Opening up Natural Resource-Based Industries for Innovation: Exploring New Pathways for Development in Latin America

SECTORIAL REPORT | Copper Mining in Chile

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Table of Contents

1 Introduction

The objective of this report is to characterize the way the copper mining sector works now in Chile and what it represents; to analyze its problems and the challenges it poses on the Chilean economy; and finally to describe some of the alternatives that attempt to tackle those problems. From this analysis and the discussion in the workshop, one or several alternatives must be chosen to be analyzed in detail in the next stage of the project.

The theoretical background of the project is the socio-technical transitions framework (Rip and Kemp, 1998; Geels, 2002, among others). The framework, described in detail in the previous stage of the project, uses the multi-level perspective (landscape, socio-technical regime and niches) to study how alternative pathways develop and break into the economy. Alternatives are usually "incubated" in protected niches, and given the particular conditions at the socio-technical regime and landscape development, niches can break into the socio-technical regime and transform it. The relationships and interactions between the three different levels is fundamental to understand their development.

The description of the dominant trajectory presented in chapter 3 is for its most part a description of the current socio-technical regime. Problems described in chapter 4 are closely associated to landscape developments and its interaction with the regime, and alternatives discussed in chapter 5 could be seen as niche developments, however some of them come from the inside of the current socio-technical regime. A detailed discussion of the interaction between the different levels and their development in time has been left for the following stage of the project, as interviews with the experts involved in the sector will make it possible to really understand how the different dimensions have interacted to produce the present situation, and the future prospects for the alternatives.

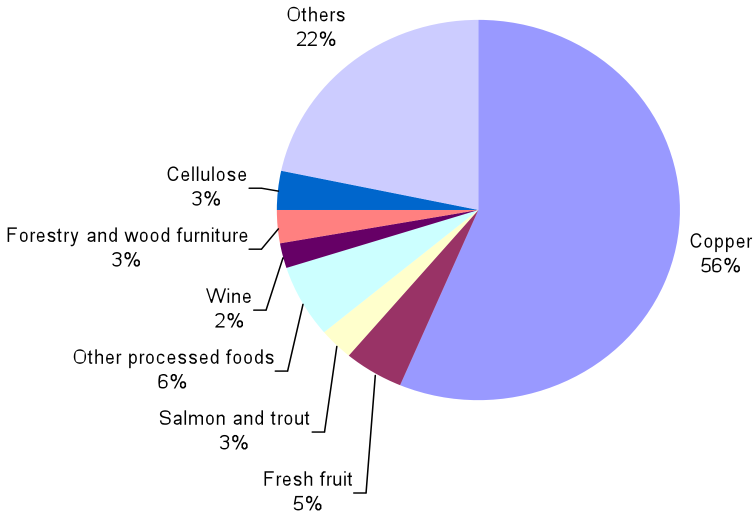
The description of the sector, its problems and its alternatives is based mostly on secondary data, as there are plenty of detailed studies on most of the topics of interest. Several key informants were identified and have been already contacted for interviews.

2 Why the sector was chosen

The following criteria were defined to determine the sector to be studied:

- Relevance for the national economy
- Existence of problems
- Existence of alternative ways of doing things that avoid these problems

The first thing to look at when thinking about relevance is the Chilean productive structure. Chile is an export-oriented economy, and a look at the main exports is a good starting point.



Chilean exports in 2010 (based on DIRECON, 2011)

As the graphic shows, copper represents much more than half of Chilean exports, around 56,4% in 2010 (DIRECON, 2011). But copper is not the only good that comprises a significant amount of exports: the food sector (including salmon, fruits and processed foods), as well as wine and cellulose are also important. In broad terms, relevant sectors are commodities and food product.

All sectors named above satisfy the relevance criteria, although copper is clearly relevant at a different level, during the previous price boom mining was a fifth of the GDP and close to 60% of exports (Titelman, 2009).

With respect to the existence of problems, all of the sectors named above face increasing environmental concerns, and some also face important pressure to increase their competitiveness, especially under a depreciated dollar. But the latter are mostly faced by cost reduction measures and technologies. With respect to environmental challenges, there have been some interesting alternatives being developed in the wine sector, but these alternatives and their problems are almost exclusively associated to environmental problems and consumer preferences, without other dimensions of interest involved.

This doesn't mean that environmental worries are not important, the point is to stress that they are not as important and varied as the problems faced by the mining sector: besides environmental concerns, mining produces important social problems, faces productive challenges, and maybe the largest concern is that its relevance is so high that it becomes a threat: the economy and the national treasury depend too much on the sector. The fact that all of these dimensions are problematic makes copper mining much more interesting for the project than the wine sector, for instance.

Therefore, the sector that will be studied is *copper mining*, mostly large-scale operations, but mid- and small size ones will also be considered, to have a complete picture of the sector.

With respect to relevance (and the economic problems), as said before it represents well over half of Chilean exports, and it has represented up to 22,8% of GDP (in 2007, SONAMI 2010b). Copper-related income represented 22% of government income in 2006 (these numbers are variable and depend on copper price, in 2009 copper was 8,7% of fiscal income) (DIPRES, 2010). Copper mining also represents a significant job source in some poor and isolated areas. The size of the sector and its relevance is the first problem: Chile is highly dependent on copper, a non-renewable resource, therefore growth based on its extraction is by definition unsustainable. Mining has not fostered the growth of domestic suppliers, and in general does not produce positive externalities on the rest of the economy due to its geographical isolation. Another issue that can be considered an economic problem is the lack of coordination for conducting R&D and the relatively small investment in it.

The sheer size of the sector also amplifies the productive, environmental and social problems it faces.

Production issues are associated to decreasing ore grades –a reminder of its unsustainability. As obviously the resource is extracted first from the places where it's easiest to obtain, every year that passes copper is extracted from more difficult places. This makes extraction more difficult and energy intensive, therefore costs increase. Also, as world copper demand increases, more and more projects are being started, and availability of fresh water for the operations becomes another critical concern. It is important to mention that most of copper mining occurs in the arid Atacama desert.

Environmental problems are associated to the production challenges just mentioned: fresh water sources are being depleted, and increasing energy demands push for the construction of polluting power stations. Besides this, the operations in the mines themselves produce significant air, land and water pollution. Following the worldwide trend, the environment is becoming a real concern for an important part of the population, pushing the subject to the top of the public agenda.

Environmental issues in turn produce social problems: there are conflicts with respect to water usage rights between mines, farmers, and human consumption. Air, land and water production affect human health, and agricultural activities. The excessive economic dependency also produces social problems, with many people depending exclusively on low quality jobs in the mining sector.

But for most of these problems, there are also alternative ways of doing things currently being tried. When talking about commodities, innovation is commonly thought to be irrelevant, but this is not the case. Technological innovations are key to improve processes and competitiveness, and to replace harmful processes and technologies with cleaner and more sustainable alternatives. The alternative technologies that will be discussed are biolixiviation (a bacteria-based process with less environmental impact than traditional methods that can be used in low grade ores), clean technologies for electricity generation, and the use of saltwater and desalinated saltwater in the mining process. All of these alternatives *come from within the dominant trajectory*, from incumbent firms. This is because of the amount of technical knowledge and experience required, as well as financial capability. The problems in the mining sector are effectively pushing for *path-repairing* alternatives to ensure its sustainability.

Besides technological innovation, the economic challenge posed by dependence on copper mining and the lack of externalities from it to other sectors is slowly being addressed through firms' and government's actions. The mining clusters should evolve and generate knowledge based sectors that can support sustainable, innovation-based growth, some examples of this will be described. This can be considered to be a very broad and general *path-breaking* alternative, at the level of the national economy, not circumscribed to the mining sector.

It is important to make clear that, in contrast with the sectors studied on the other countries of this project, there is no conflict between alternative uses for the resource or ways of exploiting it (as with the Amazon in Brazil or agricultural land in Argentina). In this case, there is only one possible use and way of extracting the resource (underground copper), but this dominant way poses significant economic, environmental and social challenges, and there are both path-repairing and path-breaking alternatives.

Besides the three criteria for sector selection, another reason why mining is interesting to study is that it is relevant for many developing countries, such as Peru, Mexico and Brazil in Latin America. Understanding how alternatives develop in the mining sector could produce very helpful policy insights for these and other economies where industries that follow a similar logic are important.

3 Description of the dominant trajectory of copper mining

The dominant way of doing things in the mining sector will be described by analyzing in detail a series of socio-technical dimensions, such as the relevant knowledge bases, industrial organization, and its policy institutions.

3.1 Production process and knowledge base

The mining process is complicated and involves a broad array of technologies and areas of knowledge. The best way to look at them is to describe the production process of high-purity copper.

The first stage is geological exploration. Even before this stage starts, the first relevant knowledge needed is about the legal conditions (and possibly incentives) for exploration and initiation of mining projects, which differ from country to country. After legal knowledge and preliminary information that leads to the decision of exploring a territory for mining opportunities, geological knowledge itself becomes relevant. Geophysical, geochemical and remote sensing methods are used to find locations for mines.

After a location is found, a project needs to be developed and evaluated, and if the firm's evaluation is positive, the project must be presented to the government for evaluation. Projects that may have significant environmental impacts (as mining projects do) must present Environmental Impact Study (EIA) to the SEIA (*Servicio de*

Evaluación de Impacto Ambiental). This is a complicated process that can take several years, and includes evaluations by many different government agencies. Lobbying abilities by the firm are important at this stage (it should be mentioned that lobbying is not regulated in Chile). After a project has been approved, the construction stage ensues, and finally exploitation, the phase more relevant to our study, begins.

There are two types of mines, both important in Chile: underground and open pit mines. As their names implies, in the former extraction is done through underground tunnels, and in the latter the mine consists simply of a large hole dug from the surface.

These two extraction processes are not fundamentally different, both need geological knowledge about the terrain and the composition of the ore, and are based on extracting material with explosives, according to a carefully elaborated plan to optimize operations. After extraction, mineral needs to be transported to processing facilities. In this stage, conveyor belts and heavy load trucks (both manually operated and automated) are used. These trucks are specially designed for mining operations and have heavy energy demands (around 2.250 litters of petrol a day [CODELCO, 2007]). It is important to optimize trucks' loads and routes to minimize energy consumption and pollution.

The core of the mineral processing requires knowledge on mechanics, physics, chemistry and biotechnology. The basic process is the following:

The first stage is grinding, where large mills are used to convert large pieces of mineral into smaller ones that can proceed to the stages where copper and other minerals are separated from the rock. Grinding is usually conducted in several serially connected mills that gradually reduce the size of rock fragments. Mills are simply large containers filled with iron balls and bars, that turn around permanently, and rocks are reduced in size as they crush against these iron pieces. The grinding mills require enormous amounts of electricity to operate.

After the pieces of rock are made small enough, they through a series of processes that first separate copper from the rock, and then increase its purity (up to a level of 99,99% of pure copper). Which process is used depends on the type of deposit. For oxide mineral deposits, the first stage is lixiviation. Lixiviation consists in spraying large piles of ore with water and sulphuric acid. This separates soluble copper sulphate from other insoluble substances. The solution obtained from lixiviation then goes to extraction by solvents, and finally to electrowinning. In simple words, pieces of impure copper (anodes, 99,6% of purity) are submerged in water with sulphuric acid, and an electric current is passed from them to plates of pure copper call cathodes. An electrochemical phenomena occurs, and the current takes copper from the impure anode to the cathode, that after the required time is removed (with a purity of 99,99%).

For other types of deposits, the first stage is flotation. This is a physicochemical process that uses air bubbles and chemicals to separate sulphurated copper minerals from the rock. The bubbles flow from the bottom of a container and then overflow out of it, carrying with it copper (and molybdenum) particles, this is called the "concentrate", that has 31% copper (up from around 1% in the original rocks). The output from flotation goes to smelting. The concentrate is dried up and then introduced into large furnaces at high temperatures. Here copper is separated from other minerals and turned into metallic copper[1]. The product is "blister" copper, with a purity of 96%. This goes to pirorefining, a process where oxygen is removed by the ignition of eucalyptus logs. The result is fire-refined copper (RAF), with a 99,7% purity. This can be sold or electrorefined, in a process similar to electrowinning.

Material is usually recirculated at different stages of these processes, to keep extracting all copper from the original rocks. However, there is a point where no more copper can be recovered economically by traditional methods. This residual mineral can treated by biolixiviation. In simple words, it was discovered that certain bacteria participated in the lixiviation process, "eating" the rock and separating the copper from it. A process using these bacteria has been developed to extract copper from mineral that was hitherto considered of too low grade to be treated.

After production, commercial knowledge and experience are necessary. Large mining companies can sell copper in spot and future markets, negotiate long term contracts with important buyers, and in general, they must hedge out risk associated to copper price fluctuations.

In parallel to the production process, knowledge from several other areas that support it is necessary: mechanical knowledge important for machinery maintenance; environmental sciences, to reduce environmental impacts and maximise reutilisation of materials; job safety; management, financial, production planning, and in general all kinds of organizational knowledge that permits operation and increases efficiency, among others.

It is evident that the knowledge base of the sector is highly technical and specialized, and this goes a long way in explaining why alternatives are not likely to come from the outside.

3.2 Industrial organization

Sectorial organization in the sector can be looked at in two dimensions: the vertical organisation according to the scale of operations, and value-chain linkages, especially relationships between mining companies and providers, and whether mining regions work as clusters or not.

Copper mining can be divided in large, medium and small scale companies. Large scale mining companies are defined by law as those that produce over 75.000 metric tons of mineral each year (considering all of their operations). They are only a handful of companies, including the state-owned CODELCO, the Chilean Antofagasta Minerals, and the rest are large multinationals like BHP Billiton and Angloamerican. Medium sized companies (over 30) currently operate in the range of 1.000 – 50.000 metric tons a year. They usually do not go through the whole process described in section 2.2, instead, they sell their production to state-owned ENAMI (*Empresa Nacional de Minería*). ENAMI continues the processing of the mineral from the flotation,

[1] These were two separated processes, until the invention of the Modified Teniente Converter, developed by the CODELCO division Teniente.

lixiviation, or smelting stages. Then ENAMI sells the product in international markets. Small sized companies produce less than 1.000 metric tons a year, and all of them sell their production to ENAMI. There are also independent artisan miners that work by themselves, under precarious conditions, and sell their production to small mines[2].

Large scale mining accounted for 93,9% of copper production in Chile in 2009 (SONAMI, 2010a). A large share of this, over 30%, was produced by CODELCO, the largest copper producer in the world. Middle scale mining accounted for 4,5% of production, while small scale mines produced 1,6% of total output (SONAMI, 2010a). Medium and small scale copper production is small relative to large scale copper, but it is significant for the economy when compared to other exports (over 3% of exports, comparable with salmon, wine and cellulose).

As companies' sizes decreased, so do the mechanization of the production process and technological capabilities, managerial capabilities, planning horizons, safety conditions and wages, but labour employed increases.

The reason for this division of production is the scale of production needed by large operations. The whole copper processing process isn't economically feasible in mines smaller than a certain size (and at the same time, some smaller mines can't be exploited by the same techniques used in large mines). That is why only the largest operations develop the whole process by themselves, and ENAMI buys all the production from smaller companies, achieving in this way the necessary economies of scale. As they don't have the economies of scale, and have to use different technologies, the smaller the mine size, the highest the average extracting costs, therefore the smaller the profits. This explains why the entrance and exit of small firms is very sensitive to mineral prices, and the amount of small mines and artisan miners operating depend on copper price cycles.

With respect to territorial organization, most of the copper production (and processing) is located in the north of Chile, notably in the Antofagasta Region. There are also important copper mining activities in the central regions of Coquimbo, Valparaíso, Santiago and O'Higgins.

The other important aspect of the sector's organization is the relationship between mines and their providers, and in general how much collaboration there is between the different actors.

Mines buy most of their supplies from large international providers, instead of domestic ones. There is a historical reason that explains that lack of local providers: large multinational mining companies began their expansion during the 1980's, and as domestic suppliers (and the necessary human capital) didn't exist in the countries they were arriving to, suppliers from their home countries expanded together with them (BCG, 2007). In Chile, the growth of the sector was in the 1990's, when international suppliers were consolidated. Moreover, Chilean companies have not expanded internationally, although there have been recent some comments aiming in that direction from CODELCO's Executive President[3].

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2 Most of them are gold miners, but copper artisan miners also exist.

3 Interview on La Tercera, April 24, 2011.

In Chile there are approximately 1500 companies that act as suppliers for the mining sector, but only 30% of them produce goods (the rest commercialize them and provide services) (BCG, 2007). Most of these companies supply also to other industrial sectors (DICTUC, 2007).

With respect to collaborative action, the lack of trust and experience in associative agreements is considered to be one of the important problems of the Chilean Innovation System, but the mining cluster in the North has been studied in detail and there are initiatives towards changing this situation. It was one of the clusters that were selected by the Boston Consulting Group as having a high development potential in Chile, in a study commissioned by the National Innovation Council for Competitiveness. This study includes a set of specific proposals to strengthen the mining cluster.

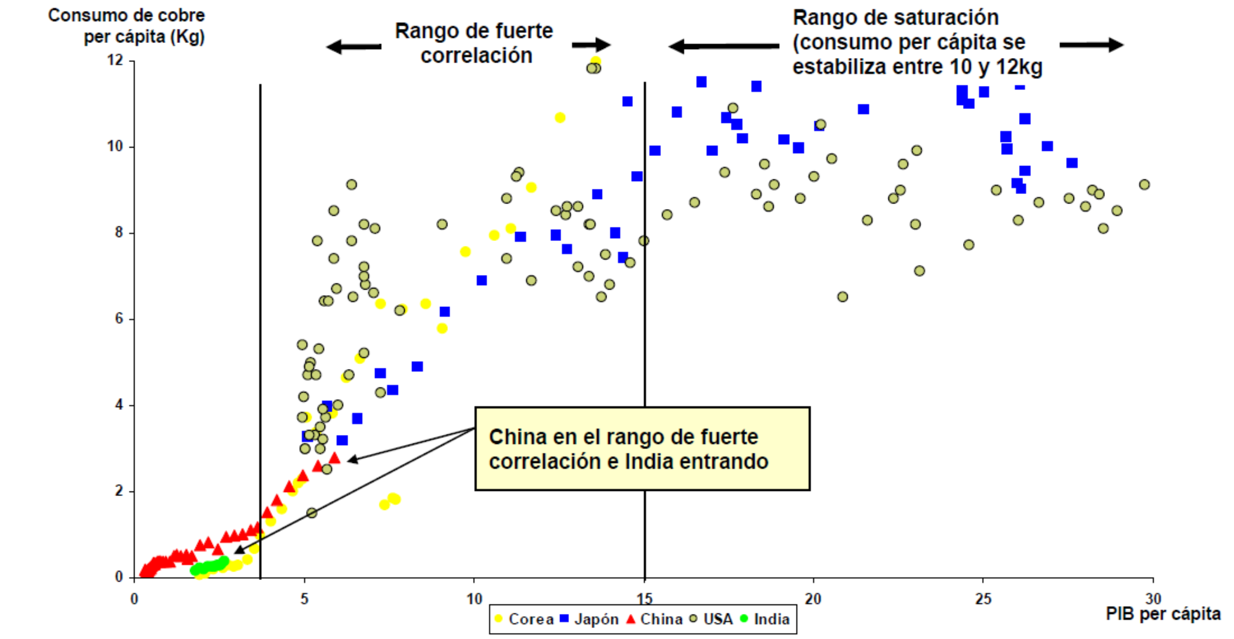
3.3 User relations and markets

As explained above, most of medium-sized mines, and all of small mines, sell their production to ENAMI. They finish the production process, and sell the resulting high purity copper. ENAMI is effectively the only buyer for all of these mines, but besides buying their production, ENAMI, being a state-owned company, has more duties related to small and mid sized mines. They help small producers hedge price risks, increase their technological capabilities and safety conditions, etc.

ENAMI, CODELCO, and the rest of the large mining companies sell their production in international spot and futures markets (in the London Metal Exchange, Shanghai Futures Exchange and New York Mercantile Exchange), and negotiate long term contracts with important buyers.

Even while CODELCO represents close to 10% of world copper production, it doesn't have price setting power, nor could a cartel as the OPEC be established, as world copper production is –except for the Chilean share– highly fragmented. After the 27% produced by Chile in 2009, Peru follows with only 7%, and the top 7 producers represent only 59% of world production, with the rest produced by many other countries (SNMPE, 2010). What CODELCO *can* do, is reduce world copper price, by increasing its production.

The high copper prices and demand for most of the past years are associated, as with other commodities, to Chinese economic growth. China's share in copper demand has increased from 5% in 1991 to 22% in 2006 (BCG, 2007). Its importance should continue in the coming years, as China is currently in a growth phase where GDP per capita is strongly correlated to copper demand. India is expected to enter this phase soon, as the following graphic shows:



Fuente: FMI, ICSG, USGS, análisis BCG

Correlation between per capita GDP and copper consumption (BCG, 2007).

With respect to suppliers, even if domestic suppliers are not as important as foreign ones, they have been growing quickly, with an average growth rate of 12% in the 1996-2006 decade (DICTUC, 2007). Besides the close to 1500 providers that are highly dependent on the mining sector (more than half of their sales), there is an even larger amount of firms that supplies the mining sector, but it is not their main client. In general, there is large heterogeneity in the share of sales from suppliers that go to the mining sector (*Ibid.*). Regarding exports, 27% of mining suppliers had exported by the year 2006, with an annual growth rate of 5% in the 1996-2006 period (*Ibid.*).

3.4 Dedicated policy institutions and political power

As will be discussed in section 2.8, the government plays several different roles at the same time in the mining sector. But with respect to dedicated policy institutions, there are several public agencies and laws important for the mining sector.

SERNAGEOMIN (*Servicio Nacional de Geología y Minería*) is the technical agency specialized in geological information. It is also in charge of supervising compliance with mine safety and environmental regulations. Their ability to supervise effectively has been put to question after the San José mine accident, a mine that after being brought to a close, was authorized to reopen without complying with the required safety conditions imposed by the authority.

COCHILCO (*Comisión Chilena del Cobre*) is a technical office in charge of advising the government in issues related to mining, and supervising and evaluating the investments and operations of state-owned mining companies.

There are other relevant agencies that are not dedicated only to the mining sector. For example, CORFO (*Corporación de Fomento de la Producción*) and CONICYT

(*Comisión Nacional de Investigación Científica y Tecnológica*), provide support for R&D and innovation in Chilean firms, including the mining sector.

Laws and regulations that are important for the copper mining sector include the water code, the constitutional law that defines the system for mining rights allocation, environmental laws that regulate the construction of new mines and their emissions, tax laws (including mining-specific taxes) and those laws related to CODELCO, among others.

Mining companies, especially large ones, have significant power and influence in decision making, given their importance for the national economy. Mining companies are gathered into a series of sectorial and regional industrial associations. Some of them are the Consejo Minero (association of large mining companies), SONAMI (*Sociedad Nacional de Minería*, which gathers all mining companies), the regional AIA (*Asociación de Industriales de Antofagasta*), and the suppliers associations APRIMIN (*Asociación de grandes Proveedores Industriales de la Minería*) and MINEXPORT, (*Consorcio Chileno Exportador de Equipos, Maquinarias, Insumos y Servicios para la Minería*).

Finally, workers' unions in large copper companies also hold significant power, and usually go on strike and obtain benefits unthinkable of to workers of other sectors.

3.5 Cultural meanings

Copper is popularly known as "Chile's salary", this is perhaps the best expression of its cultural meaning. The general population is aware of the relevance of copper for the Chilean economy and public finances.

On the other hand, a sector of the population sees in mining a large environmental threat, causing air, water and land pollution, water scarcity, and inducing the construction of environmentally unfriendly power stations, because of its high demand for electricity. These topics have been very high on the public agenda the last couple of months, with emblematic cases of health problems caused by mining facilities and massive demonstrations against thermal and hydroelectric power plants projects.

3.6 Employment

Large mining operations have very high salaries by national standards, and employ an important amount of highly qualified individuals, but their are not labour-intensive. There has also been some controversy regarding subcontracting, and a law regulating it was passed some years ago but didn't completely eliminate problems. Subcontracted workers chores are sometimes very similar to directly employed workers, but have worse salaries and job conditions (safety, benefits, etc.).

Medium scale mining is more labour intensive, but not too much as it is still highly mechanized. It accounts for approximately 6000 direct jobs, plus the indirect ones. Small scale mining employs directly over 15000 people and more in high prices cycles. Besides the amount of direct and indirect jobs, it is important to mention that most of them are located in very poor areas with little job alternatives, some towns are completely dependent on mining, such as El Salvador.

However, just as labour demand increases in smaller mines, salaries decrease: in medium scale mining they can be as low as a third as those in large mining, and even lower in small scale operations. This is directly related to productivity: in 2009, tons produced per person were 144, 46, and 11 in large, medium, and small scale mining respectively (SERNAGEOMIN, 2010a).

Regarding indirect jobs through suppliers, by 2006 those that are highly focused on mining produced 200.000 jobs, plus some additional 200.000 jobs on companies for which supplying the mining sector is less than half of their sales (DICTUC, 2007).

3.7 Role of the State

The Chilean State has a complex and broad-reaching role in the dominant copper trajectory. On one hand, it owns CODELCO, a company responsible for around 10% of the world's copper production, and the government's budget relies heavily on income from copper. On the other, it must regulate the sector, including incentives for exploration, defining rules for establishing new projects, and taxing them, and also worry about the social and environmental issues caused by copper mining. It also plays a role in promoting research and associativity in the industry. It is evident that there can be contradictions between its objectives, for example, CODELCO's (and the treasury's) interests may clash with alternative sustainable pathways that increase production costs.

3.8 About the historical development of the trajectory

In the following sections, problems and alternatives will be discussed, but these alternatives are either path-repairing, or path-breaking but related to the whole economy, and not the mining sector. In other words, there seems to be no alternative that would replace most of the main features of the regime, especially the production process and the sector's organization. This could be caused by a "lock-in" under the current conditions, where even they way people think about the sector is simply being reproduced and alternatives are not being considered. A brief review of the history of the copper sector might make more clear why this is the case.

Copper has been used since around 6.500 BC in Asia. Copper was present in nature as "native copper", i.e. pure ores of the metal could be found. Without the need for purification, copper was easy to obtain and to work with. But native copper began to run out as early as 4.000 BC, and extractive and metallurgic process began to be used (CODELCO, 2007). Copper was already being smelted by the Sumerians, and Romans improved on their methods to smelt suldife ores (CDA, 2011).

In Chile, there are records of copper extraction by 500 BC in the Atacama desert (Innova Minería, 2007). During colonial times mining was one of the main activities in Chile. Its technological level was very low, but this was no problem because ore grades were incredibly high, around 30%-60% (Icarito, 2010). Grades started to decrease, and when blast furnaces began to be used, in the first half of the nineteenth century, capital became a binding constraint; local landowners could not exploit some of the mines, and foreigners started financing small mines (Mellafe and Salinas, 1987). But still by the second half of that century most of mining was done in small labour intensive mines with high ore grades (MINMINERIA, 2011).

At some point in the nineteenth century Chile became the world's first copper producer and exporter, but by the end of the century high-grade mines began to run out, causing Chilean production to fall dramatically: copper mining virtually came to a stop.

World copper demand kept increasing, but economically exploitable mines were running out. The technological innovation of flotation made it possible to exploit ores with a content of copper of 1%-2%, previously considered as useless, causing a revolution in copper extraction. But production with the new process demanded large installations, continuous operation, and significant amounts of capital, not available domestically. In 1904 the Braden Copper Co. began the construction of El Teniente mine, and the Guggenheim family began operations in Chuquicamata in 1911 (CODELCO, 2007). This was the beginning of large scale copper mining in Chile.

From this moment on, the technology used in these large scale mining operations has been constantly improving, but always along the same lines, as these were and are the only available methods to economically exploit low grade ores. Economic incentives promoted the improvement of these technologies, to exploit lower and lower ore grades at reasonable costs, and environmental or social issues were not being considered. The table below shows how grades and production changed dramatically during the past century, together with the approximate date where different technical innovations started being used by the mines currently operated by CODELCO. Even as grades have been decreasing quickly, technology –along roughly the same trajectory– has made it possible not only to maintain, but to increase production levels to keep up with demand.

Year	**Grade (%)**	**Production (thousand tons)**	**Technical innovation**
1901	4	80	Flotation
1907	3.4	90	Open pit mining
1949	1.5	390	Improved smelting and flotation
1980	1.3	810	Electrowinning and solvents
1990	1	1100	On-off lixiviation piles
2000	.8	1200	Biolixiviation

Grade and production on mines which are currently CODELCO property, with the approximate date of introduction of important technical innovations (CODELCO, 2007).

Another interesting thing to mention is the process based on burning trees used to deoxidize blister copper. It was developed by the Welsh in the nineteenth century, and even with all modern metallurgical technologies, no better alternative has been developed (CDA, 2011). In other words, since smelting began thousands of years ago, only two or three other important technologies have appeared in the last century, and all efforts have been directed towards improving them to maintain and increase production levels as grades decrease.

An important aspect of large scale mining, is that it brought large salaries and levels of unionizing never before seen in the country (MINMINERIA, 2011).

With respect to small and medium sized mining, the SONAMI was founded in 1883. It proposed the creation of the Mining Credit Bank that started operating in 1932 (SONAMI, 2010b). Its objective was to promote smaller scale mining, installing mineral buying agencies and processing plants, to make it feasible to exploit small scale low grade mines. In 1937 they asked for a public smelting facility that was inaugurated in 1952 (Paipote). In 1960 both were merged together to form ENAMI, which plays those roles up to the present day (SONAMI, 2010b).

So, large scale mining was born because of new technologies and through the adding up of small mines by ENAMI and its predecessors, smaller scale mines were made feasible. And still with the presence of ENAMI, because of lower technological intensity, smaller mines have higher costs, so their entry and exit to the market is highly sensitive to mineral prices.

With respect to the State, after the saltpeter trauma in 1925-1960, there was awareness of the need to use copper to foster economic development. In 1955 a special mining tax was passed. In 1966 the "Chilenization" of copper began, after which the Chilean State possessed 51% of large mines. Finally, in 1971, the congress voted by unanimity to nationalize large scale copper mining companies (MINMINERIA, 2011; CODELCO, 2011).

Comparing Chile to other countries, the first thing that becomes evident is that the single technological trajectory described before is not a characteristic of the domestic mining sector, but a global technological trajectory that has been developed jointly by the large mining companies around the world. This is not only a conclusion of extensive research on secondary information, but it has also been confirmed by important actors of the mining sector. The main environmental organizations operating in the country do not propose any significant, path-breaking alternatives to the dominant regime either.

Regarding industrial organization, the same divide between large and smaller mines exist in other countries. Comparing to developed countries with important mining sectors, such as Canada or Australia, the main differences are that they have more stringent regulations and higher labour costs, but at the same time, they have better human capital and technology in smaller mines, as well as better exploration and capital raising systems, which creates a space for smaller companies, especially in exploration. But even if small mines have some technological intensity, it is in general much less than in large mines.

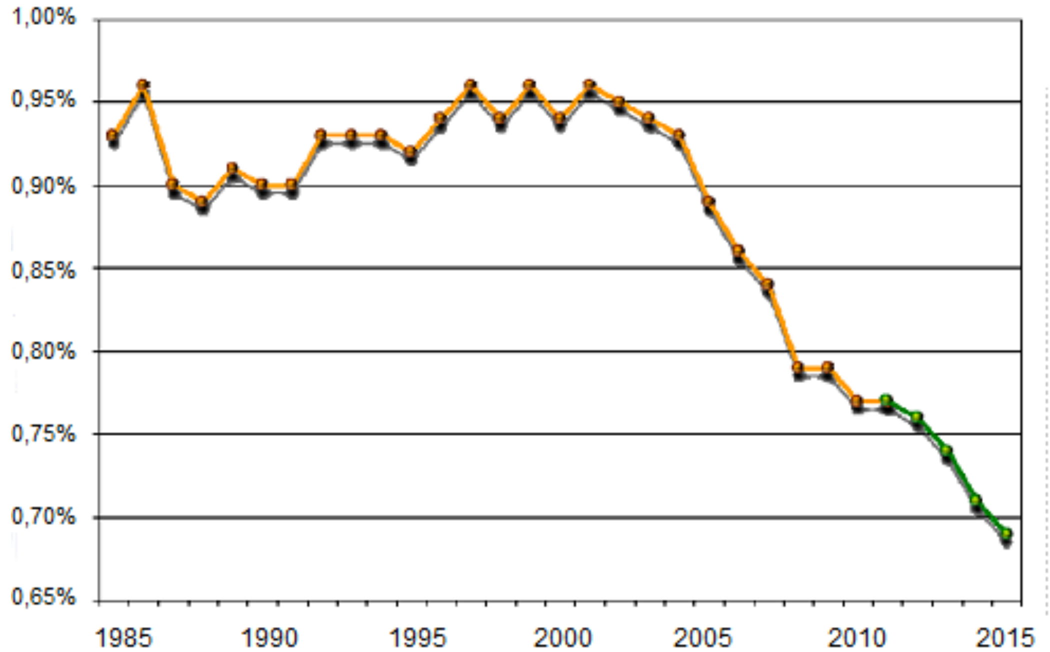
The low levels of technology in Chilean small and medium-sized mines also explain in part why virtually all research is concentrated on large-scale mining.

4 Description of the dominant trajectory's problems

The challenges that the current dominant trajectory faces will be grouped in four categories: production, economic, environmental, and social issues. Production was included as an additional category because they are important problems faced by the current regime that are pressing for the development of alternatives.

4.1 Production

The main productive problem faced by copper mining is the declining ore grades and its associated problems. This is expected to happen with all non-renewable resources; the resource is extracted first from the places where it is available in large proportions and is easy to obtain. As these locations are slowly depleted, it is necessary to look at places that were not considered before because it wasn't economically convenient to do so, and sometimes not even technically feasible. This is the same that has happened with oil that is now being extracted from underneath the ocean, something that wasn't thought of some decades ago. Technological advances have made possible to economically extract resources from more difficult places (lower grade ores in the case of copper), together with increasing commodity prices. These are in part associated with the the prospects of limited supply, but they are mostly caused by increasing demand from large and quickly developing countries, particularly China and India.



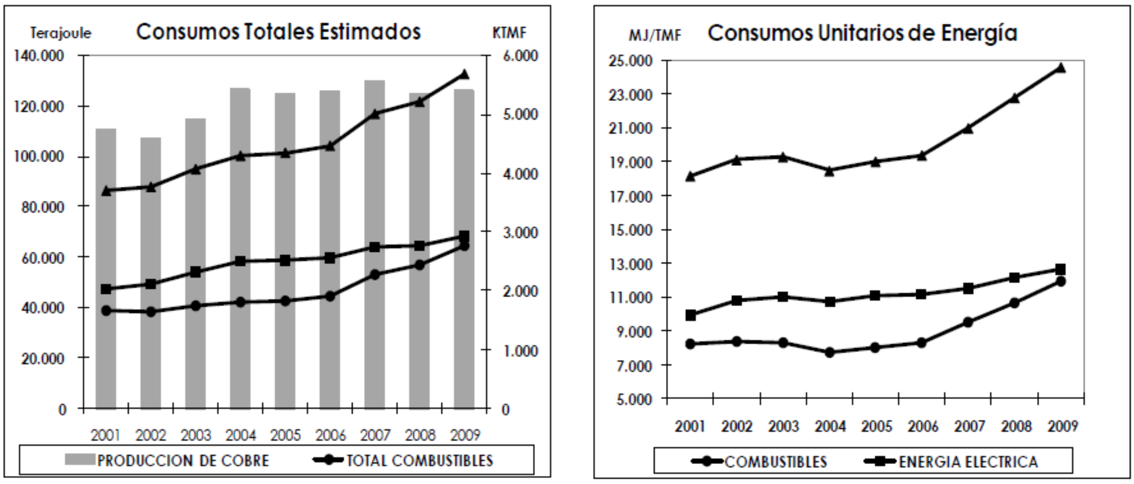
Declining copper ore grades in Chilean mines, with projection for the 2011-2015 period (Jofré, 2011)

What the graphic above shows is certainly worrying: for the long term, it is a present day symptom of copper depletion, and for the short and mid term, it poses considerable challenges. Even if technology improves and prices make it feasible to extract copper from lower-grade ores, there are important costs and problems associated with it.

Extracting copper from lower grade ores increases costs significantly, mostly because of the increased energy needed in the process. One of the main factor causing the important increase in energy demand the last years is the decline in ore grades (COCHILCO, 2010a).

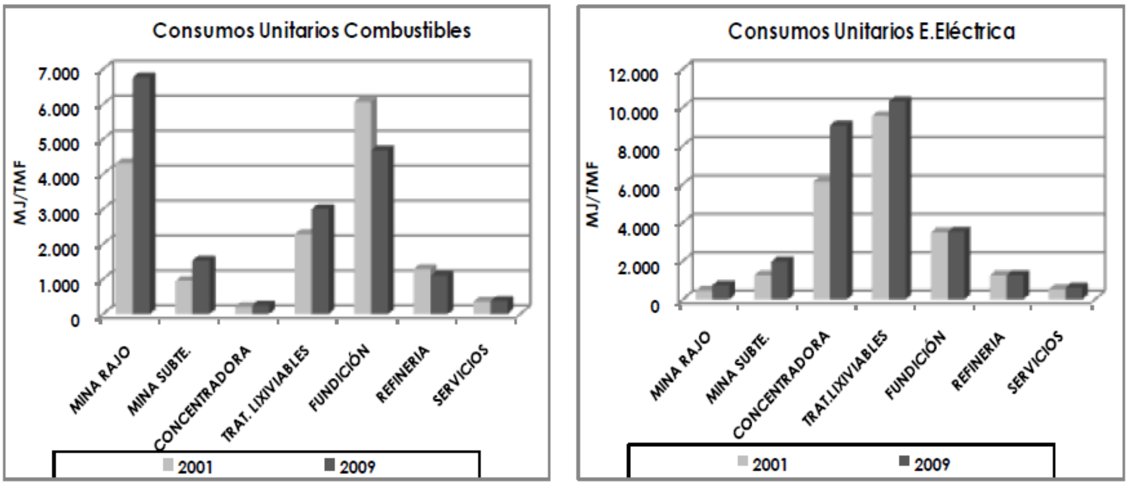
New mining projects start from significantly lower ore grades that in previous decades, and in old mines, mineral is being extracted from more distant and difficult places. The increases in energy demand come from lower ore grades, longer carrying distances and steeper slopes, and harder mineral (COCHILCO, 2010b).

The figures below show how copper production has not increased substantially, while energy demands have.



Left panel: Total copper production, fuel and electricity use.
Right panel: unitary consumption: energy needed to produce one ton of refined copper (COCHILCO, 2010b).

One of the areas where energy consumption has increased dramatically is fuel use in open pit mines, because of carrying distances and slopes as more distant parts of existing mines are being exploited.



Unitary consumption of fuel and electricity according to production area (COCHILCO, 2010b).

Even more than increasing extraction costs, the worst problem caused by higher energy demand is the environmental impact caused by direct fossil fuel burning in mining operations and the indirect effect through the construction of power stations. Large mining companies estimate that two thirds of their greenhouse gases emissions are indirect, through electricity generation (Área Minera, 2011).

Another factor that is increasing extraction costs is water: most of mining in Chile occurs in the Atacama desert, the driest in the world. The social and environmental problems related to water shortage will be discussed later, but it is important to mention that it is a factor that increases extraction costs and is making more difficult the development of new projects, as water supply is fundamental for the operation of mining facilities. Ensuring access to water and transporting it from its source to the mines are increasingly costly for new projects.

4.2 Economic

The main economic problem caused by the copper sector is the excessive dependence on it. Some areas in the north of the country rely heavily on mining, but jobs are highly sensitive to international prices, and in the long run the resource will be over. But more importantly, the treasury relies heavily on taxes on mining companies and on profits from CODELCO (and armed forces also depend on CODELCO's sales under the current system).

Copper demand and price are exogenous for the country and a plunge in any of them would have very serious effects, especially if it is sustained (the Chilean economy already had a traumatic experience with saltpeter around a century ago). Only four Asian countries account for almost 50% of exports, and eight countries account for two thirds of world copper consumption (BCG, 2007). It is clear that problems in Asia would have strong repercussions in the Chilean economy. Even if macroeconomic management has been sound, considering conservative copper price estimates for planning and assigning excess copper income to funds used for countercyclical measures, a plunge in copper demand (that could be caused by substitution, a problem whose likelihood increases with high prices[4]) would be problematic.

Moreover, if demand and prices stay high, copper reserves will eventually run out. The website of a community for innovation in the copper sector in Antofagasta, states that *"The region of Antofagasta is an endless source of mineral wealth"*[5]. This is a shocking example of how scarce serious thinking about the long term is.

Copper demand will eventually decrease dramatically or reserves will run out. Either way, mining regions, and the whole Chilean economy, must be prepared for this event. The natural thing to do is to promote horizontal linkages and the development of suppliers that could export products and services to other mining countries and economical sectors. For example, biotechnology, engineering services, remote machinery maintenance, etc. In other words, take advantage of the static advantages to build dynamic, sustainable ones, intensive in knowledge and advanced human capital.

Currently, a very small amount of Chilean suppliers export, and their export volumes are small considering the global market size (BCG, 2007). And in the local market, most of the supplies are bought from large international companies, although now the public and private sector are aware of this issue and committed to developing domestic suppliers. One of the reasons why Chilean mining suppliers didn't develop is the timing of the development of the sector. There was a mining boom in other countries in the

4 The main substitute is aluminium (BCG, 2007). There have been projects aimed at finding new uses for copper (Consejo Minero, 2011), but their significance is marginal (i.e. if copper stopped being demanded for its traditional industrial uses, these alternatives uses would produce an insignificant demand). Regarding current high prices and substitution, increasing production in Peru and Mexico are seen as positive, as they keep copper price under control (Titelman, 2009).

5 http://www.innovamineriaantofagasta.cl/buscar.php?seccion=60

80’s, and as mining multinationals expanded through the world, they relied on their domestic suppliers for countries where no quality domestic suppliers existed. The boom in Chile occurred in the 90’s, and by that international suppliers were already highly developed. Moreover, Chile had –and still has– a shortage of advanced human capital that prevented the development of suppliers. International suppliers also have their research labs at their home countries, and conditions for installing themselves in Chile are not the best (not so cheap labour, insufficient technical and advanced human capital, lack of qualified suppliers, and besides Peru, not much mining activity in the neighbouring areas).

Another economic problem associated to mining is that it works as an enclave economy. This means that as the sector is geographically so isolated from the rest of the economy, there are no spillovers to the rest of the economy, or at least not as much as there should be. The geographical isolation is responsible for the lack of linkages to other sectors and in part for the insufficient development of suppliers; firms may choose to produce supplies by themselves instead of buying them.

There is another problem that can be considered an economic problem, more precisely an R&D and technology one. Most of the challenges faced by the sector (the ones discussed in this section and in the following ones) are common to the industry, and appropiability of outcomes from R&D is low (e.g. optimization of water and energy use). This means collaboration in research between firms and between them and universities is critical for overcoming these challenges. However, the lack of trust and associativity is a landscape problem, one of the critical problems faced by the Chilean Innovation System.

Moreover, R&D investment in the Chilean mining sector is low compared to other mining countries. In Chile, it accounts for around 0,5% of the sectors’ GDP, compared to 1,0% in Australia or 1,2% in Canada (BCG, 2007).

Finally, a shorter term worry is the low levels of investment in exploration: Chile has 38% of known copper reserves, but in 2006 it received only 15% of exploration investments, a share that has been decreasing (BGC, 2007). This problem is at least explained by the particular legal system for allocating exploration and exploitation rights. The system, designed in the 1980’s and tied to the Constitution, determines that mining rights are allocated by the judiciary, instead of through an administrative procedure, as in most mining countries. But the main problem is that, in the way that it is set up, the system makes it possible to hoard rights indefinitely, without any obligation to actually conduct any mining exploration at all (Ramos, 2011). Obviously, this system doesn’t promote competition. Besides this, another reason explaining the low levels of exploration is the lack of government incentives, in comparison to other mining countries (BCG, 2007).

4.3 Environmental

While the protection of the environment was never particularly strong in Chile, apparently this is starting to change, as the topics in the public agenda during the last years show. This could be a very important landscape development in determining how the mining sector evolves.

Mining activities degrade the environment in almost all possible ways: they pollute air, water, and land, they deplete fresh water sources, and because of their high electricity needs, produce environmental damage indirectly via new power stations. These are important ways in which the socio-technical regimes affect its landscape, that in turn reacts producing pressures on it.

The main air pollution problem caused by mining are greenhouse gases, emitted directly by mining companies when burning fuel, and indirectly (power generation and fuel production). Smelting processes also produce harmful emissions, mainly sulphur dioxide (SO_2) and particulate matter (PM_{10}). Two emblematic cases are the pollution in the areas of the smelting facilities in Caletones and Ventanas. In the latter, there was recently a much publicized case of mass intoxication in a neighbouring primary school due to a sulphur dioxide cloud. Emissions of toxic gases can also result in soil pollution, as heavy metals and other particles accumulate on the ground.

With respect to water pollution, liquid industrial waste is regularly poured into the ocean, rivers, and salt lakes. These discharges are regulated by law, but firms not always respect allowed emission limits. For example, in October 2007 CODELCO (Ventanas plant) was fined by a government agency for this reason.

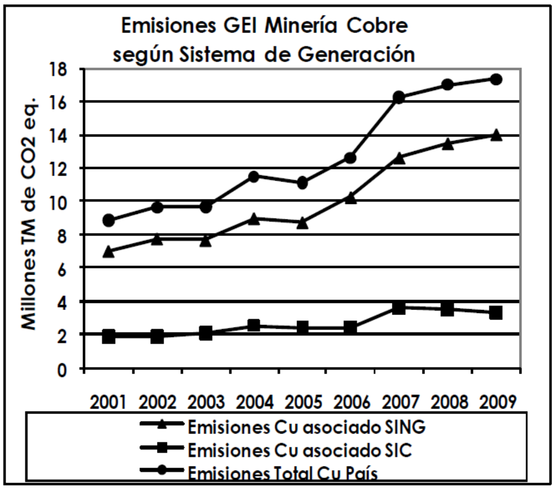
The other problem related to water is its availability. Most copper mining is located in the arid northern region of Chile, securing fresh water availability is one of the major difficulties faced by new mining projects. Most of fresh water is still used by farming, but in some regions mining activities account for around 30% according to some estimates (Skoknic, 2009). The problems go back all the way to 1981, where the current water use regime was established. Water rights were then allocated for free and are now subject to speculative actions. In some cases more rights that physical river flows were allocated, breaking the natural cycle of the resource, with the subsequent depletion of rivers and underground water sources (*Ibid*.). Nevertheless, it’s in the mines’ best interests to reduce water consumption, and water use optimization and recycling are a permanent concern.

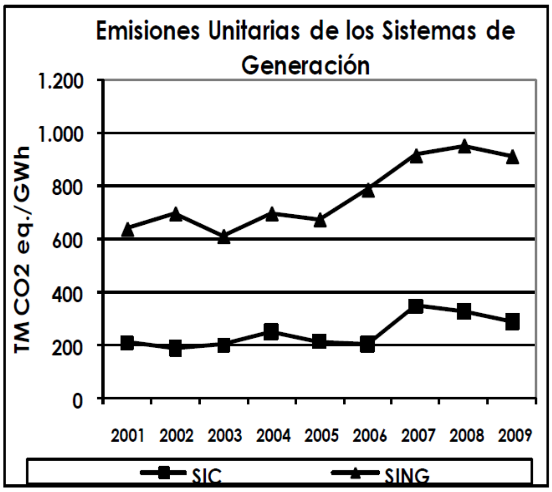
There are three types of solid residuals produced by mines. Massive, “others” and solid industrial waste (CODELCO, 2001). Solid industrial waste includes tires, old batteries, filters, etc. The “others” are outputs from different parts of the production process, like muds with arsenic. There is not much secondary data available on these residuals. “Massive” solid residuals are usually said not be represent major threats. They are made up of sterile material, slag and tailings. Sterile material is the name given to the rocks that must be removed to get to the rocks rich in mineral. It is never treated, and doesn’t pose a major threat. Slag is the solid residual from the burning in smelting plants. The worst solid residual are tailings. Tailings are mixes of water, rocks, and minerals that are not useful for reprocessing or reuse. Tailings are deposited in secure basins, and water then evaporates from them. It should be mentioned that Chile currently doesn’t have a norm regulating permitted soil pollution levels.

Earlier this year, a report that identified dangerous abandoned mines (until the mid nineties there were no rules for the closure of mines) surfaced thanks to a journalistic investigation. The report, elaborated by SERNAGEOMIN (that was not published officially because of questionings to its methodology by current authorities) found that some closed, abandoned mining operations, represent significant health and environmental threats. Most of the problems are associated with tailings basins, which are not as safe as they should: sometimes the tailings were just covered with dust, making them look like harmless hills, that are actually filled with dangerous substances that can pour into underground fresh water deposits, or collapse into landslides, as it happened with a basin after last year's earthquake, killing four people. (Ramos, 2010)

The final environmental challenge of the copper mining sector is energy use. As was described in the productive problems, decreasing ore grades means higher energy demands. Fossil fuels are used in the mines, mainly for the trucks, and huge amounts of electricity are needed for grinding, electrowinning and other processes (in 2008, 53,2% of direct energy demands in copper mining were electricity [COCHILCO, 2010a]).

A problem that will likely affect all Chilean exports is the carbon footprint. This may be a worse problem for other sectors, because copper is a commodity and most of the demand comes from developing countries. Nevertheless, it must be considered when thinking in the long term, both on pure environmental grounds, and in terms of the effect this could have on Chilean copper exports. Chile's energy grid has had a worrying increase in the share of electricity produced by burning fossil fuels. Chile has separated electrical systems in the North (SING) and center (SIC) of the country. Mining accounted for 17,5% of the SIC's demand and 82,2% of SING's in 2008, representing 33,7% of the total generation by both systems (COCHILCO, 2010a). This explains why those who oppose to some controversial power stations projects argue that the mining sector, and not the industry in general or households, are responsible for the environmental damage caused by their construction and operation. The following graphics show carbon emitted by the copper mining sector and unitary emissions in each electric system (ton CO_2eq/ GW hour).





Left: carbon emitted by copper mining
Right: Unitary carbon emissions by electric system
(COCHILCO, 2010b)

And the worries about the carbon footprint come from the fact that in 1990, 66% of the total SIC and SING generation was hydroelectricity, versus 45,5% in 2010. The rest is generated by coal burning (42,3%) and other fossil fuels, with only a marginal contribution from renewable energies (besides hydro). In the SIC, currently 50,3% of installed capacity is thermoelectrical, and in the SING, 99,6%. This is explained by the lack of rivers further south. If all projects currently in evaluation were built, 70% of installed capacity by 2015 would be thermal generation (ECUACIER, 2011).

4.4 Social

Social problems associated to the dominant trajectory can be grouped in two areas: jobs-related, and environment related.

Economic dependence on copper extraction was discussed previously. In terms of jobs, this means that many people, some in very poor areas, depend on small and medium sized mines, as there are no other job alternatives. These jobs have several problems. In smaller firms, they tend to be precarious, without formal contracts and the associated social security benefits, and safety conditions are usually not the best (as exemplified by the renowned case of the 33 miners trapped underground). Safety inspections have also shown to be insufficient to deal with safety problems. In 2010, 45 mine workers died, 42% of them in mines that were operating irregularly (SERNAGEOMIN, 2010b). The problem of precarious jobs is taken to the extreme by artisan miners, who operate in complete informality.

Finally, besides the informality and insufficient safety conditions, these jobs are not permanent in time, they are highly dependent on copper prices.

The other groups of social problems are derived from the environmental issues that were described in some detail in the previous section: air, land and water pollution, and increasing demands for fresh water and electricity. Besides their direct environmental effects, they also have negative social effects in neighbouring communities.

All kinds of pollution described in the previous section may have health effects on neighbouring populations. And besides direct damage to human health, pollution can have serious effects on agriculture. Old residents of a town close to the Ventanas smelting plant, Los Maitenes, report how after the mining facility started its operations in 1964, plantations were burnt by toxic clouds, and agriculture, its main economic activity, became impossible[6]. A couple of decades later, the place is almost a ghost town. Environmental rules may be more stringent now (although not much, it is the same plant that produced mass intoxication in a primary school a few weeks ago), but this is still a good example of what unfettered emissions can cause.

The other environmental-related social problem is water shortage, which also affects humans and agriculture. In some cities in the North of Chile, such as Copiapó, fresh water for human consumption is scarce, and natural sources are getting more and more depleted. If farmers have serious troubles trying to obtain water for their crops, and availability of fresh water for human consumption is in doubt, public sentiment against mining will undoubtedly increase, and with fair reason.

[6] Information based on interviews conducted in 2005, on the context of a sustainability workshop.

5 Description of alternatives

Before going in more detail with alternative pathways, the particularities of the sector that is being studied. Most of the mining is done by large corporations, and entrance of small, new firms is unfeasible because of financial requirements and the need for extensive technical knowledge and experience. This means that contrary to some other sectors, innovation and alternatives must come from incumbents, and not from small new firms that may take risks with radical innovations. This said, it doesn't mean that alternative do not exist. What happens is that alternative pathways come from *inside* the dominant trajectory, and given that most companies are worried in the first place about profitability, most alternatives come from the productive challenges that are increasing their costs: they are the response to the pressures imposed on them by their social and natural environments. The interesting thing is that several measures oriented towards the productive and economic problems of the sector have significantly better environmental and social outcomes than the way things had been done traditionally. Evidently, these are all path-repairing alternatives, as path-breaking ones are unlikely to be feasible in a sector like mining.

Whether this alignment between environmental and economic interests is fortuitous, a result of the firm's environmental awareness and interest in improving their relationships with the community, or the result of the increased availability of environmentally friendly technologies and researchers working on them, is something that should be studied in more detail in the following stage of the project, in light of the socio-technical transitions framework. The fact is that many new projects are orienting the mining sector to a more sustainable future. It seems like the pressures that mining is facing, resulting from stressing the social and natural environments in which they operate, can only be reduced by replacing the harmful methods for more sustainable alternatives.

Another important point to consider is that alternatives coming from firms, rather than being broad, comprehensive ideas that encompass a totally new way of managing the whole mining sector, are projects oriented at a particular challenge, but which also have positive effects on different environmental outcomes. Whether they can be considered to be *niches* or they are really part of the socio-technical regime, is something that will be understood with the deeper study of the alternatives and the interaction between landscape, regime, and niches.

On the other hand, the long term unsustainability of the sector is an issue of big concern for the Chilean economy, which has taken measures to exploit the comparative advantages on copper and other resources and use them to transform the economy into a knowledge and innovation based one, that could sustain long term growth. This is a significant path-breaking alternative, that if successful would radically change they current socio-technical regime for the whole Chilean economy.

Alternatives will be analysed in the same four categories used in the previous section, but each project will be discussed in detail in the section of its associated challenge, rather than its outcomes.

5.1 Production

Biotechnology

The main productive problems in copper mining are decreasing ore grades, which complicates mineral extraction and increases energy demands, and the availability of fresh water. In all of these areas there are interesting alternatives being worked on.

One technology where Chilean producers have been on the technological frontier is biolixiviation. This consists in using certain bacteria to obtain copper from low grade ores which cannot be exploited by traditional methods. And besides recovering mineral from tailings, obtention through biolixiviation is more friendly with the environment that traditional methods (CODELCO, 2007).

The bacteria are not harmful for human health, and biolixiviation does not release toxic gases, and requires little energy (in contrast to smelting for instance). The negative impact is associated to the production of acid by the bacteria, and its eventual leaking to underground water sources (that should not happen under proper safety conditions) (COCHILCO, 2009).

Currently around 10% of[7] copper is obtained by biolixiviation. A large challenge now is to extend the use of this process to higher grade ores, instead of using it only for what was previously considered useless residuals. CODELCO has been experimenting in this direction (COCHILCO, 2005).

There is one more interesting aspect with respect to biolixiviation and sustainable economic development. Improving the biolixiviation process stimulates the biotechnology sector that could export this technology to other mining countries. It is possible to modify the bacteria at genetic level, for example to reduce their production of acid, or to make it able to obtain copper from different types of ores.

Moreover, the branch of biotechnology called biohydrometallurgy has two branches: biolixiviation and bioremediation. The latter is the use of microorganisms to remove pollution, particularly to remove heavy metals from the liquid residuals produced by the mining process (CODELCO, 2007; COCHILCO, 2009). The use of biolixiviation in copper may stimulate a biotechnological industry specialized in biohydrometallurgy, i.e. it would be creating a knowledge intensive sector that could survive copper.

Renewable energies

Chile is very rich in renewable energy sources: wind, ocean, geothermal, and solar energy are available, and some of them in vast quantities and continually or almost continually available, making the highly reliable. The argument against them is their current generation costs. But incentives for their improvement, both from increasing prices in other sources and environmental objectives by some governments, are quickly increasing their efficiency. According to a report by the NRDC (Natural Resources Defence Council) in collaboration with Bloomberg New Energy Finance, that was recently exposed in the energy commissions of the Chilean parliament (NRDC, 2011),

7 Informal conversation with a BHP-Billiton employee from the biolixiviation area.

several renewable sources are already competitive in their costs in Chile, and even solar will be in the coming decades. And this without considering the negative externalities of energies currently in use. These energy sources could also sell carbon bonds. The point is that mini-hydro, geothermal, biomass, eolic, and solar energies should significantly increase their share in the Chilean power generation systems, and copper mining may play a role in their initial development.

Copper mining is always energy intensive, and even more as ore grades decrease. While the bulk of new power stations built during the last years, and those that are approved and ready to be built, are thermal stations (most of them coal based), there have been some small scale projects on alternative energy, several of them associated to mining companies, that are especially interested in energy availability and cost.

According to COCHILCO (2010a), alternative energies already being used in Chile are biomass, eolic and mini-hydro. Geothermal projects are in development.

An article in Area Minera (2011) reviews some of the alternative energy projects operating or in planning stages by that year:

CODELCO is building a photovoltaic plant for the Chuquicamata mine, the first of this type in the world to be built without subsidies. During 2010 they invited a tender for an eolic park that would represent 6% of CODELCO Norte's division electric consumption, with 50 MW, and a similar eolic park is considered for the Gaby mine. There is a pilot project in Teniente to generate electricity from tailings.

Doña Inés de Collahuasi mining company had positive results with an evaluation thermal solar plant, and has exploration rights for geothermal energy in five areas. Preliminary studies show that there is potential for power generation. The Chilean Association of Geothermal Energy is worried about the improvement of the regulatory framework to increase incentives for exploration and investment.

There is also a government tender in process for a photovoltaic and a solar concentration plant, the latter in a join effort with several mining companies (DF, 2011a). The government also promised an USD 85 million fund to support the installation of pilot renewable energy plants and the construction of transmission systems to support smaller scale plants (Área Minera, 2011).

Besides power plants based on clean energy, there are other interesting projects regarding energy used. For example, CODELCO is testing biodiesel and biogas use, and trying to recover energy from Teniente converters and water vapor (*Ibid.*). In general, all mines are permanently increasing their energy efficiency, and these measures are in general positive from an environmental point of view

Water availability

Another area that poses productive challenges and where sustainable alternatives exist is the need for fresh water. These alternatives can be grouped in desalination, use of salt water, and technologies and processes that improve water use.

Desalination plants for human consumption currently operate in Arica and Antofagasta, where the fresh water situation was critical. Operation of desalination plants is expensive because of their high energy requirements, therefore it is more suited to industrial than residential use. For mines, it is even more energy intensive, as they need to pump desalinated water from the ocean to the mine. But as water costs increase, desalination increasingly becomes an option.

Escondida mining company currently uses desalinated water in some of their processes. They started operating a desalination plant in Antofagasta in 2006, and are planning the construction of another one.

A desalination vessel was also offered by the company Water Standard. This ship stays offshore and pumps desalinated water to the mines. The ship can obtain energy from the national electric system of from its internal diesel generators.

Desalination should ideally be done with green energies. But even if it is not, at least it reduces the pressure on natural water sources that are being depleted as excessive use doesn't allow them to replenish.

Another, much more sustainable option, is the use of seawater in the production process. A research project on using seawater in the flotation process started in 2009, with support from CORFO and several mining companies that formed the consortium Amira International.

Earlier this year, Minera Esperanza, an Antofagasta Minerals' project, began operations. Minera Esperanza is the first mine in the world that uses 100% of seawater (not desalinated) in its operation. Several other companies, including CODELCO, are preliminary considering the use of seawater. The results from this pioneering project will probably be determinant in the future of this alternative.

Using seawater is not free of problems: first of all, water needs to be pumped up the mine from the ocean, so distance from the sea and altitude of the mine are important determinants of its feasibility. Moreover, seawater corrodes machines much more than fresh water, so more expensive materials need to be used. Finally, not all types of ores can be processed with this technology. Nevertheless, it is in general cheaper than desalination, it demands far less energy for its operation, and helps alleviate the problem of water availability.

Besides desalination and the use of sea water, companies are permanently experimenting with alternatives to reduce their water use and increase water recycling. Some examples are thickened tailings and the use of saltwater in certain parts of the projects, as Minera Michilla in the lixiviation process (COCHILCO, 2008).

How these alternatives fit into the socio-technical transition framework, if they are niches or not and what impact they can be expected to have in the socio-technical regime, will be understood in the thorough analysis of the next stage of the project.

5.2 Economic

The main economic problems are excessive dependence on copper, from the perspective of the whole national economy and the non-existence of economic sectors that could survive the end of copper. These should be suppliers of knowledge intensive products and services, that should be stimulated by the copper mining sector, but grow beyond it. Associated problems are the fact that mines work as enclaves, without producing externalities on the rest of the economy, the insufficient levels of R&D by most mining companies, and the lack of R&D collaboration.

These are different problems, but they are closely related, and they point to the challenge faced by economies based on non-renewable natural resources. They have a comparative advantage on them, specialize on their extraction, and when the resource is no longer demanded or runs out, the main driver of the economy disappears. What the Chilean National Innovation Council proposes is to use the experience and knowledge in the copper sector –and other natural resource-based sectors– to develop industries of knowledge intensive products and services. If these sectors are properly linked to the rest of the economy, produce lateral migration of technologies and other externalities, they could help turn the Chilean economy into an innovation-driven one. In other words, they would take advantage of the static advantages given by natural resources to develop dynamic advantages based on advanced human capital, knowledge, and innovation.

Existing projects that aim in this direction will be reviewed in this section. First projects oriented to the development of suppliers and associativity between actors in the mining clusters (to make of it a cluster that exploits its knowledge-related advantages, and not only physical proximity). Then projects oriented to the promotion of R&D, and collaborative action in R&D. Finally some examples of knowledge intensive services and horizontal linkages to the rest of the economy will be commented. Even if there is significant overlap, it is important to understand that all of these are different issues; these projects, especially if public policies are involved, should understand the problem they want to solve if they are to work well.

Development of suppliers and associativity in the mining cluster

The importance of developing highly qualified domestic suppliers has been on the agenda for some time already, and several measures have been taken by central and regional governments, as well as by privates. As the report by the Boston Consulting Group (BCG, 2007) shows, there is world tendency for delocalisation of services, something that Chile should take advantage of, entering some innovation and technology intensive market niches where there is exporting potential.

The first important actions have been the formation of the supplier association Minexport, cofinanced by CORFO. COCHILCO and the Chilean agency for the promotion of exports (Prochile) have been helping this association to make business in foreign countries (COCHILCO, 2006).

Regarding particular regions, COCHILCO (2006) reviews actions oriented towards strengthening linkages and increasing local provisioning of goods and services. In the Region of Tarapacá (recently split in two), CORFO has helped firms with potential for innovative exports to obtain ISO certifications. In the Region of Antofagasta, where most of copper mining is located, CORFO, the regional government, the Mining Ministry, and local firms, started the "Antofacasta mining cluster" integrated territorial project (PTI) in 2002. Besides this broad reaching programme, there have also been support for certifications and a regional business incubator, among other measures. In the Atacama Region, Minera Candelaria has a supplier development programme, that has received support from CORFO, and a regional development corporation (CORPROA) is promoting linkages in the local mining sector.

But it is important to mention that it is not unusual that measures in this direction end up being only good-sounding plans and proposals. For example, there was a very promising initiative with participation from the Mining Ministry, Consejo Minero, SONAMI, and the national industrial associations SOFOFA and CPC. They proposed a strong long-term agenda for the development of mining-related sectors, but no concrete actions were ever conducted.

R&D and collaboration in R&D

The problems with R&D are two: the insufficient spending on it from the mining sector, vis-à-vis competing mining countries, and the lack of collaboration in R&D, considering that important problems affect the whole sector, and can only be solved by joint actions. As mining companies are not really direct competitors, it shouldn't be complicated for them to work together, but lack of trust and collaboration is an important problem in Chile.

CONICYT, together with the Antofagasta regional government and two local universities, launched in 2006 the research consortia CICITEM (*Centro de Investigación Científico y Tecnológico para la Minería*). CICITEM has two main research lines, biominery, and process engineering. The latter is oriented to increasing process efficiency and reducing environmental impact. The former is centred on biolixiviation, certainly both are knowledge intensive and have business potential. Besides biolixiviation, the center works on biofuels and biorremediation, the cleaning of polluted water with bacteria, technology closely related to biolixiviation, but that can be applied in many sectors besides mining. This center has established collaboration networks with several important international research centers, and on the domestic side, they work with local firms on their research needs (COCHILCO, 2006; CICITEM, 2011).

Another project sponsored by CORFO, CONICYT, the Mining Ministry and the Agriculture Ministry, is the "Genoma Chile" programme. One of its branches is biominery, that is oriented to biolixiviation and other related technologies, such as bioinformatic applications. In this programme CODELCO is working together with BHPBilliton and the Japanese Nippon Mining & Metal Co. Ltd (COCHILCO, 2005).

CORFO is also promoting the installation of important technology development centres in Chile, the first of them was the German Fraunhofer, and more recently the arrival of the Australian Csiro for the development of mining technology. Csiro will operate together with CICITEM and two universities, as well as CODELCO, BHPBilliton, Anglo American, and Antofagasta Minerals, and more companies could eventually join (CORFO, 2011).

An initiative coming from the private sector is a regional innovation centre for the Latin-American mining sector, recently opened in Antofagasta by 3M. It is oriented to, and it's oriented to open innovation and the development of innovative ideas from the Region, not necessarily coming from 3M (DF, 2011b).

Besides the increases in R&D and R&D collaboration, an important aspect of these initiatives is the positive externalities they have on the economy, for example on the advanced human capital working on them.

Knowledge intensive services and lateral linkages

Some of these were already mentioned above: biolixiviation and optimization of mining processes are knowledge intensive areas that could be turned into exporting industries. Biorremediation is a good example of lateral migration, the experience obtained by biolixiviation research can be used to produce environmental solutions for other polluting sectors.

The analysis of innovation databases from the previous stage of the project also showed that the mining sector was demanding research from *other* economic sectors, related to environmental protection and certain knowledge intensive sectors.

CONICYT requested a study to identify global business opportunities in the information and telecommunication technologies sector related to the mining sector. The idea is to develop local suppliers for these global niches (COCHILCO, 2006).

Finally, a very interesting project, and first of its class in the world, was developed in Chile by the Swiss company ABB. They installed a remote monitoring centre to provide supervision, diagnosis and assistance, in real time, for mining machinery and critical assets. The service could be extended to other sectors where ABB supply machinery, such as cellulose and concrete (Área Minera, 2009). This project was supported by CORFO through InvestChile.

As for the productive alternatives, the interaction between landscape, regime and niches, the reasons behind the particular projects, the history of their development, and their results, will be better understood with the help of detailed interviews with key informants from both the public and private sectors.

5.3 Environmental

As explained before, most of the environmentally positive alternatives are motivated by productive problems (alternative energy sources, desalination and use of saltwater, biolixiviation).

Besides those, there are some other things that should be considered. Environmental demands for firms have been increasing during the last two decades, but they are still distant from those of developed countries, and the potential problem of capture of the authorities is also worrying.

Another relevant aspect is the increasing environmental concerns of the population, as recent massive demonstrations have shown. There is also an increasing awareness from the general population about their environmental rights, and increases in lawsuits against polluting firms.

There are a few other environmental measures that were not described in the productive alternatives. Collahuasi was the first mining company in Chile to do a complete measurement of its carbon footprint (Área Minera, 2009). CODELCO has taken some innovative recycling measures in different steps of their process. For example, selling old truck tires as rubber to for asphalt production, used oil from trucks is used in explosives, and used iron balls from mills are melted to produce new balls. They have also experimented with biodiesel and biogas, and several air pollutants are captured and used to produce sulphuric acid (CODELCO, 2007).

5.4 Social

Most of the improvements regarding the social problems described in the previous section relate to improvements in the environmental problems, and those in turn come from productive problems. Regrettably, apparently there is not much going on in this area besides that.

The division between large, medium sized and small companies depends on productivity issues that will not change. What can be done is to improve job security and safety conditions, and some measures in this respect are taken by ENAMI. There have been several support programs to train small miners in safety and better technologies. The first version of this programme was criticized because it confused social and productive objectives, but the overall evaluation was positive, so programmes in these areas have continued (Cipma-IIPM, 2001). ENAMI also plays a role in helping small and medium miners to deal with price variability.

Corporate social responsibility has been a fashionable concept in Chile lately, and large mining companies have joined this trend. Whether this has had positive impacts on the communities that are affected by their operations is still unknown, as the only study on this respect was an auto-evaluation of its action done by the same firms.

There is an important caveat regarding alternatives and social outcomes. The most important alternative described is the path-breaking transformation of the Chilean economy into a knowledge-based one. This should increase the importance of advanced human capital in the Chilean economy, and could eventually become a threat for inclusion, if the complete distribution of human capital across the population is not shifted upwards. The challenge is to increase *everyone's* human capital, and the *share* of "knowledge workers" in the economy. Otherwise, this knowledge-based economy could actually increase the already shameful inequality of the Chilean economy.

6 Conclusions

The dominant trajectory for copper mining was described in detail, following it's main problems and some alternatives that mitigate or could eventually eliminate some of these problems.

It is important to remember the distinction made between economic and productive problems. The productive problems are putting pressure on the firms to explore new technological pathways with better outcomes, while the economic problems are related to the long term situation of the Chilean economy, and both firms and government have been working on this.

As was stressed before, alternatives coming from the firms are in general path-repairing, as path-breaking ones would come from outside the dominant trajectory, something unfeasible in a sector with such a large technological specialization and huge capital requirements. Nevertheless, these path-repairing alternatives do seem to have potential to produce significant improvements over the negative environmental outcomes from the way the sector currently operates (and on the pollution-related negative social effects). There are not so good perspectives for the social problems, probably because they are not aligned with the firm's interests as the environmental outcomes are.

On the other hand, copper has been a blessing for the Chilean economy, but at the same time it has made it vulnerable because of its excessive dependence on it. The government has been working together with mining firms on several initiatives oriented to developing knowledge intensive, innovating exporting sectors that could survive the demise of the copper industry. The development of these sectors should be driven by the experience and learning developed in the sectors in which the country has a comparative advantage, like copper. This would be a path-breaking alternative not for the mining sector, but for the whole Chilean economy.

For the next step of the project, it is necessary to decide if the firm-related, path-repairing technological alternatives are explored (one or several), or the public-private initiatives oriented to a path-breaking future for the Chilean economy are studied in detail. For this stage, additional sources of information will be innovation funds data and interviews. Several key actors from both the public and private sectors that have already been identified and contacted will be interviewed. This will be important to be able to go beyond the secondary information available, and understand the alternatives in the context of their interaction with the socio-technical regime and landscape, their historical development and future perspectives.

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