temperature between 55 and 60°C) is submitted to a DC current, and the copper is deposited on stainless steel cathodes. This deposition process takes several days.
- The exhausted solution is extracted from the electrowinning plant, it preheats the incoming solution, and is again incorporated into the solution that goes to the leaching piles.
- Once sufficient copper is deposited, the cathodes are removed, the copper removed, washed and packed for shipment, and the cathodes are again inserted into the electrowinning vats to repeat the process.

Heat is needed at several stages in this process. Hot water is needed to wash and clean the vats, cathodes and anodes. But most importantly to provide enough temperature to have the electrowinning vats at an optimal point as fresh solution is added.

Normally this is done using diesel fired water heaters, which heat up the incoming solution from anywhere between 50 to 55°C (the final heating is done by the joule effect in the electrowinning vat itself). It's not a large temperature increase, since the outgoing solution preheats the incoming; but flows are very high.

Thermal requirements vary according to the size of the mine, but usually lie between 5 to 20 MWth as a nominal load. Thermal requirements increase in winter, and are higher at night. Even though the electrowinning vats have thermal insulation and systems to reduce evaporative losses, there still are significant thermal losses.

The idea of using solar energy to provide process heat for this requirement dates from the late 1990's. El Abra copper mine conducted several studies in which one of the author's participated. But, at the same time, natural gas was made available from Argentina at a price of 1/3 of diesel fuel. So the project was shelved.

Again in the early years of this century, new projects were studied. Fuel prices were again very high and there was rising concern about greenhouse gas emissions. Finally three projects were commissioned, two large scale systems and a small scale system. The main characteristics of each one is presented in **Table 2.**

Tab. 2: Solar Thermal Plants for Electrowinning Processes

Name	Operator (commissioning)	Technology	Collecting surface (m²)	Capacity factor	Comments
Pukará de Hatur	Enermine 01 Dec 2012	Flat Plate (Wagner Solar)	435	80%	Power purchase agreement
Centinela	Antofagasta Minerals 02 Jan 2013	Parabolic trough (Abengoa)	10.000	50%	Operated by Antofagasta Minerals
Gabriela Mistral	Pampa Elvira Solar 19 Aug 2013	Flat Plate (Sunmark)	39.000	80%	Power purchase agreement

We now compare the two largest plants, as regards their main characteristics:

Tab. 3: Comparison of Centinela and Pampa Elvira Solar Thermal Plants

Name	Technology	Primary circuit	Storage	Thermal delivery	Comments
Centinela	1280 single axis parabolic troughs with polymer reflector	Pressurized water with antifreeze and corrosion inhibitors	Three 120 m³ pressurized water tanks. Operate between 70 to 140°C	Up to 140°C	Can be unfocussed to prevent overheating
	Glass covered non evacuated selective surface receptor	Two collector fields		Heat exchangers for final heat delivery	
Pampa Elvira	39.000 m² flat plate collectors with selective surface	Pressurized water with antifreeze, corrosion inhibitors	4.300 m³ of nonpressurized water operates between 60 to 90°C	Up to 90°C	Tilt of collectors can be seasonally adjusted
		Backup storage for primary fluid	Active stratification control	Heat exchangers for final heat delivery	

From a technical point of view, all three plants have been successful. Only the Centinela plant had some initial problems due to parabolic trough alignment and the need for special cleaning care due to the reflecting surface (a polymer) and the occasional deposition of acidic mist on the reflecting surface.

Two different economic models were used. In the case of Centinela Mine (Antofagasta Minerals), they called for a turnkey plant and assumed the operation. So investment was upfront, and operation and maintenance was assumed by Antofagasta Minerals. At first there were some teething difficulties, but the system has operated satisfactorily for well over a year and lives up to expectations.

In the case of Minera Gabriela Mistral and Pukará de Hatur, the developers offered a *PPA (power purchase agreement).* In essence there's a contract for selling thermal energy, and the developer takes care of day to day operation and maintenance as well as the operation of the backup fossil fuel heaters.

These authors consider that the *PPA* system has advantages, since experience has shown that this benefits optimal power production and better maintenance.

There are several other plants of this type under consideration. However the low cost of copper during the last year has caused delays in the signing of new contracts for new plants.

4.2. Technical Options and Special Issues

From a strictly technical point of view, systems that use solar tracking (i.e. parabolic troughs or linear Fresnel) should be better than flat plate systems. On a per square meter basis, costs should be lower, tracking improves output during daytime and pressurized water can be used for storage. Also these systems are more resistant to freezing and it's simple to prevent overheating.

But in fact, there's a very limited offer of both small parabolic troughs and/or Fresnel systems. And due to small production runs, the per square meter cost still tend to be high.

Large parabolic troughs are probably not very applicable because winds in excess of 5 [m/s] are common and high winds do exist.

Another problem that must be addressed is soiling. In fact this is quite a complex problem. It's very site dependent, and our experience shows that any activity near the solar fields (unpaved roads and some traffic) can influence soiling very much.

Also in the leaching and electrowinning process, very large amounts of solution that contain sulfuric acid are used. Unless the solar field is very carefully chosen, mist with some acid can affect the collectors. This can both be a problem from the point of view of soiling, as well as affect the materials of the collectors.

To better assess these problems the *Solar Energy Research Center (SERC-Chile)* project is now establishing both an experimental platform as well as specialized researchers in these problems.

4.3. New Applications

There are many other possible applications for large scale solar heat systems. Some of them are quite attractive, but demand further research. In particular:

- Solar desalination: Both the mining industry and coastal cities demand large amounts of (scarce) freshwater. Today the only option studied has been reverse osmosis (RO). However thermal desalination using MED (Multiple Effect Distillation) could be an attractive option. In theory these methods should be cost-competitive with RO. And in fact they could be less expensive, since RO plants have constant problems with membrane durability.
- Solar heating of the leaching piles: the flow of leaching solutions to the leaching piles is huge. On the order of several thousand cubic meters per hour. At the laboratory and small scale level it's been proved that copper recovery and process time are significantly improved with temperature increases of the leaching fluid of not more than 5 to 10°C. This brings significant opportunities to improve the processes and even think of *solar cogeneration.* That is install a large CSP plant near one of the mines, and cool the condensing block by rejecting the heat into the leaching piles. Many problems have to be addressed, but the opportunities for improvement are multifold.

5. Conclusions

The development of solar energy systems in Chile have evolved very rapidly, with no public subsidies. The principal existing advantages have been the need for new energy supplies at competitive costs, and an excellent solar resource.

In this atmosphere many companies have come into the country with new projects. These have had a very large impact on the energy matrix, but there are also emerging problems. These are mainly:

- High concentration of PV projects in certain areas. This has led to a very large drop in spot electricity prices. So only projects with PPA agreements become feasible.
- The shift in the energy market has shown the need for a strong improvement of the electrical transmission grid. This is now being undertaken.
- Soiling is a very variable problem, but collector field cleaning can have a significant effect on both performance and overall costs of the system.
- The (present) low price of copper and other commodities have delayed or postponed projects that are feasible from the technical and economic point of view.

Today there are two active institutions that are addressing these and other problems. These are the *Solar Energy Research Center (SERC-Chile),* a consortium of six Universities and Fundación Chile, that are devoting much manpower for research and development; and *Fraunhofer Solar Chile,* a research and development center established jointly between ISE-Fraunhofer (Germany) and the Catholic University (Chile), with the Chilean Government funding. Both institutions are working in a coordinated fashion.

Many research lines exist. Only to mention a few:

- The study of high penetration of variable renewable energy (both wind and solar) into the existing and future energy grids. These studies are being used for the planned expansion of the grids.
- Better knowledge, modelling and prediction of solar energy (beam, diffuse and global) both on a spatial and time basis for Chile.
- Measurement and effect of solar spectra on the performance and operation of solar systems. Above 2500 meter altitude in the desert, there are significant amounts of short wave UV (UV-A) and less long wave atmospheric absorptance. These are being first measured, and then we will determine if there are significant effects in the performance or durability of solar systems.
- Energy storage (especially thermal storage). The emphasis is on using low cost materials to provide thermal storage for CSP plants.
- *Solar Mining:* the intensive use of solar energy to both improve existing mining processes and reduce the carbon footprint and life cycle cost of the mines (jointly with Suttgart University).
- Other areas: these include water desalination, microgrids, legal issues and other areas

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Illustrations

Fig. 1: The original Las Salinas desalination plant and a photo of the same location in 1979[1]

Fig. 2 The flat plate collector field in El Salvador (1982)

Fig. 3 The "La Ola" solar house (1982)

[1] First photo from Hirschmann, all the others by R. Román

Fig. 4 The "Amanecer Solar" plant. First 100 MW grid tied system in Chile (2014)

Fig. 5 Part of the flat plate collector field at "Pampa Elvira". The tilt mechanisms can be seen

Fig. 5 The “Centinela” parabolic trough plant. The tracking is east-west

Fig. 6 The “Centinela” parabolic system storage tanks. Each has a capacity of 120 m³