

Mining experts' perspectives on the determinants of solar technologies adoption in the Chilean mining industry

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ABSTRACT

The energy demand in Chile arises mostly from mining, its largest industry that accounts for about 35% of total electricity consumption. Energy generation to satisfy this demand depends completely on imported fossil fuels. As a result, the mining industry faces several energy related challenges. In particular, the cost and environmental impact of fuel sources are threatening the competitiveness of the industry and urge for new developments. In that regard, the importance of using clean and cost-competitive renewable energy sources has increased significantly in Chile and several government policies helped to increase the investment in them. The impact has been particularly large in the development of solar energy in the northern part of the country, where almost all mines are located. In fact, the country has become one of the largest solar markets in Latin America thanks to its abundant solar resources, favorable market conditions, and successful policy reforms. Solar energy then, could play a significant role as an alternative to satisfy the mining industry's energy demand offering a broad range of technological solutions. This study examines the key issues -barriers and drivers- influencing the adoption of solar technologies in the Chilean mining industry from the perspective of mining actors. As a result of the analysis the paper also provides a scope for appropriate policy interventions.

1. Introduction

Over the last decades, Chile has experienced a remarkable economic performance with high growth rates, low unemployment, low inflation, and a significant reduction in poverty [1]. Chile's economic development has been mostly based on the exploitation of natural resources, which accounts for 75% of overall exports [2]. Historically, the mining industry has been a fundamental productive pillar in the Chilean economy. The world's largest reserves of copper and lithium are located in Chile. In fact, Chile is the leading copper-producer in the world as it supplies a third of the global copper output.

Since the early 1990s, the mining industry has represented, on average, 8.5% of the country's total gross domestic product (GDP) and 47% of its exports. In 2016, the mining industry accounted for 51% of total exports and was 8.1% of the GDP [2]. The current projections from international and local experts show that the mining sector in the Chilean economy will continue playing an important role [3]. However, the industry faces important challenges that needs to overcome to be able to keep a significant role in the long-term. Some of them are energy related and are also significant enough to threaten the profitability and competitiveness of the industry. The role of energy is certainly an

important factor given the fact that the cost of energy represents between 20% and 40% of the total cost of mining operations. A number of successive energy crises over the last decade in Chile has resulted in a serious threat to the local economy, dragging the mining sector into a critical situation due to high costs and even availability of energy.

In this regard, addressing the energy challenges is an important matter if Chile wants to keep being a relevant player in the global mining industry in the future. A first step in the right direction was taken by the government when setting the policy goal of fostering a reliable, affordable, and environmentally clean energy to sustain the economy. In this context, renewables were considered an important contribution to the country's energy diversification strategy. Having a great potential in terms of natural resources and a promising business climate made the country an ideal marketplace for renewable energy project developers. As a result, over the last few years Chile experienced a remarkable energy transformation towards renewable energy. As of January 2011, installed renewable capacity was 591 MW representing just 3.8 per cent of the energy mix (15,268 MW). In May 2017, only five years later, it reached 3793 MW, representing 17 per cent of the total capacity (22,846 MW) (CNE, 2017) [4]. It is not surprising then, that Chile has grown into the largest producer of solar energy in Latin

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America.

The Atacama Desert, which has one of the highest rates of solar radiation in the world, is located in the north of Chile, precisely where the world's largest copper reserves are located [5]. Given that the expansion of solar technologies in the energy mix has progressed at a pace faster than expected due to their significant reduction in costs, the mining industry has the opportunity to use solar technologies in its mining operations and overcome some of the energy challenges they face.

In this context, we examine the key issues influencing the adoption of solar technologies in the Chilean mining industry from the perspective of mining actors. The analysis allows a better understanding of barriers and drivers and also provides information for appropriate policy interventions. The research findings are a valuable contribution for the industry and for researchers as they improve the knowledge about the major issues affecting the diffusion of solar technologies in the mining sector in general, and not only in Chile. They are also a valuable input for policymakers aiming at promoting the use of solar technologies in the industry and developing suitable policies for that purpose.

There are several studies in the literature addressing the barriers and motivators for the adoption of solar technologies. The specific focus in this literature is limited on the power generation sector and residential consumers in the context of various countries [6–8]. Given the fact that the mining industry accounts globally for 11% of the total final energy consumption and 38% of industrial final energy consumption [9] examining the determinants of the solar technology adoption in the mining industry represents an important contribution to the literature. In general, there is lack of comprehensive academic research in terms of examining the barriers preventing the adoption of solar technologies in the mining industry and this study contributes to fill that gap, especially in terms of considering the view of mining experts.

The paper continues as follows: Section 2 gives an overview of the key energy challenges the Chilean mining industry faces; Section 3 provides a literature review to examine the issues influencing solar technology implementations in the mining industry; Section 4 describes the research methodology; Section 5 presents and discusses the results; and finally, Section 6 concludes.

2. Energy challenges of the mining industry in Chile

The mining industry has historically used only imported fossil-based fuel sources – diesel, oil, coal, and natural gas – to meet its energy demand. While facing volatile commodity prices, even though prices were quite low for several years, the continued reliance on imported fossil fuels created serious challenges for the industry. These challenges can be classified under five broad topics: growing energy demand and costs, increasing energy dependency from external sources, increasing opposition from communities to new investments in conventional energy sources, growing environmental and social unrests, and rising energy demand for desalinization water plants.

2.1. Energy demand and costs

The rapid economic expansion over the past decades in Chile created a significant boost in energy consumption. As of 1990, energy consumption was 11.099 (ktoe¹) and reached 25.145 (ktoe) in 2015, a 130 per cent increase in 15 years [10]. Industry and mining are the two largest economic sectors consuming energy in the country. In 2015, industry represented 23% of final consumption and mining represented 17%, the latter mostly copper [4]. The mining sector energy consumption is mainly electricity (35%), diesel (26%), and biomass (20%). In this context, the electricity consumption of the copper industry

increased from 14.985 GWh in 2003 to 23.128 GWh in 2014, around 63% in a decade. The projection of the Chilean Copper Commission is that the demand will grow even faster, reaching 41.100 GWh in 2025 [11].

The increasing dependence on imported sources and a steady growing energy demand have resulted in both high and unstable electricity costs for the mining industry. After labor, energy constitutes the largest fraction of total operating cost in mining. Furthermore, the share of energy expenses has been continuously growing over the last 20 years, as the cost of energy in Chile increased significantly and became one of the most expensive among mining countries. According to COCHILCO, the cash-cost of producing copper in Chile was US\$0.63 per pound in 2004 and reached US\$2.50 in 2013, a 350% rise [12]. A significant fraction of that increase is due to higher energy costs. The cost factor is especially serious at off-grid remote locations, where mining companies often have to use expensive diesel generation. The cost of diesel in remote zones not only depends on the oil price but also on other factors such as transport and theft, which affect the final cost significantly. For these reasons, the cost of electricity can reach up to 300 USD/Mwh at off-grid mines in remote locations [13]. A sharp escalation in costs has exacerbated productivity issues in the mining sector, generating a large disadvantage with respect to its competitors in the rest of the world. In fact, today the cost of energy in Chile's mines is twice as much as their peers in neighboring Peru, another top mining country. Growing energy costs together with energy demand remain an important matter then, threatening the competitiveness of Chile's largest industry and posing a major challenge for new developments.

2.2. Energy dependency

Historically, the generation of electricity in the Great North Interconnected System of Chile (SING) – where most of the mining operations are located – has relied almost 90% on fossil fuel sources. As of 2017, 67% of the total installed power generation capacity in Chile was based on fossil fuel sources, mostly coal and diesel [4]. Since Chile has almost no reserves of fossil fuels, all resources are imported [14]. In addition, its neighboring country Bolivia –which is very rich in natural gas– refuses to sell it to Chile for political reasons. Therefore, natural gas needs are met with expensive Liquefied Natural Gas (LNG), averaging two- to three- times the price of natural gas in North America. The heavy dependence on energy imports generates high vulnerability to external shocks, not only in terms of price but also on supply availability. The clearest example occurred in 2004, when the gas crisis in Argentina took place and exports to Chile were unilaterally curtailed [10]. In addition, the external dependence amplifies the volatility of energy prices, which makes it more difficult to predict energy costs when evaluating projects.

2.3. Opposition from communities

Over the last couple of decades, the country has experienced several consecutive energy crises due to negative shocks in both energy prices and energy supply. For example, in 1999 and 2011, the shortage of energy supply implied rationing electricity for several months. This situation urged the government to seek rapid investment in the sector with the objective of fostering a more reliable supply and diversifying the country's energy matrix. Despite an overall attractive investment climate and encouraging market conditions, investments in new projects have been difficult to materialize. The main reason is the opposition of local communities to large conventional projects because of their expected environmental and social impacts [15]. As a result, several energy projects—especially the large ones like Pangué/Ralco, HidroAysén, Barrancones, and Castilla—have provoked intense public debates that delayed their approval processes and, in most cases, ended up in the rejection of the project.

¹ In thousands tonnes of oil equivalent (ktoe).

Table 1
Solar projects implemented in the mining industry.

Mining Company	Mine	Solar Developer	Financing	Connection	Country	Capacity	Plants	Area of solar
Cronimet Mining AG	Thabazimbi	Cronimet Power Solution	Own Investment	Off-grid	South Africa	1 MW	Solar PV-Diesel	2 ha
Galaxy Resources	Mt Cattlin	Swan Energy	Own Investment	Off-grid	Australia	3,6 MW	Solar PV-Wind-Diesel	6 ha
Barrik Gold	McCarran	Stellar Energy	Own Investment	Off-grid	USA	1,5 MW	Solar PV-Gas	2.5 ha
Rio Tinto	Weipa Bauxite	First Solar	PPA	Off-grid	Australia	6,7 MW	Solar PV-Storage-Diesel	12 ha
Shanta Gold	New Luke	Redavia Solar	Rental	Off-grid	Tanzania	1 MW	Solar PV-Diesel	2 ha
Antofagasta Minerals	El Tesoro	Abengoa	PPA	On-grid	Chile	10,5 MW	CSP Solar	6 ha
Anglo American	Collahuasi	Solarpack	PPA	On-grid	Chile	25 MW	Solar PV	45 ha
Quiborax	El Aguila	E-CL	PPA	On-grid	Chile	2,3 MW	Solar PV	5 ha
Imagold	Rosebel	Renewable Energy Resource C.	PPA	On-grid	Suriname	5 MW	Solar PV	10 ha
Antofagasta Minerals	Chuquicamata	Solarpack	PPA	On-grid	Chile	1 MW	Solar PV-Diesel	6.3 ha
Sandfire Resources NL	DeGrussa	Juwi Renewable Energy Pty Ltd	PPA	Off-grid	Australia	10,6 MW	Solar PV	20 ha
Codelco	Minera Gaby	Sunmark	PPA	On-grid	Chile	32 MW	Thermal solar	43,9 ha

2.4. Environmental and social unrest

Energy consumption in mining occurs intensively in almost all stages of the production process: blasting, excavation, crushing, transport, grinding, and then smelting and refining when producing copper cathodes. A heavy reliance on fossil fuels in mining operations has created serious environmental concerns in the surroundings of large mining sites. The mining industry in Chile emitted a total of 13.9 million tons of CO₂ in 2015, 29% more than in 2010 [16]. The sharp increase in Greenhouse Gas (GHG) emissions in the industry is largely caused by the use of diesel (89%), but also petroleum and natural gas (10%). Despite the significant economic benefits of the mining activity, communities residing in proximity to mines have long struggled against the harmful effects on health and environment. Thus, over the last few years, better organized and more active environmental movements have emerged, generating serious problems for the operation of mining companies. Consequently, environmental regulations are becoming increasingly stringent, especially in the permitting process for new mines. In addition, mining companies face a constant risk of stigmatization from financial institutions for environmental and social reasons [17]. In fact, over the last few years, Social License to Operate (SLO) has become an important issue in extractive industries. A study by Ernst and Young [18], shows that the need to obtain a SLO ranked third on a list of the top ten industry challenges.

2.5. Desalination water plants

The large increase in water demand from the mining industry has generated a critical situation in some regions in the north, where mining operations are mostly located and water is scarce. An increasing water deficit has caused serious conflicts between mining companies and other water users, especially the agriculture sector that fears that mining projects would reduce the quality and quantity of their water sources. This situation forced the mining industry to find alternative water sources to prevent further environmental problems and to solve local conflicts. Desalination represents a potential alternative, allowing to produce industrial water from seawater to be used in remote and desert areas where water is scarce. A report by Cochilco, predicts that seawater will provide more than half of water consumed in the copper mining industry by 2026 [19]. The transition toward energy intensive desalination plants will lead to doubling energy consumption. However, the cost of energy remains a main challenge for the implementation of desalination projects, as power costs account for 30–60% of the total operational costs of water desalination [20].

3. Literature review

Nowadays, many of the world's largest mining companies are striving to find alternatives to integrate clean and cost competitive renewable energies into their operations, especially solar and wind

technologies. The global mining industry currently consumes around 400 TWh of electricity a year, but renewable energy -excluding large hydro- only accounts for 0.1% of the total supply [21]. Estimations by Navigant Research [22] show that by 2020 more than 1438 MW consumed by mining operations will rely on renewable energies globally. In South Africa, for example, Votteler and Brent [23] identified 21 renewable energy projects operating at mining sites and 11 of them employ solar PV energy.

Mining firms currently engaging with renewable energy technologies are using three main business models [24]. The first one is an "industrial pooling" model, under which a mining company signs a long-term power purchase agreement (PPA) with generation plants and the conditions of the contracts are freely defined by both parts. In this case, the mining company acts as an off-taker, merely contracting the purchase of energy and avoiding any investment. The second one is a "self-generation" model, in which case a mining firm develops, finances, and operates a solar plant on its own land, taking all the risks involved. Under this business model, a mining firm may also establish a partnership with an external solar energy developer. Through this partnership, it can benefit from the developer's experience and share the risks. The third model is "net metering", under which a grid-connected mining firm develops, finances, and operates a solar plant on its own land. However, in this case, the utility company purchases the excess capacity generated by the renewable plant of the mining firm. Table 1 shows existing solar projects, by type and their main characteristics, implemented in key mining countries.

The following subsections highlight the main findings in the academic literature on drivers for and barriers to the implementation of solar technologies in the mining industry.

3.1. Drivers for implementing solar technologies in the mining industry

The term 'drivers' in the context of this research is defined as the reasons why mining industries would integrate solar energy technologies in their operations. Recent findings show that cost and emission reduction are the main drivers in this regard. Zharan and Bongaerts [25], for example, developed a decision-making approach to evaluate the integration of solar energy sources into the mining sector. The research is based on case studies and a cost analysis in key mining countries. Based on a comparative analysis, their results show that although the CAPEX (Capital Expenditures) of solar PV projects is higher than the CAPEX of fossil fuel projects, solar projects have no fuel costs and, hence, become more attractive within a project lifetime. Therefore, the LCOE (Levelized Cost of Energy) for solar PV projects declines over time. In other study, Vyhmeister et al. [26] performed an optimized techno-economic analysis to study the implementation of optimal solar and wind-based technologies in the copper industry. Their results show that replacing 10% of the current electrical energy requirements of the mining industry with solar and wind-based technology in the Antofagasta region in Chile could meet a total of 28,133 MWh/y of electrical

energy needs of mining industry and bring significant environmental and economic benefits for the copper industry.

The use of solar technologies for heating water and different solutions in mining processes has also been pointed out as a crucial driver to the solar adoption. Chandia et al. [27] examine the potential implementation of solar thermal heating in mining process in Chile. Their results show that the installation of flat plate collectors to heat water for mining processes is strongly recommended due to its economic and environmental benefits. For instance, depending on the total flat plate collector area, up to 14,204 t of CO₂ can be saved. Furthermore, a research by Metkemeyer [28] indicates that the use of solar thermal energy in copper heap leaching processes can increase the solution temperatures significantly. As a consequence, copper recovery increases up to 5%, depending on the copper mineral type. In addition, the economic evaluation shows that in comparison to conventional heating-technology, the operational cost of the solar system is much lower.

Additionally, mining industries either in isolated zones or quite far away from the main power networks usually use mostly diesel, which is not necessarily cost effective in terms of production efficiency. Besides, its use generates risks for the mining operations in terms of power quality and stability. Integrating solar technologies into remote mining operations can be a promising alternative [29]. Soberanis et al. [29] study the economic feasibility of renewable energy for off-grid mining deployment in the Canadian territory of Nunavut. The results show that the installation of a PV system in this remote community is economically feasible for an energy demand of 3000–6000 kWh per day, approximately. The implementation of renewable energy can generate yearly savings of almost 50,000 l of diesel and meet approximately 9% of the total energy consumption in Nunavut. Similarly, Ansong et al. [30] conducted a technical and economic analysis of using solar PV as part of a hybrid electric power system to power a mine in an off-grid area in Ghana. They report that this option would produce 152.99 GWh of electric energy per year and achieve a 30% cost reduction.

The development of seawater desalination technologies has recently become a viable solution for preventing the severe water shortages faced by the mining industry. However, since the desalination process consumes a large amount of energy, developing a sustainable and cost-effective energy desalination process is still a main challenge for a massive use of these technologies. A few recent studies suggest that the use of solar energy in the desalination process can be, in fact, a sustainable alternative. Zhang et al. [31] study the applicability and economic viability of different solar water treatment technologies, considering actual applications in recent years. The main result is that, compared to conventional fossil-fuel based desalination plants, water costs of small to medium scale solar desalination plants are in the range of US\$0.2–22/m³, which are much higher. However, costs for large-scale plants are between US\$0.9/m³ and 2.2/m³, showing that solar based alternatives might be economically viable in the near future. Moreover, in most cases, the environmental cost of using conventional fossil-fuel based technologies has been extensively ignored in the economic evaluation.

Finally, based on a detailed review of the literature, Table 2 reports a list of the 10 most relevant drivers identified in the academic literature.

3.2. Barriers to the adoption of solar technologies in the mining industry

Despite the already proven potential benefits that solar technologies offer, the scale and implementation pace in mining have been slow. The main reason is the existence of several barriers preventing solar technologies from competing in the marketplace and achieving the necessary large-scale deployment. One of the substantial barriers in the case of mining operations is the concern over their reliability and intermittency. As a matter of fact, Jung and Villaram [42] show that the intermittent nature of solar energy generates risks in term of power supply security, given that it does not provide a continuous supply, and

Table 2
Potential drivers for adopting solar technologies.

Driver factors	References
1. Competitive offer in power prices - Cost reduction	[25,26,29]
2. Sustainable improvement in productivity	[32,33]
3. Reduction in heating costs of solutions	[34]
4. Reduction in conventional energy for the desalination process	[31,35]
5. Application of renewable plants in isolated areas	[25,29,30]
6. Predictable and stable energy costs	[25,26,29]
7. Reduction in carbon emissions	[32,36,37]
8. Company reputation/marketing strategy	[24,38,39]
9. Cooperation with other similar industries	[24];
10. Commitment to social responsibility	[40,41]

mining typically maintain 24 h operations. Another problem with the intermittent nature of solar energy is that the solar energy profile, in particular of solar PV, does not match the load profiles associated to mining operations.

The technical maturity of some solar technologies, in particular CSP (Concentrating Solar Power), is also considered a crucial barrier. The study by Gangazhe [43] reports the lack of technical and economic feasibility of battery storage technologies as a key deterrent for the use of solar technologies in South African mining. In another study, Votteler and Brent [23] show that the mining industry lacks a sufficient knowledge and awareness of solar technologies and its associated benefits. Additionally, Hamilton [21] reports that the significant capital costs associated with the construction of solar plants make them unattractive for the mining industry, which is especially relevant in the case of self-generation models. From a financial perspective, self-generation models not only have higher investment costs but are also considered to be riskier investments due to their longer payback periods [44,45]. As a result, they might not be economically feasible for mining projects with a relatively short or uncertain mine life [25,46]. This is also true for PPA contracts. In practice, a solar plant would usually target a 20-to-25 years PPA, which might be a long -time horizon for some mining projects and create a “mismatch” between the life of the mine and the number of years necessary for solar developers to recoup their capital investments.

In addition to these barriers, it is relevant to consider that several mining countries lack a comprehensive legal and regulatory framework that incentivize mining companies to invest in solar energy [47,48]. In particular, there is no legal framework allowing the sale of excess electricity into the grid. Finally, most mining companies lack the expertise for handling solar projects, which affects its acceptance as a viable technology. In fact, most of the electrical engineers employed by mining companies to operate their plants are specialized in conventional technologies and their knowledge does not usually extend to solar technologies.

Table 3 shows a list of 18 barriers that have been identified in the academic literature potentially hindering the adoption of solar technologies in the mining industry.

4. Methodology

The research methodology basically consists on designing a questionnaire based on the literature review, then implement it as the main data collection method, and finally performing a statistical analysis of the data. The questionnaire was specifically developed with the purpose of conducting an online survey on mining experts' opinions about key issues affecting the adoption of solar technologies in the Chilean mining industry, even though the same survey could be applied to gather experts' opinions in any mining country. The main components of the survey design are based on the methodologies employed by [6] and [59].

The methodology for the study consists of three phases, which are

Table 3
Potential barriers to the adoption of solar technologies.

Barrier factors	References
1. Lack of a baseload energy from solar technologies	[46,49]
2. Solar technologies in Chile are “quite new”	[50,51].
3. Resistance to change for using solar technologies	[52,53,43]
4. Preference to invest in energy efficiency projects instead of solar projects	[54]
5. Inability to meet the energy demand required	[54,55,43]
6. Lack of priority addressing energy challenges in the mining industry	[54,56]
7. Lack of cost-effective storage technologies	[24,43]
8. Lack of public policy incentives to use solar thermal energy in mining	[57]
9. Long term PPAs generate contingent liability on the balance sheet	[57]
10. Duration of PPAs – risk due to volatility of the copper prices	[53,57]
11. Mismatch between the mine life span and the time necessary to recoup the capital investment	[57,58,52],
12. Lack of skilled labor in the mining sector	[24,43,58]
13. High capital investment requirements	[21,43]
14. Higher payback periods for large solar projects	[44,45]
15. Political and regulatory uncertainties to invest in solar projects	[47,48]
16. Lack of financing sources to invest in solar projects	[52,57]
17. Administrative hurdles for project implementation	[57]
18. Lack of regulation to sell surplus energy	[57]

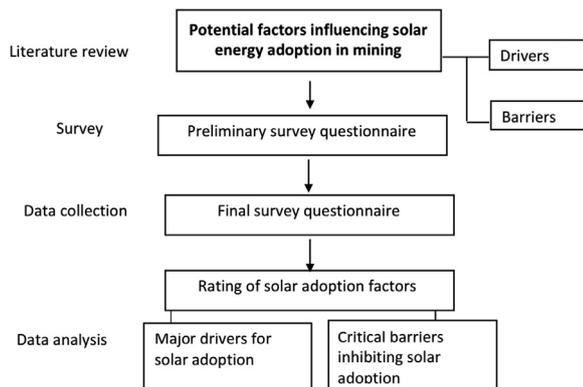


Fig. 1. Research framework.

shown in Fig. 1 and then described in the following subsections: questionnaire design, data collection and statistical data analyses.

4.1. Questionnaire design

Surveys have been widely employed to collect data from experts on the different factors influencing the adoption of certain technologies or innovations [6,60]. Specifically, research based on surveys has been extensively applied to examine the main determinants in the adoption of renewable energy technologies in power systems.

The questionnaire was designed based on the evidence reported in the academic literature regarding the adoption of solar technologies and it contains two parts. Part 1 explains the research objectives and includes background information regarding the experts' position, years of experience in the mining sector, maximum level of academic studies, and profession. In Part 2, based on the literature review, experts were asked about the role played by a selection of potentially relevant barriers to and potential drivers for adopting solar energy in the mining industry. Before sending out the survey, a content validation was conducted in a small pilot study to establish the extent to which the factors found in the literature were in fact the most relevant. The final list of potential drivers and barriers are presented in Tables 2 and 3 respectively. They were determined based on the literature review and the feedback from the pilot study.

The survey participants were requested to evaluate the relative significance of each barrier and driver on a five-point scale [6,59]. In addition, they also had an option to freely comment regarding any barrier or driver. The scale ranged from “5”, meaning “extremely important” -indicating the maximum impact on the development of the technology if the barrier were mitigated- to “1”, meaning “least important” and indicating the least impact on the adoption of the technology. No-responses obtained a “0” score indicating that the respondent does not consider the given barrier as an obstacle or a driver for the adoption of solar technologies in the mining industry.

4.2. Data collection

The sample design to implement the questionnaire was determined based on the Quota Sampling Method (QSM), a non-probability sampling method that guarantees representativeness and ensures to collect the necessary information for statistical significance of targeted groups. Primarily, it targets to obtain a representative sample from a not necessarily random selection of individuals, where sampling continues until the quotas are achieved [61]. In the case of this study, the sampling of individuals corresponds to mining experts in Chile who were targeted as the specific relevant group.

The questionnaire survey was sent by email to the selected sample consisting of local mining experts, practitioners, and academics. The definition of expert for this purpose was: “someone with special skills or knowledge evidenced by his/her leadership in professional organizations, holding office in professional organizations, presenter at national conventions, published in recognized journals, etc.” [62]. Therefore, all respondents were directly involved in the mining sector and had good understanding of the energy needs in the mining industry. The selection of suitable potential participants was mostly done through personal networks and also directly approaching specific representatives [6]. The survey was sent out to the experts, attaching a word processor file and a web link to permit online responses. All participants were asked to complete the survey based on their experience and knowledge of the mining industry. The survey process continued until the number of responses reached the quota determined by the QSM to obtain a representative sample and allow consistent statistical analysis [63]. In order to obtain statistically representative results, with a confidence interval of 90% and a margin of error of 0.1 [6], an average response rate of 30% is required [64], which corresponds to 26 responses in this case. At the end, a total of 30 valid responses were received.² In order to encourage participation, the experts were informed that the aggregated results could be shared with them.

The survey participants represent 17 different institutions in Chile with an average of 23 years of experience in the mining sector. More specifically, as shown in Table 4, experts with less than 10 years of experience were only 16.1% of the sample, while 29.0% had between 10 and 20 years of relevant experience, and 54.9% had more than 20 years of experience in mining sector. In terms of their role in the mining industry, 12.9% of the experts were managers, 35.5% had director level positions, and the remaining 51.6% held scientific positions such as professor, mining advisor or senior researcher in the organizations. Finally, with respect to the educational background of the experts, 9.6% possessed undergraduate education, 16.2% had a master degree, and a 74.2% held a PhD degree in engineering and social sciences.

4.3. Statistical data analysis

As it was explained before, the respondents expressed their professional judgments on the main drivers and barriers for implementing solar technologies in the Chilean mining industry using a five-point

² If the central limit theorem holds, a sample size higher than 30 responses permits to conduct statistical analysis.

Table 4
Main characteristics of experts.

Years of relevant professional experience in the sector:	%
less than 10 years	16.1
between 10 and 20 years	29.0
more than 20 years	54.9
Education background in engineering and social sciences:	
B.A. degree	9.6
Master degree	16.2
Ph.D. degree	74.2
Work position in the organization:	
CEO or director level	35.5
Manager level	12.9
Scientific positions	51.6

Likert scale. The Likert scale is a widely employed method to scaling responses in survey research. In management research is used for rating the relative significance (from 1 -not critical to 5 -very critical) of factors based on experts' opinions [58].

The analysis of the survey includes four different statistical analyses. First, the Cronbach's alpha coefficient (α) was estimated [65] for assessing the reliability of the five-point Likert scale.³ The Cronbach's alpha coefficient ranges between 0 and 1 and a higher value of α increases the significance of the test [66]. Second, to determine the relative importance of individual drivers and barriers, we computed the mean value for each one and then ranked them. If two or more factors had the same mean score, the higher rank was assigned to the factor with the lowest standard deviation (SD) [59].⁴ Third, in order to assess whether each driver and barrier was statistically significant, we use a *t*-test at a 5% significance level.⁵ Finally, a Chi square test was employed to check the independence of the answers in the survey.

5. Results and discussion

Responses to the questionnaire provided useful information about the relative significance of different factors influencing the potential role that solar technologies can play in mining. Separate analyses based on the overall results for drivers and barriers are presented and highlighted in the next subsections. In addition, the top-ranked factors are discussed.

5.1. Overall results on drivers

Table 5 summarizes the experts' perceptions on the relative role played by 10 drivers on the adoption of solar technologies in the mining industry. The Cronbach's alpha coefficient is 0.807 -greater than the threshold of 0.7- showing then that the dimensions using the five-point scales are, in fact, reliable. The mean score of the different factors ranges from 4.31 to 3.10, with a global mean of 3.97. These results show that all the factors considered are relevant in driving the adoption of solar technologies. The most important driver is "Meeting heating needs through the use of solar thermal energy", with a mean value of 4.41 (SD=1.1186), followed by "Replacement of the use of conventional energy for the desalination process" (mean = 4.31; SD = 0.9298), and "Having a competitive offer in power prices - to reduce operational and maintenance costs (mean = 4.28; SD = 1.1618).

The *t*-test analysis shows that only one of the 10 factors rated by the experts is not significant (Sustainable improvement in productivity).

³ The Cronbach's alpha coefficient is developed by Cronbach in 1951 and is commonly use to measure the internal consistency of a questionnaire that contains multiple Likert-type scales or items.

⁴ The standard deviation measures the degree of dispersion the dataset has from the mean.

⁵ The *t*-test is a method for testing hypotheses and in this case is used to determine if the mean of each factor is statistically different from zero.

Table 5
Results on drivers.

Driver factors	Mean	Standard Dev.	t-test
1. Competitive offer in power prices	4.2759	1.16179	0.001
2. Sustainable improvement in productivity	3.3448	1.31681	0.531
3. Reduction in heating costs of solutions	4.4138	1.11858	0.000
4. Reduction in conventional energy for the desalination process	4.3103	0.92980	0.000
5. Application of renewable plants in isolated areas	4.0000	1.13389	0.025
6. Predictable and stable energy costs	3.8276	1.03748	0.003
7. Reduction in carbon emissions	4.2414	1.09071	0.001
8. Company reputation/marketing strategy	4.0000	1.06904	0.018
9. Cooperation with other similar industries	3.1034	1.01224	0.044
10. Commitment to social responsibility	4.1724	1.00246	0.001
Cronbach's alpha	0.794		
Chi-Square	50.539		
Level of significance	0.000		

Consistently, the Chi-square test indicates that there exists a high level of agreement among the experts regarding the rankings of the different drivers.

The results regarding the most important driving forces for the adoption of solar technologies in the mining industry are consistent with the empirical evidence in the literature [28].

The extraction of copper requires a three-step energy intensive process consisting of heap leaching, concentration by solvent extraction, and metal recovery by electro-winning. Historically, the combustion of fossil fuels, including coal, oil, and natural gas, has been the only feasible way to produce the levels of heat required for these processes. However, recent technological advances in Concentrating Solar Power (CSP) technologies potentially allow their incorporation for industrial heating. The most commercially advanced CSP technologies are power tower, parabolic trough and linear Fresnel. Parabolic trough and linear Fresnel solar concentrators can achieve temperatures ranging from 150 °C to 400 °C, while a tower power can reach up to 1200 °C [67]. The heating needs in the mining industry can be divided into two main temperature ranges: 40% of mining operations require temperature between 100 °C and 400 °C, while 60% require below 100 °C. Electro-winning, for example, is one of the main processes in copper mining used to maximize copper purity using electricity and water heaters. Depending on the design of the electro-winning plant, the water heaters function between 60 °C and 90 °C [68]. Given these conditions, the possibilities of integrating solar thermal energy in mining process seems quite encouraging.

The second critical driver in the ranking is 'solar energy application for desalination'. Availability of water is one of the most significant factors affecting current mining operations. The scarcity of fresh water resources in northern Chile has become a source of conflict between miners and the rest of the consumers, especially farmers. For this reason, many copper companies have been increasingly investing in seawater desalination plants to obtain industrial water and then pump it up to the mines in the Andes Mountains. The Chilean Copper Commission (Cochilco) estimates that desalination will supply half of the water demand of the copper mining industry by 2026 [12]. The transition toward energy intensive desalination plants, however, will lead to doubling energy consumption. Therefore, it is important to highlight again that power costs in water desalination represent between 30% and 60% of total operational costs. There are basically two types of desalination technologies widely used for obtaining industrial water. The first type is a thermally activated system, in which evaporation and condensation are used to separate water from salt. The second type is a pressure-activated system, in which pressure is applied on the salty water to force it through a membrane and then leave the salt behind [69]. Currently, thermal solar energy water desalination is considered to be a viable method that could be used either by producing

Table 6
Unsubsidized levelized cost of energy: solar technologies vs conventional technologies in 2017.

Sources: Own elaboration based on data from Lazard.

Solar Technologies	\$US/MWh	Conventional technologies	\$ US/MWh
Solar PV-Utility Scale	46–53	Diesel Engine	197–281
Solar Thermal Tower with Storage	98–181	Nuclear	112–183
		Coal	60–143
		Gas Combined Cycle	42–78

the thermal energy required for the first type of technologies or by producing the electricity required for the second type. In fact, many technical and economic studies on solar energy applications in the desalination process show that the use of solar energy is a technically mature option [31]. The cost of freshwater production from solar energy-powered desalinated systems is lower than other fossil fuel alternatives in remote areas where access to electricity is not available. However, for a commercially viable large-scale application, technological advances are needed to improve even more their efficiency and reduce their capital costs.

Finally, it is important to highlight the driver ‘Having an attractive PPA offer’, which was ranked as the third most relevant by the experts. An unprecedented drop in solar energy prices over the last decade has sustained claims that solar technologies can offset the energy costs of mining. Today, the lifetime cost of solar energy -both PV and Thermal Tower with Storage- is far lower than the cost of diesel generation. As a result, off-grid mining sites can have lower costs using solar instead of diesel generation (See Table 6). The Lazard’s latest annual Levelized Cost of Energy Analysis (LCOE 11.0) shows that utility-scale solar PV has declined its cost of generating electricity between 2009 and 2017, making it cost competitive compared to conventional technologies such as coal and nuclear (See, Fig. 2). The LCOE values for Solar Thermal Tower with Storage ranged between 98 and 181 \$US/MWh in 2017, which is expected to lead a significant deployment of solar energy technologies in the mining industry.

5.2. Overall results on barriers

Table 7 summarizes the results on the relative importance of barriers to the adoption of solar technologies. The experts were requested to rate 18 factors potentially hindering solar energy adoption. The Cronbach’s alpha coefficient is 0.794, showing that the dimensions using the five-point scales were reliable. The t-test of the means indicates that 15 out of the 18 factors were statistically significant. The mean score of the different factors range from 4.17 to 3.07 with an overall mean of 3.97.

The most critical barrier, as ranked by the experts, is “resistance to

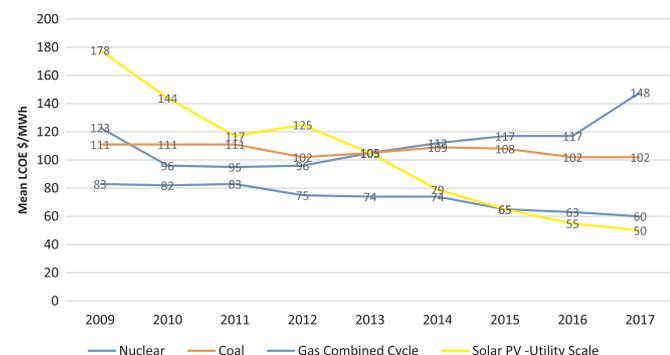


Fig. 2. Average LCOE values for selected technologies between 2009 and 2017. Sources: Own elaboration based on data from Lazard

change from the use of traditional technologies” (mean = 4.17; SD = 1.10418). The following barriers in the ranking are “Lack of cost-effective storage technologies” (mean = 4.10; SD = 0.90019) and “Lack of public policy incentives to promote the use of solar energy in mining (mean = 4.07; SD = 1.06674). In terms of magnitude of importance, these are the only three barriers with a mean score above 4.00.

The fact that resistance to change was reported as the most important barrier is probably not surprising. Almost any unfavorable reaction, opposition, or force that prevents change is considered resistance [70,71], which introduces costs to society through inhibiting the use of new and better technologies to address a variety of economic, environmental and social challenges. The key point, however, is that resistance to new technologies is usually driven by perceptions and not necessarily by evidence.

There are several reasons that can explain the resistance to switch to solar technologies in the mining industry. These may include lack of interest in shifting from conventional energy to solar technologies, lack of confidence in solar technologies, high uncertainty, fear of failure, and fear of improper handling of the change. Delucchi and Jacobson [72] estimate the costs, including technology and material requirements, of converting energy supplies to clean and sustainable sources. Their findings show that there are no technological or economic barriers to converting all energy supplies to renewable energy sources. It just depends on societal and political will. Hamilton [21] stresses that there is a perception in the mining industry that solar energy is not a proven technology, capital costs are too high, and also financing is too costly. Consistently, Cormack et al. [73] report that while integration of renewable technologies into mining processes are becoming more common, mining companies still face organizational and cultural barriers frequently preventing a faster adoption of these technologies. They stress that the responsibility for energy procurement and consumption is often fragmented within the organization. Energy management not well integrated into the companies’ management system leads to a lack of awareness of the full range of renewables solutions and the value creation opportunities available, as well as the inability to articulate and evaluate the necessary actions for exploiting them.

Finally, another significant barrier is the lack of cost-effective storage, which was pointed out as the second crucial barrier. Mines operate nonstop, requiring firm baseload power 24 h for almost every day the whole year. However, solar energy is inherently variable and does not meet these baseload needs. Depending on local conditions, without storage, solar energy is restricted to serving, on average, just 30% of a constant demand. Energy storage technologies are considered, for this reason, supporting technologies with great potential for meeting these challenges as energy can be stored and then converted to electricity when needed. Consequently, the deployment of energy storage can facilitate the expansion of solar technologies in the mining industry, providing greater power reliability and availability [74,75]. Nevertheless, many advanced energy storage technologies are still in a pre-commercialized stage and some challenges need to be solved for their widespread deployment. In particular, the high capital cost is one of the critical barriers for their deployment [76].

6. Conclusion

Over the last couple of decades, a mix of high energy prices, supply constraints resulting from the energy dependence from external sources, growing environmental concerns and social unrest, and a steadily increasing energy demand, have challenged the competitiveness and future development of the Chilean mining industry. Addressing these challenges is an important issue for the mining industry and the whole economy. Most mining countries, but especially the developing ones, are facing similar challenges.

In response, the mining sector is currently working on deploying innovative energy-saving strategies and evaluating different options to incorporate renewable energy technologies into its operations. At the

Table 7
Results on barriers.

Barriers	Mean	Standard Dev.	T test
1. Lack of a baseload energy from solar technologies	3.59	1.08619	0.002
2. Solar technologies in Chile are “quite new”	3.55	1.15221	0.012
3. Resistance to change for using of solar technologies	4.17	1.10418	0.023
4. Preference to invest in energy efficiency projects instead of solar projects	3.66	1.07822	0.334
5. Inability to meet the energy demand required	3.93	1.25160	0.003
6. Lack of priority addressing energy challenges in the mining industry	3.21	0.94034	0.005
7. Lack of cost-effective storage technologies	4.10	0.90019	0.018
8. Lack of public policy incentives to use solar thermal energy	4.07	1.06674	0.021
9. Long term PPAs generates contingent liability on the balance sheet	3.31	0.96745	0.543
10. Duration of PPAs – risk due to volatility of the copper prices	3.76	0.83045	0.042
11. Mismatch between the mine life span and the time necessary to recoup the capital investments	3.45	1.08845	0.017
12. Lack of skilled labor in the mining sector	3.24	1.12298	0.002
13. High capital investment requirement	3.41	0.98261	0.652
14. Higher payback periods for large solar projects	3.34	1.11085	0.000
15. Political and regulatory uncertainties to invest in solar projects	3.31	1.31213	0.001
16. Lack of financing sources to invest in solar projects	3.41	1.15007	0.000
17. Administrative hurdles for project implementation	3.07	1.19317	0.001
18. Lack of regulation to sell surplus energy	3.45	1.32520	0.013
The Cronbach's alpha Chi-Square	0.741		
	48.251		
	Level of significance	0.000	

same time, Chile's energy landscape is undergoing a dramatic transformation, spurred by a rapid expansion in renewables, especially solar technologies in the northern region of the country. Given that most of the mining industry and the world's largest copper reserves are located precisely in the north of Chile, the mining industry has the opportunity to adapt solar technologies into its operations and overcome some of the energy challenges they face.

In this context, this paper examines the key determinants influencing the adoption of solar technologies in the mining industry from the perspective of mining experts. Given the limited empirical research on the determinants of renewable energy adoption in the mining industry, this study contributes to the academic literature on this topic but also to body of knowledge available for industry practitioners and policy-makers working on these challenges in different mining countries.

The research -based on the designed, implementation, and statistical analysis of a mining experts survey- examined the most relevant 10 drivers for and 18 barriers to the implementation of solar technologies in the mining industry. In the survey the experts evaluated each driver and barrier using a Likert scale. The results show that the top three drivers, ranked by the degree of importance, are meeting the needs of mining processes through the use of solar thermal energy (mean score of 4.41), solar energy application for the desalination process (mean score of 4.31), and having an attractive PPA offer (mean score of 4.28). With respect to the barriers inhibiting the implementation of solar technologies, the most critical one is resistance to change (mean score of 4.17), followed by the lack of cost-effective storage technologies (mean score of 4.1), and the lack of public policy incentives to promote the use of solar thermal energy in mining (mean score of 4.07).

Mitigating the identified barriers and creating further incentives remains a key challenge for the mining sector and it might be necessary to maintain its competitiveness in the future. Based on the results of this research, some recommendations for integrating solar generation at large scale into mining operations are as follows. First, more public and private research and development is needed to properly evaluate the potential of solar applications in mining. Second, implement small-scale pilot tests and then disseminate the results to show the potential advantages of using solar energy. Third, establish the right economic and regulatory incentives for the integration of solar technologies into mining practices. Fourth, provide some type of public financing or guarantees to obtain private funding for implementing solar technologies in mining projects. Finally, the mining industry needs to invest in human capital and design management capacities to facilitate and

reduce the fear and resistance associated to the adoption and implementation of technological change.

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