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

CASE STUDY | The Use of Seawater in the Productive Process

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1. Introduction

This report corresponds to the findings of one of the four case studies conducted in Chile as part of the project "Opening up natural resource-based industries for innovation: Exploring new pathways for development in Latin America". One of the types of "alternative pathways" we are interested in are "path-repairing" alternatives, i.e. those that correct problematic aspects of the dominant sociotechnical regime, but without the possibility of inducing significant changes in the way the regime works.

As we described in the sectoral report, there are some technologies that have been developed and adopted by mining companies because they help them reduce some of their productive constraints, and at the same time, have significantly better social and/or environmental outcomes. One of these is the use of seawater in the productive process. With fresh water (either over or underground) becoming increasingly expensive, and in some cases not being available (i.e. a theoretically infinite price), the alternative of using seawater is increasingly attractive. There are two broad areas in this direction: the use of desalinated seawater, or the use of seawater directly in the productive process. In this study we will focus on the latter, although we will also make comments with respect to desalinated water. After all, copper mining in Chile might have no alternative in the future but to extract water from the ocean.

At the same time, is it important to mention that this case also has an aspect of "path-creation", as important technological efforts have been developed by domestic firms to make this alternative possible.

The report starts by describing the methodology, explaining the water shortage problem and the story of seawater use in the productive process. After these introductory sections, we analyze the five main questions of our study:

1. *How widespread has the alternative become?*
2. *How distant is the alternative to the dominant trajectory?*
3. *To which extent is the alternative promising or delivering better outcomes?*
4. In which ways has the availability of internet and/or other ICT technologies contributed to the development of the alternative?
5. Which are the main barriers that block the diffusion of the alternative?

Finally, we present a summary of our findings for these questions.

2. Methodology

As for all the cases under study, we base our work on both secondary information and primary information obtained from interviews to key informants. While the secondary information was fundamental for the previous stage of the project, where we described the dominant trajectory and its problems, in this stage we base ourselves on the primary information and follow a case study methodology (Flyvbjerg, 2006). Still, there is a significant and fast-growing amount of secondary information, which will be particularly useful for understanding the extension of this alternative.

We focus the study on the issues discussed in the Consolidated Paper (Marin and Benavente, 2011) that summarizes our adaptation of the Transitions Framework to study the problems of sustainability and generation of diversity in Latin American economies, starting from natural resources.

We conducted interviews at engineering firms and to high executives of a mining group that has been key in the development of this technology. Also to other experts that have seen the development of this technology from academia or government agencies that help us give more context to the case.

We used the software QSR NVivo 8 to analyze the data collected. We coded different fragments into concepts, research questions, and actors. This allowed us to later produce queries that crossed, for example, research questions with different important concepts of interest, to easily analyze our data but to do it in a very thorough way.

3. Context: Fresh water shortage

As we described in some detail in the sectoral report (Benavente and Goya, 2011), water shortage is one of the main constraints that new mining operations are facing. Around 9% of total water consumption in Chile is related to mining (World Bank, 2011), but in the northern Antofagasta Region it is as much as 70% (IAT-RedSur, 2012). And Antofagasta and its neighboring mining regions are desertic regions, where water scarcity is an increasingly worrying issue, both for agriculture and human consumption. In fact, 'water' was probably the most repeated problematic concept throughout our fieldwork, together with the "social license to operate". According to a World Bank report from June 2011 states that the average water availability per person North from Santiago is less than half of the recommended minimum levels for a sustainable development. And this might keep going down if there is more consumption than recharge.

From the perspective of mining companies, the simplest problem can be the price they could have to pay to secure water rights. But in some cases it is not a matter of price, there is simply no water available close the area of a potential mine. And when there is water available, it is not as easy as paying its high price. There is also the "social license to operate"; communities are becoming increasingly aware of their rights. And there have been some remarkable developments during the last year and a half in Chile both in terms of social movements and judicial actions affecting polluting industries and controversial investment projects.

Beyond the natural dryness of the northern region, the problem is closely associated to the fall in ore grades. Even with over US$35.000 million in investment during the last 8 years, *production levels are decreasing*, the huge investments made by large mining companies have been only to try to keep production levels constant. Even with significant improvements in water efficiency (in some cases close to 90% of recirculation, which means that the original water extracted is circulated around 8 times inside the production process before), the reduction in ore grades, together with the high copper prices that encourage new investments, the net result is that water demand keeps increasing. According to Cochilco's numbers, water consumption for copper production could increase in 45% between 2009 and 2020, even considering the great increases in efficiency (between 2000 and 2006 only, the water required to process a ton of mineral went from 1.1 to 0.79 cubic meters, a reduction of 28%. But experts think that most operations are close to its efficiency limits, at least the limits at which the operations would still be competitive.

On the other hand, during the last couple of decades, more water rights have been assigned than water that actually exists. The system is so absurd, that surface and underground waters are considered as independent, i.e. the legal system does not understand the way the water cycle works. In the words of a former head of the General Direction of Waters, *"many Chilean economists ignored or forgot 'the most elemental issues of hydrology, such as the continuity of the hydrological cycle or the random character of hydrological variables"*. Evidence of underground water depletion is as old as the 1970's, but the State kept giving even more rights for nonexistent resource. The obsession with *property rights*, under not properly defined rights, in a hydrological sense, has meant that the water rights that have already been granted will be impossible to exercise. It is a clear case of the Tragedy of the Commons. When industries depend on a common pool resource –in this case fresh water– it is important to understand the factors that shape firm's behavior and the actions that are needed to preserve the resources and the long term sustainability of the activity (Iizuka and Katz, 2011). In this case, we are probably already beyond the tipping point and the only alternative will be to turn the Ocean for water. Although it is important no mention that mining companies are not the only actors to blame, as regulations have been bad, agriculture consumes much of the resource, and natural conditions are not good.

Another factor comes in to complicate the problem: climate change. There is still no consensus on whether it will increase or decrease rain in northern Chile, but some people blame it on the cumulative water scarcity registered during the last decade, with the La Niña phenomenon striking repeatedly and producing two strong droughts in only four years. This could be only a temporary phenomenon, or a sign of a dangerous longer term trend.

With actual available water decreasing, and water demand increasing, in an area where water competes directly with agriculture and human consumption, the natural place to look at when thinking about the sustainability of copper mining was the Pacific Ocean. Although there have been some operations with seawater for a long time, only in the last couple of years the technology has been considered seriously by mining companies, in part because there was a pioneer firm that took the first plunge.

4. Use of seawater in the productive process

As discussed before, there are experiences of using unprocessed seawater, as well as desalinated seawater. The problem with saline seawater is that all mining processes have been developed to work with fresh water, and saline water introduces two important risks: the corrosion caused to the equipment by salts, and the uncertainty about how chemical processes will work under saline conditions. This is why most experiences with seawater have been using desalinated seawater.

The main difference between the use of desalinated and saline seawater in the productive process is the large amounts of energy that are required for the desalination process. The positive aspect for firms is that they can work just like they do with fresh water, without worrying about corrosion or chemical differences in their processes, and this could compensate for the high desalination costs. However, the negative impact on energy requirements (at least until renewable energies overtake coal-based alternatives) tilted our interest toward the use of non-desalinated seawater. Besides, using saline water involves much more technological learning and development than using imported technology to desalinate and then work in the same way as usual. It should be kept in mind however that it is not possible to use saline water under all technical conditions. We will focus the analysis on non-desalinated water, but we will make many mentions to desalinated water across the report, as they are similar alternatives in terms of the main outcome improved: freeing up fresh water for human consumption and agriculture.

The first reports of the use of seawater in the productive process are as old as the 1920’s, in a flotation[1] plant that is currently in ruins in the city of Tocopilla. This was one of the first sites in the world where copper flotation was performed with saline water. At the end of the 1980’s,

[1] Flotation and lixiviation are two different processes to obtain copper, the use of one or the other depends on the ore conditions. There are more details about this on the sectoral report (Benavente and Goya, 2011).

the same company (Compañía Minera de Tocopilla) started lixiviating[2] copper with seawater, in what is reported as the first case in the world. In 1990, a much larger –and influential for the industry– seawater lixiviation plant began its operation: Minera Michilla[3]. Apparently there was not much connection between the two cases. Michilla was installed in an area where no fresh water was available, therefore seawater was the only way to go. The size of the operation was much larger than Tocopilla's, but still relatively small, so a desalination plant was not economically reasonable. The technology used was built on top of a patented technology that had recently been acquired by Michilla's owners. This technology had been developed by Minera Pudahuel, a medium sized company that operated deposits close to Santiago and is recognized in the industry as one of the leading examples of innovation. Because of different characteristics of their minerals, as well as the pressure to operate cleanly because of its distance to the capital, Pudahuel was the precursor of several important technologies[4]. Many people agree on the importance of the human team behind these innovations at Pudahuel. Currently Michilla's owners (Antofagasta Minerals, the only private Chilean-controlled company among the large scale operators) promote and sell this technology to lixiviate in saline environments (the 'cuprochlor' process) to other companies.

The know-how developed at Michilla was the basis of a further escalation of the technology. Antofagasta Mineral's latest project, Esperanza, is the first large scale copper mine to operate with saline water (it is around five times the size of Michilla). Esperanza pumps over 600 liters per second from the Pacific Ocean all the way to the mining operation, at 145 km, and at around 2.300 meters over sea level. Four pumping stations are needed, together with the infrastructure necessary to provide them with the electric power they need. Around 10% of the water is desalinated, for human consumption and the final cleaning of the copper concentrate, and the rest is used without desalinated on the different stages of the production process (notably the flotation). Because of the costs of pumping the water to the mine (around USD 1.2 per cubic meter, mostly in energy), they are extremely efficient with its usage, including the use of thickened tailings technology, as described in other of our case studies. An

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[2] See footnote 1.

[3] Minera Michilla is owned by Antofagasta Minerals, the mining branch of the Luksic group. The Luksic's are Chile's wealthiest family, controling leading companies in mining, industry, finances, food, and telecom, with a total worth of around USD 18 billion (Forbes, 2012). Antofagasta Minerals controls the mines Los Pelambres, El Tesoro, Michillla, and Esperanza in Chile, and is working on its internationalization. Its Chilean operations, with 640,000 tonnes of copper, represented around 12% of Chilean copper production in 2011 (Esperanza, 2012; COCHILCO, 2012).

[4] Sociedad Minera Pudahuel was formed in 1969 to acquire two medium scale mining deposits from a subsidiary of the Anaconda Mining Company. One of them ran out in 1978, and the second one, "Lo Aguirre", began operations in 1980. Several key technological advances were developed for this mine, including Thin Layer Leaching (a type of lixiviation process), Chloride Leaching (lixiviation under saline conditions) and a form of biolixiviation (using bacteria). The company obtained several patents for these technologies. Lo Aguirre was shut down in 2000, and the company innovated again in designing a self-financing closure plan for the mine.

important difference between Michilla and Esperanza is that Michilla is a highly empirical, experience-based operation. A larger scale project needs more certainty in their processes, and this required the development of a previously nonexistent basic knowledge about the flotation process with seawater.

Antofagasta Minerals is considering seawater for its future projects, Antucoya could receive water from the same pipe as Esperanza does today. But more important, after Esperanza's large-scale operation with seawater, most other companies are evaluating the alternative, even in their large scale projects, something that was not done before.

An interesting case that needs mention is Algorta Norte, even if it is not copper mining. Algorta Norte is a iodine mine that began operating in 2011. It is located at 1.300 meters over sea level and that obtains water from a 75 kilometers long underground pipeline, seen in Figure 1. It is currently the only non-metallic mine using seawater in Chile. They report that they did not consider the use of fresh water to be certain and sustainable in the long run, and that is why they invested over 50 million dollars in this pumping system.

Currently all new projects seem to be considering the alternative of Ocean water, either non-desalinated or desalinated. Out of currently operating mines, Minera Escondida –one of the largest copper mines in the world– obtains 15% of its water needs from their desalination plant Coloso, and they are planning to expand this plant. Minera Candelaria (owned by Freeport McMoRan and Codelco) is building a US$ 300 million desalination plant, and Codelco's Radomiro Tomic next expansion phase will use desalinated water (after evaluating also the use of non desalinated seawater). Another project that deserves mention is CAP's (an iron and steel company) desolation project, although it is not copper mining. They are planning a large desalination plant, and considering selling desalinated water to other mining companies.

Figure 1 - The construction of Algorta Norte's underground seawater pipeline. (Source:Mch.cl)

The main problem associated to seawater, either desalinated or not, is the pumping costs, considering that most projects are far away from the coast and sometimes several thousand meters above sea level. Besides this, desalinated water has the increased cost and energy requirements of the desalination process, and on the other hand, non-desalinated water has the problems of increased corrosion and difficulty for recovering other minerals side-products (notably molybdenum).

On the other hand, the main and remarkable benefit is that *no fresh water needs to be extracted from surface or underground sources*. This is, together with energy availability, by far the largest constraint for future mining projects, and even a problem for existing operations, as their ore grades start to fall and their input requirements increase. This is an important improvement in terms of reducing stress on the resources, and at the same time a relief for communities and companies that do not need to embark in large legal and media battles to obtain the legal and social licenses to operate.

5. Q1: How widespread has the alternative become?

Following our adaptation of the Transitions Framework, described in the Consolidated Paper (Marin and Benavente, 2011), we describe the diffusion of the alternative in terms of networks, expectations, learning processes and policy initiatives.

5.1 Networks

As we described before, seawater was initially used in the 1920's, but more influential projects were developed in the beginning of the 1990s. Currently seawater is being used by Lipesed and Mantos de la Luna (originally owned by Minera de Tocopilla), Michilla and Esperanza (from Antofagasta Minerals), as well as Taltal and Las Luces (from Minera las Cenizas[5]), that as Michilla, do both flotation and lixiviation with seawater. There is also Algorta Norte, in iodine mining.

When Michilla developed its productive process, it had no alternative to seawater, as fresh water was not available. The development of the technology, besides the knowledge acquired from Minera Pudahuel, was done collaborating with suppliers as well as Outokumpu (the Finnish firm). The general tendency of innovation in mining is to go towards open innovation, with several participants besides the mining companies playing key roles.

[5] The mining group Las Cenizas was born in 1978, and currently controls three processing plants and several mining deposits with a total yearly production of 25,000 tonnes of fine copper. The company plans to invest US 130 millions between now and 2015, to increase their yearly production to 31,000 tonnes (Quepasamineria, 2012).

The largest operation is Esperanza, which was based on the capabilities developed at Michilla for around 20 years. In the rest of the world, there are some experiences in Canada (in the 1970's), Indonesia and Australia, but these are mostly smaller scale mines where seawater or saline (but not from the ocean) water is easily available (without the need of long and resistant ducts).

When Esperanza was being developed there were several informal conversations between their executives and higher executives at other mining groups, such as BHP-Billiton and Codelco, and these were highly skeptical of Esperanza's process with seawater. The experience of the Indonesian Batu Hijau mine, the largest seawater copper operation before Esperanza, was not considered a valid example, as conditions are different. There were also more formal contacts with other executives, for example Codelco's executive president visited Esperanza five months before its inauguration and declared that they were looking at how things worked out at Esperanza, thinking on Codelco's future projects.

Besides the mining projects themselves, it is important to look at suppliers and the eventual formation of knowledge networks. Chilean companies have participated in some of the projects. The engineering company Propipe, for instance, a relatively young firm (founded in 2003) has worked in projects related to seawater with Codelco, BHP-Billiton, Antofagasta Minerals, and Anglo American, as well as other smaller scale companies. It is well known that the same engineering companies work with the different mining companies, and that knowledge can circulate through them.

The Australian association Amira that works as a hub for collaborative research projects in the mining sector, landed in Chile in 2005. They have had three projects related to flotation with saline water, with participation from Xstrata, Codelco, Antofagasta Minerals, BHP-Billiton and Anglo American. One of the reasons why Amira achieves collaboration between mining companies is because they work on precompetitive projects, without immediate results: *"As projects in that phase have a high cost and risk, the industry benefits by associating, but if the solution was immediate, all would prefer exclusivity"*.

The research center CEITSAZA, focused on issues related to water in the desert and formed by a University in Northern Chile, the research center CIMM and several mining companies, has also worked on projects that are relevant for these technologies. One of the center's objectives is to *"articulate a collaborative network with International institutions for the transfer of technology and the development of initiatives oriented to the efficient and sustainable use of the hydric resource"*. They recently brought a Chinese expert from an Australian university that participated in different instances with students and industry representatives to discuss issues related to saline water use in copper mining.

5.2 Expectations

As close as two years ago, there was much skepticism about seawater, in part because of the large uncertainties and lack of knowledge about chemical properties and processes. But with increasing water costs, conflicts with communities, decreasing water availability, and now several mining operations successfully using non-desalinated water in their process –most notably the large-scale example of Esperanza– things have changed.

Large companies, such as Codelco, Barrick, Anglo American and Teck Cominco are considering the use of seawater to make their projects feasible, as well as Antofagasta Minerals themselves for new projects, using Esperanza's pipeline. Teck Cominco, for example, is considering building 190km long pipelines that would provide 1.000 liters per second for one of the two projects where they are considering seawater, as they do not have another alternative. Some are still careful and consider it, but mention that their *"first objective is to maximize the efficiency of the water they already have"*. The technology might also be exported to countries such as Perú. For example, the project "Tía María" is looking at this alternative, after being denied environmental permission, among other reasons, because of opposition from local communities to the use of wetland waters.

With the initial risk already assumed by someone, it is expected that this will trigger many other developments across the sectors, as it is common with new technologies in the mining sector. Risk is much lower for those that prefer to be *"the second best"* rather than the first.

But there are still doubts knowledge gaps and everyone is looking to currently operating projects with seawater to see how things will evolve.

With respect to non-metallic mining (such as Algorta Norte), firms are expected to move towards seawater, as they are close to the ocean vis-à-vis copper mines, and in general there are less problems with the productive process when using this water.

5.3 Learning processes

Learning about seawater in the productive process has been in large part concentrated in the Antofagasta Minerals mining group through their experience with Michilla and now Esperanza. There were some previous operations, but not as influential, as well as smaller in scale.

The technology for lixiviation with seawater comes from the developments at Minera Pudahuel, a company recognized in the sector for its innovativeness and its high quality human resources for applied research. Both the patent rights and some engineers went from Pudahuel to Michilla. Michilla (that has done both flotation and lixiviation) also collaborated with its suppliers and with Outokumpu, doing an *"intense piloting work"* to have certainties about the process' workings and to find design parameters.

Antofagasta Minerals developed much empirical experience in Michilla, and it was possible to transfer the knowledge about sulphures flotation, through its engineers and operators, to their new Esperanza project, that demanded both this experience and the development of the theoretical underpinnings of this processes. Executives from the company indicate that both tacit and explicit knowledge has been transferred across mining operations. The scaling up of the flotation process was the greatest challenge, with a plant that processes around a hundred times the volume processed at Michilla, and ores that are more complicated to process. Esperanza has had trouble in operating at design levels. There were comments in the industry that pointed towards problem with the seawater supply, but the company denies these claims, and blames problems with some specific machinery, together with the natural adaptation and learning needed when starting up a project of this magnitude that involves several important technical innovations (besides seawater, they are operating with thickened tailings technology).

Currently the other companies that are evaluating the technology work with the same engineering firms that worked on Esperanza, acting as an important channel for collaborative learning and knowledge exchange. Hundreds of domestic engineers work on these engineering firms, both at offices in Santiago and Antofagasta, closer to the mines. Only a small part of what processing copper with seawater involves intellectual property that can be transferred formally across firms, most of the knowledge is public, and possessed by the individuals that have participated in the different projects.

5.4 Policy initiatives

Policy initiatives have not been fundamental for the development of this alternative, except for the *poor water rights allocation rules* that have been in place for around 30 years, which were an important contributor to the current water crisis.

However, there has been public funding in some projects related to this technological trajectory. For example, some of AMIRA's projects, that include issues related to flotation with saline water, received Corfo funding. The research center CEITSAZA, that has worked on desalination with BHP, as well as on a project about obtaining industry-quality water from secondary quality water, has also received Corfo funding, through InnovaChile. Funding has gone to the center in general, as a way to promote the development of innovation capabilities, as well to particular projects. It is through one of these projects that the Chinese expert mentioned before was invited to Chile.

It has been argued that there is ignorance on the side of policymakers regarding this technology. For example, there was a legislative project that aimed to force mining companies to use desalinated water, completely ignoring the possibility of using saline water.

The government has stated that they want to strengthen the agency in charge of water management, including a project with World Bank funding to modernize their technologies. A recent World Bank report found that climate variability *"has a significant socioeconomic impact in a country like Chile, which bases strongly its development on the intensive exploitation of their natural resources"*. But there are no mentions to improving the current legal framework that produced the granting of more water rights than what was available, and could be blamed in great part for the current deficitary situation.

There is one interesting space where government could help coordinate agents. Desalination plants are very expensive to build, and scale economies are important. But mining companies are worried about the water for their processes, and not about providing water to others. The case of CAP (a domestic siderurgic company) is interesting. They are building a desalination plant, and as a way to reduce their investment costs, they plan to sell desalinated water to other mining companies. Algorta Norte is also evaluating the possibility of selling some of the saline water that they are pumping from the Ocean. Some of our interviewees suggested that the government could play a role in coordinating the different agents that could be interested (including not only mining companies, but also farmers and suppliers of drinking water). The government could also help by defining a national vision and an integrated strategy for the different basins.

Summing up, there has been funding to some interesting research projects, but most of the development along this trajectory has been done by private companies that forcefully needed to operate with seawater to make their operations feasible. On the other hand, the government could play a coordinating role where projects with large capital costs could improve the water situation, and the current framework for water rights, that produce unsustainable water consumption levels could be improved, but there are no initiatives aiming in that direction (at least not any one that could have political support).

6. Q2: How distant is the alternative to the dominant trajectory?

6.1 Guiding principles

As in the other cases, the main guiding principle is the same. Mining companies aim for profits, and when the only way to make a project feasible demands technologies that need higher investment and operational costs, they will do it as long as the projects remain profitable.

Using seawater or desalinated water was not necessary before, when water was cheaply –or even freely– available. Now that is not the case, and moreover, communities complain strongly about water being taken away by mining companies.

The use of seawater in the production process has the “side benefit” (from the perspective of the mining company) to absolutely eliminate water-related conflicts with communities. They are willing to pay high costs in part because of this, but mostly because *there is no alternative*. Mining companies, at least the vast majority of the times, do not choose an expensive alternative only because of its environmental and/or social benefits. This is true both for the companies that started using these technologies (including saline and desalinated seawater), as well as for companies that are now evaluating these alternatives. Using seawater does reduce the social costs, that are increasingly important for new projects, but they cannot be compared to the cost of not being able to exploit a mine, especially in the current scenario of high commodity prices.

And as many interviewees have stated, the sector seems to be quite conservative. Mining companies like *"being the second best"*, i.e. not being the one that assumes the costs of experimenting, but rather using technological advances that someone else already tried. However, when the conditions force them to do it, companies will assume those costs if the expected returns are high enough. In other words, the first company that is *forced* to try a new technology will do it, and if it works out, *the rest will follow*.

6.2 Products

The final copper products do not change when any of these Technologies are used. When saline water is used, the final product needs to be washed with fresh water to remove its chloride contents.

What can be a difference related to products when saline water is used, is that there are problems recovering molybdenum. This mineral is recovered mostly through flotation, as a byproduct of copper operations.

6.3 Technology

When using desalinated water, there are no differences in the production process, except of course for the installation and operation of the desalination plant and the pumping system to take the water to the mine. But when saline seawater is used, special care is needed to avoid corrosion, and to recover the minerals efficiently from the ores, as chemical conditions change and this can affect the process.

Metallurgists are especially worried about the corrosive potential of chlorides, but as we were told at Antofagasta Minerals, *"analyzing conceptually the processes of flotation and lixiviation with seawater, the seawater does not introduce any fatal flaw into the system. It just makes it more complicated"*. It is not *"as simple as you were used to"*. Appropriate technological answers are needed, that can give the high levels of certainty that are needed for operations of this magnitude, where it is not reasonable to operate in an "artisanal" way as it was being done in smaller operations.

The difference therefore, when using saline water, is that materials used (as well as paints and linings, for example) need to be corrosion-resistant, and the different chemical reactions in the process need to be "tuned" to work with water that has different characteristics. In fact, the water that feeds the process is seawater, but the water that recirculates inside the process is very different (for flotation, the pH needs to be adjusted with chemicals, and in the case of lixiviation, the process itself modifies the chemical composition of the water).

In the case of iodine mining, they normally work with solutions that are high in chlorides, and the iodine itself is corrosive, so operating under those conditions was already normal.

Summing up, these technological differences are translated into higher capital and operational costs. The pumping system, with its pipeline, pumps, and the infrastructure to supply electricity to them, implies an important initial investment. Materials need to be special for saline water, and in the case of desalination, the desalination plant must be built. In the operation, energy costs to pump the water are very high. In the case of desalination, high amounts of energy are also needed for desalination, and in the case of saline water, it must be considered that there can be higher corrosion levels (and therefore maintenance costs), and possibly other problems across the process.

The processes currently in use for lixiviation with saline water can be seen as "competing" with another interesting technological alternative: biolixiviation[6] (with saline or fresh water). Apparently lixiviation with water with high levels of chlorides has the advantage that the process, as it does not involve living organisms, is easier to control. There is also evidence of significantly faster processing times and higher levels of recovery. However, still none of these technologies has demonstrated that they can deal effectively and competitively with chalcopyrite[7], the type of deposit that is seen as key for the long term development of copper mining in Chile, as other easier to process deposits will begin to run out. However, very recently (during June 2012) Codelco and Biosigma (joint research venture between Codelco and Nippon Mining & Metals) announced that Codelco will conduct an industrial scale pilot operation with low ore grade chalcopyrite using biolixiviation techniques developed by Biosigma.

6.4 Industrial structure

While desalination is only feasible for very large scale projects, the experiences with saline seawater are mostly in medium scale operations. However, all large scale projects seem to be evaluating both alternatives nowadays.

It is interesting that initially the knowledge to work with saline water was developed at relatively small operations, to be then scaled up inside the same mining group that already had experience with a medium-sized operation. Suppliers (of chemicals) have also been mentioned as important for these developments. Engineering companies appear as a medium through which learning can be disseminated, particularly knowledge about the water extraction and pumping technologies.

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[6] Also known as bioleaching, this is lixiviation driven by living organisms, a cleaner process that has been used for a long time but has been limited in its application because of its long processing times (which is measured in years), and the conditions under which it has been possible to make it work. There are more details about this process in the Sectorial Report (Benavente and Goya, 2011), Section 5.1.

[7] The processes work but they are not competitive, they demand high temperaturas that make their industrial level application difficult. Currently flotation is used to process this mineral, when the scale is large enough to make the process efficient.

6.5 Knowledge

The differences in terms of knowledge base relate to the differences introduced by the saline water. In terms of material, different ones need to be used to reduce the corrosion problem.

But the knowledge needed about the operation of the flotation (and eventually lixiviation) with seawater (especially at large scales) is much more relevant, because it is new knowledge that has been created domestically as it has become necessary. First knowledge about lixiviation and flotation at small scales were developed, and for Esperanza the knowledge necessary for large scale flotation with seawater was created. At the same time, the knowledge about this process has been more formalized, as it was basically empirical, rather than scientific knowledge.

6.6 Culture and values

As described in the section 6.1, the main motivation behind the use of seawater is making projects feasible. It is not a matter of being more environmentally friendly or reducing costs (rather the opposite).

The "social license to operate" is a central component of the evaluation of any new mining project, and water use is possibly the most complicated factor behind the "social license" equation. Companies are taking much more care about the issue, but as it happens with other cases under study, the final motivation are profits. It is unclear how much we can consider the emergence of this issue as a cultural change in mining company, or simply the adaptation to different conditions in their natural and social environments.

Where a cultural change has indeed happened is in the population, which both at a national level and at the level of small communities, is much more aware of their rights and ready to fight against private firms and the government if necessary to protect them. This has happened not only in Chile, it has been an important "landscape" development that has changed the context where firms operate.

7. Q3: To which extent is the alternative promising or delivering better outcomes?

Following the classification used in the Chilean sectoral report, we will describe alternatives that improve productive, economic, environmental or social outcomes. Firm-level *productive* improvements are considered because some of the main problems of the dominant regime are associated to productive restrictions, and these are fostering the development of alternative pathways. And at the same time, some of these alternatives oriented at reducing productive problems produce important improvements in the outcomes we are interested in (environmental, social, and economic). The *economic* problems we studied are related to the long term dependence of the Chilean economy on copper exports, and the need for developing technological capabilities.

In terms of better economic outcomes, this alternative can be looked at from the prism of path-creation. It has helped develop local knowledge and engineering capabilities, something that is fundamental if we consider natural resources as a source of knowledge demand that could help diversify the Latin-American economies.

7.1 Productive

Using seawater in the productive process lifts what is increasingly becoming a binding constraint for new projects: water availability. Many projects now *must* go to seawater (either saline or desalinated) because it is simply not possible to keep using fresh water sources: even if they sometimes had the legal rights to do it, that could have direct impact on local communities drinking water supply. The impact in terms of image and conflicts would be just too high to take for the companies. In other cases taking water away from communities is not even an option. Without the knowledge and technologies to use seawater in the productive process, some new projects could not materialize.

If we compare the use of saline versus desalinated water, there is a tradeoff between the high energy costs of desalination, and the costs associated to corrosion and potentially lower recovery levels. There does not seem to be a clear winner in this respect. But if corrosion and efficiency can be controlled and accounted for with certainty, the huge energy savings associated to saline vis-à-vis desalinated water are likely to tilt the balance towards saline water. And as energy represents most of the operational costs, the magnitude of the cost difference is also significant. In the case of Esperanza, around 30 MW would be necessary for desalination, similar to the energy used for pumping water to the mine. Saline water costs US$ 1.2 per cubic meter, and desalinated would cost US$ 2.2. This sums up to a US$ 33 million difference a year, besides the US$ 700 million of investment needed for a desalination plant.

7.2 Economic

There is an important aspect of *path-creation* in this alternative. Although some people claim that more could have been done, Chile is still one of the countries responsible for some significant advances in this technology.

Innovation has not came from the risk-loving attitude of mining companies, but rather from necessity, when some attractive deposits could not be exploited by previously used and well-known technologies. But even if the triggers are the pressing technical and environmental conditions, the fact is that the human capital and the necessary technological capabilities have been available to develop new technologies when it has been necessary. And human capital refers not only to educated engineers, but to people that can led teams, take risks, and push innovations ahead. At the same time, the coexistence of several mining companies means that when one develops a new technology, the others might start using it –and adapting it and improving it.

An interesting factor is the "competition" between the technologies for biolixiviation and for lixiviation in saline environments. There are several mining groups doing research on both of those areas in Chile. There are two competing lines being developed at the same time, and both are associated to important environmental improvements vis-à-vis the currently dominating regime. Some Chilean mines are currently pushing the technological frontier in both technologies, and most notably, there are domestic groups doing it: Codelco in biolixiviation and Antofagasta Minerals in chloride-lixiviation. Both of them have patents registered both in Chile and in the US.

Moreover, the high costs of water pumped from the ocean encourage the use of water-saving technologies, such as thickened tailings. The learning from those developments can also be transferred to other companies, even if they do not use seawater.

With respect to desalination, apparently most of the technology has been imported, and the domestic technological effort has not been as important as in the use of saline water in the process. But both technologies have been relevant in producing demand for engineering services, a sector that has grown steadily together with the mining sector, and that is currently exporting to countries such as Perú and Colombia.

The technologies related to using seawater in the productive process could be one more of the technologies that produce demand for local engineering and research capabilities, and eventually turning the export of these kinds of services a relevant activity for future economic development. The mining sector has been moving towards more "open" innovation, which means that collaboration is required, and the participation of several actors is important. Besides the general demand for research and engineering, it is possible to think on the emergence of very specialized clusters, as the firms that are permanently working on water efficiency technologies in Israel, for example.

One area where more coordination and collaboration between actors would be useful is building common infrastructure for the sector. But this is more feasible for desalination plants than for systems to pump seawater, as pipelines must be built especially for each operation that needs the water. Moreover, desalination is also relevant for drinking water and agriculture, making the coordination of different actors (to achieve the necessary scale for efficient operations) more likely, although it would probably still need encouragement from the public sector.

7.3 Environmental

Not extracting hydric resources from surface or underground sources, that have been subject to great stress and depletion during the last decades, is an environmental improvement that cannot be exaggerated. The main social and environmental problem associated to copper mining is its use of fresh water, that in the dry Atacama desert, competes directly with agriculture and human consumption.

The use of seawater makes it possible to keep extracting copper, even under difficult technical conditions that require more inputs than before, and to do this without affecting the water supply for other activities.

There is an interesting case of a Mining company, Minera Candelaria (owned by Codelco and Freeport-McMoRan, which controls it), that will return water rights to the government. They are currently building a desalination plant, and when it starts operating, they will reduce their extraction from the Copiapó river basin and transfer back to the government some of their allocated rights.

If we compare the use of saline water to the alternative of desalinating it, the reduced energy use is another important environmental benefit: although some solar and eolic parks have been built lately by mining companies, most of the electricity used by the sector comes from thermal, coal-based plants. These have actually increased their share in generation during the last decade, worsening Chile's record in carbon emissions. And although saline water implies more maintenance, *"the balance states that it is energetically more efficient"*. Figure 2 shows an estimate of the potential impact of desalination on total electrical consumption of the mining sector in 2015 and 2020 (the light blue part of the bar, 20% of the total by 2020).

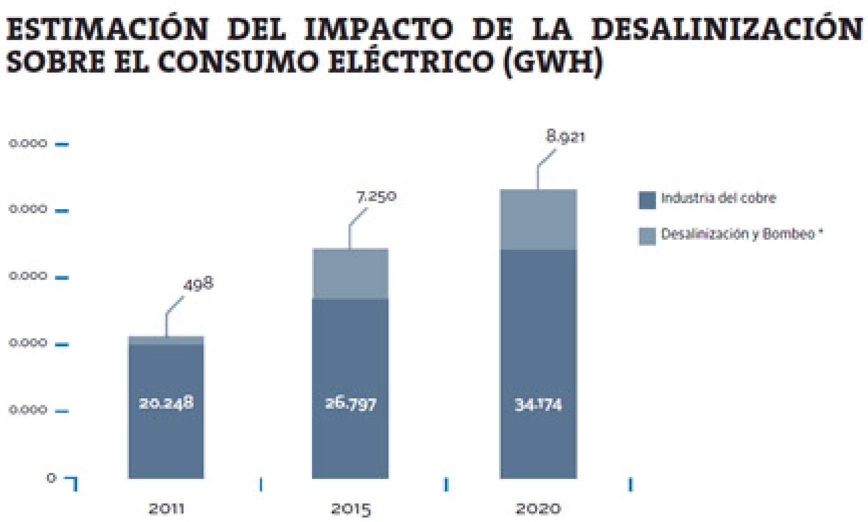

Figure 2 – Impact of desalination on total electrical consumption in copper mining. (Source: Quepasamineria.cl)

There are other relatively small environmental improvements associated to the use of seawater. For example, in the case of Algorta Norte, the plant is designed in such a way that residuals are recirculated and there are no emissions back to the ocean. Another is that when saline water is used, there is less dust emission from tailings, as the chlorides form a “scab” that stabilizes the residuals.

7.4 Social

The reduced energy consumption mentioned above (vis-à-vis desalination) means that there will be less pollution caused by energy generation, and this in turn means less social problems caused by copper mining.

But the most relevant improvement is again reducing the stress on the little fresh water available in the Northern regions. Although the use of this technology *was not* motivated by social concerns, their positive social impact is huge, and this also includes two types of benefits for the firms. One is simply a matter of public image. But another, very important benefit, is that environmental evaluation processes are simplified, as the topic that causes more conflicts with local communities is absolutely removed from the agenda. It is even possible (at least in theory) that the companies could supply water (saline and desalinated) to other activities that need it, where it wasn’t available before.

The “social license to operate” is a very important step in the development of new mining projects, and in some cases it can stop projects from materializing. There are cases where companies could have used water rights that they legally had, but they had to leave that possibility aside. Doing it would have meant taking drinking water away from communities, something that simply cannot be done, even if *“lawyers are willing to defend it”*.

In sum, using seawater *“solves at once the main environmental issue and the main point of conflict with communities”*.

8. Q4: In which ways has the availability of internet and/or other ICT technologies contributed to the development of the alternative?

The internet is as important as in any other sector for easing coordination and communication between actors, but it doesn’t appear to play a role beyond that in this case.

Software and computational power to assist in the different planning and design phases is of course important, but not something characteristic of this alternative pathway.

When asked about the importance of these technologies specifically for technologies like the use of seawater in the process, one mining executive clarified that ICTs are *“habilitators”*, and not *“an end in themselves”*.

9. Q5: Which are the main barriers that block the diffusion of the alternative?

9.1 Capabilities

One of the main reasons why this technology is not widespread is that there is not much experience with it and evidence of its results. As the seriousness of the water scarcity problem only recently started pushing all projects to evaluate the alternative of seawater, there have been very few projects using these technologies.

With relatively few cases, knowledge about it cannot be compared to that about the traditionally used processes, which are much better understood. There are therefore still doubts, especially about how serious the corrosion problems are, how chemical reactions work, and whether this is more cost-effective than using desalinated water or not. These issues will probably be cleared as experience develops. The lack of capabilities is rather a consequence of the lack of experience. As with other technologies, there is also the issue of scale: mines in Chile are large by international standards, so technologies are difficult to scale-up, and this usually demands the creation of new knowledge and capabilities.

There is also a lack of knowledge about alternative technologies at other levels, for instance, a law project that forced companies to use desalinated water was proposed, and the socially and environmentally better possibility of saline water was not even mentioned by this project.

9.2 Economics

Pumping seawater inland and to very high altitudes is extremely expensive, both the initial investments and the operation. Desalination costs or the investments needed to avoid corrosion are also very high. If the alternative was not considered seriously by most companies before it was not only because of technical uncertainties, but mainly because of its costs. But as water becomes expensive and runs out, this cost barrier begins to be surpassed. Still, companies that have water rights will continue to use them in most cases, except when scarcity is so extreme that using them would leave communities without drinking water.

There are some fears about what will happen with Chilean mining's competitiveness if seawater ends up being their only alternative. These fears however, suggest that the high competitiveness and returns associated to this extractive activity might be so at the expense of large negative externalities.

For desalination, several people have mentioned the potential benefits of coordinating different actors to achieve scale economies, but there are not many initiatives in this direction. This is expected to be like that, as the lack of coordination and collaboration are common problems in Chile.

9.3 Vested interests

There are two potential problems in this area.

One is the interest of companies that supply desalination solutions. There has been much interest from companies in promoting different desalination alternatives across mining companies. And this promotion usually goes together with strong critiques to the use of non-desalinated seawater in the process. One possible interpretation of the law project that aimed to force mines to use desalinated water is that it was not merely ignorance, and that this initiative was being pushed by private interests from the desalination industry.

Another potential clash is with biolixiviation[8]. Important efforts and interests have been created in the domestic industry, that could promote the use of biolixiviation over lixiviation in high-chloride solutions.

9.4 Infrastructure

There are several issues related to infrastructure that can difficult the expansion of these technologies.

First of all, existing plants cannot be easily converted for this technology, as the corrosion problem implies the need for different materials. The use of saline seawater is only feasible for new projects or expansions.

Another is related to the machinery: suppliers are not necessarily experienced and knowledgeable about operations with saline water.

The construction of the pipelines entails another problem: they pass through many properties with different owners, which means that rights of way must be negotiated with each of them.

9.5 Cultural

As with most new technologies, people at all levels –in this case, executives as well as those involved in the productive process– are somewhat fearful.

Those betting for seawater were called *"crazy"* by people at other companies, who doubted that the technology could work. Some said *"they would never use seawater"*, only to be evaluating the alternative one or two years later.

[8] This was discussed on sections 6.3 and 7.2.

9.6 Natural

As has been found throughout the cases, natural conditions usually play the largest role in determining the technologies used by mining companies, by posing different types of restrictions.

In the case of seawater this is not the exception. Copper is not found in one single form, but as part of different types of minerals, and their characteristics are determinant of which techniques can or cannot be used.

At the same time, if fresh water is easily available, there is no point in complicating things.

Location also matters. As shown in figure 3, most of the commonly cited examples of seawater use across the world, as well as previous operations in Chile, are very close to the ocean. When mines are more distant, as well as at higher altitudes, costs increase dramatically.

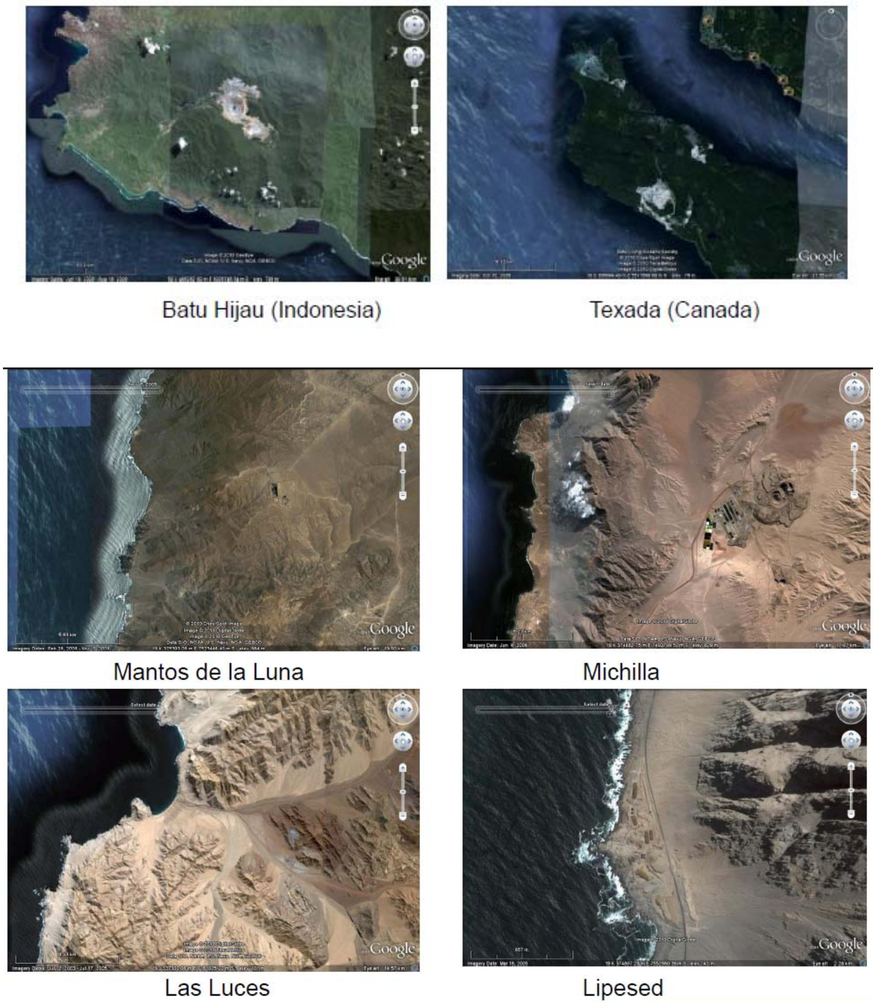

Figure 3 - Mines using saline seawater are closet o the coast. (Source: Philippe et al., 2010)

10. Summary

In this report, we covered our main research questions for the case study of the "use of seawater in the productive process", focusing on the direct use of saline water in the process, but considering also desalination. We looked at these technologies mostly in their *path-repairing* dimension, i.e. alternatives that do not have the potential to produce radical changes in the dominant sociotechnical regime, but that nevertheless produce relevant improvements on environmental and social outcomes, reducing some of the many important problems associated to copper mining. But the alternative also has a *path-creation* component, if we consider the technological developments associated to it.

The use of seawater is relatively old –in Chile it started in the 1920's– but it only recently became an alternative that is evaluated by all new projects. Most of the technological development associated to using saline water has been inside one particular mining group (Antofagasta Minerals), something that eased knowledge transfer, as people could be moved across operations. The fact that one company already assumed the initial experimentation costs, as well as the current critical water condition, means that now all mining companies, including some that absolutely discarded this alternative a few years ago, are always considering it for their new projects (both the saline and desalinated alternatives). However, these are still the last options, if a cheaper and "normal" water source is not available, and the project is good enough to go for these expensive alternatives. When developing this technology, Antofagasta Minerals acquired knowledge from a very innovative Chilean mining company (Minera Pudahuel), had some exchanges with suppliers, and also with foreign companies. Currently engineering firms might turn into an important channel through which at least some of the knowledge about the subject is diffused. There are also some isolated projects that try to articulate different actors in water-related research. There are still doubts about how well this technology performs, but there is no doubt that both saline and desalinated sea water will continue to increase their importance in the Chilean mining industry (even in non metallic mining, such as iodine). Policy initiatives have not had much relevance for the development of this alternative, except maybe for the *policy mistake* in the way that water rights have been allocated during the last 30 years. Some people propose that the government could help coordinate agents to promote the development of desalination plants.

Regarding the distance from this alternative to the dominant regime, the alternative is chiefly a change in a key input with its associated changes across the process. The companies' guiding principles are always the same: maximizing profits. If a project cannot be developed with fresh water, they will use seawater, and will happily accept all of its positive by-products. This is more likely to happen now, as there are already several successful experiences, particularly one large scale project that is operating with saline water. An important difference in terms of products is that Molybdenum is not recovered with saline water under current technology, so

desalination is still necessary if its recovery is important[9]. The main differences with the dominant regime are technological, and involve the use of different materials to cope with high-chloride water in the process, as well as understanding how chemicals reactions might be different under those conditions. When desalination is used, this is not the case, but instead a desalination plant must be constructed and operated. All of these changes mean much higher investment and operational costs. The core of the process does not change in either case. An interesting development is that lixiviation with saline water can be seen as competing with biolixiviation, another technological alternative with positive environmental outcomes vis-à-vis the dominant regime. In terms of industrial structure, the technology has been scaled-up from smaller to larger scale operations, and suppliers of chemicals and engineering services have been important. The cultural change that is relevant for this technology is more on the side of communities: people do demand their rights now, and this means that it is more difficult for companies to take their water. Companies have been internalizing everything related to the "social license to operate", which has increased in relevance dramatically during the last years, not only in Chile, but in many other countries.

The main improvement associated to this technology is obviously reducing the stress on fresh water sources. Water is the most controversial factor when discussing new projects with communities, and using seawater completely eliminates this problem. This is a remarkable change for communities –that will still have to be efficient in their water use, but will not compete for it with mining companies– and also in pure environmental terms. Underground reserves levels have been decreasing steadily and these technologies could make it possible to keep extracting copper, and to help fresh water reserves to recover at the same time. Comparing the use of saline water to desalinated one, the former produces much less environmental impact, because desalination is a process that demands very high amounts of energy, mostly generated from coal. From the perspective of the firm, besides simplifying project evaluation and improving their images, these technologies make it possible to exploit deposits that otherwise could not be exploited. From a *path-creation* perspective, necessity has pushed for these technological developments, and in turn this has produced knowledge demand for engineers and other suppliers, and learning and knowledge development at different levels[10]. This could be one more brick in developing domestic innovation capabilities, both in a general sense, and eventually in specialized areas, such as water efficiency (where Chile could be much more advanced than currently is). The "competition" between two technological alternatives being improved in Chile (biolixiviation and chloride-lixiviation) is an interesting phenomenon that could further promote technological development.

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[9] Fresh water is also needed for cleaning the final product (concentrate) and for human consumption, so the eventual operations that would use seawater, would also likely have small desalination plants.

[10] More in everything related to saline water use, as desalination technologies have been imported for the most part.

ICTs have not been particularly relevant for this alternative. They have been used for communication, coordination, and to assist the planning of projects, but none of these are exclusive to this sector or technologies.

In terms of barriers, the main ones are costs, natural conditions, and confidence in the technology. Using seawater is *very* expensive for mining companies[11], so it is not always reasonable to do so. This is closely related to one of the natural factors that matter: location. Pumping is one of the most important costs, and it gets more expensive as mines are at higher altitudes and farther away from the ocean. But another natural condition, the type of mineral found in the mine, is also relevant. Seawater extraction techniques are not –at least currently– appropriate for all minerals. Moreover, there is still relatively little knowledge and experience with these technologies, which added to the risk-averse Chilean culture and the large scale of Chilean mining operations, has slowed down the adoption of these technologies. There are possibly also some vested interests: desalination companies might have lobbied (in the private and public sectors, although there is no evidence of this) against using saline water, and the development of biolixiviation might act against the adoption and development of chloride-lixiviation techniques. Finally, there are some barriers related to infrastructure. Current operations cannot be easily modified to operate with seawater, machinery suppliers might not have knowledge about operating with seawater, and pipelines demand negotiating rights of way with many different land proprietors.

[11] On the other hand, it can be argued that these costs are simply the internalization of costs that were previously transferred to the society as externalities.

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