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106/2020

KlimRess – Impacts of climate change on mining, related environmental risks and raw material supply

Case studies on copper and lithium mining in Chile

For our Environment

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KlimRess – Impacts of climate change on mining, related environmental risks and raw material supply

Case studies on copper and lithium mining in Chile

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Abstract

The following case study is one of five country case studies carried out as part of the project 'Impacts of climate change on the environmental criticality of Germany's raw material demand' (KlimRess), commissioned by the German Federal Environment Agency (*Umweltbundesamt*, UBA). The project team comprised adelphi, ifeu Heidelberg and the Sustainable Minerals Institute of the University of Queensland. The aim of the project was to assess how climate change potentially affects the environmental risks of mining and raw material supply chains.

This case study analyses BHP Billiton's Escondida copper mining operations and SQM's Salar de Atacama lithium mine in Chile. Both operations are located in the Atacama Desert, which is characterized by extreme aridity. The Escondida copper mining operations have a very large land footprint, require large water and energy inputs and generate large amounts of mining waste. The environmental impacts of lithium mining are smaller compared to the impacts of copper mining. However, the extraction of brine and freshwater that occurs in the context of lithium mining is very controversial as it alters the hydrological system at the site and in the surroundings. Processing, whether of copper or lithium, has a smaller environmental footprint than mining.

In the Atacama Desert, climatic changes, especially projected water stress, are expected to aggravate current environmental impacts of copper and lithium mining and processing. Wet weather extremes are also expected to exacerbate or cause environmentally adverse impacts. Climatic changes will potentially have a lesser effect on lithium mining and processing. As about 30 per cent of the global copper production and 30 per cent of the global lithium production takes place in Chile, any disruption in production could impact the global security of supply of both materials.

Kurzbeschreibung

Die vorliegende Fallstudie ist eine von fünf Länderfallstudien des im Auftrag des Umweltbundesamtes (UBA) durchgeführten Projekts „Auswirkungen des Klimawandels auf die ökologische Kritikalität des deutschen Rohstoffbedarfs" (KlimRess). adelphi, das ifeu (Institut für Energie- und Umweltforschung Heidelberg) und das Sustainable Minerals Institute der University of Queensland untersuchten dabei die möglichen Auswirkungen des Klimawandels auf mit dem Bergbau einhergehende Umweltrisiken und Rohstofflieferketten.

Diese Fallstudie analysiert zwei Bergwerke in Chile: Das Escondida-Kupferbergwerk von BHP Billiton und die Lithium-Mine Salar de Atacama von SQM. Beide befinden sich in der Atacama-Wüste, welche durch extreme Trockenheit gekennzeichnet ist. Das Escondida-Bergwerk hat einen hohen Land-, Wasser- und Energieverbrauch und erzeugt eine große Menge von Bergbaureststoffen. Der Lithiumabbau in Salar de Atacama hat vergleichsweise geringere Umweltauswirkungen. Jedoch ist die damit verbundene Förderung von Sole und Süßwasser sehr umstritten, da diese in das hydrologische System am Bergbaustandort und in der Umgebung eingreift. Die Weiterverarbeitung beider Rohstoffe belastet die Umwelt weniger als deren Abbau.

In der Atacama-Wüste werden klimatische Veränderungen, insbesondere die zunehmende Wasserknappheit, die Umweltauswirkungen der Gewinnung und Weiterverarbeitung von Kupfer und Lithium verstärken. Auch durch Starkregenereignisse sind verstärkte umweltschädliche Auswirkungen des Bergbaus zu erwarten. Der Abbau und die Verarbeitung von Lithium werden wahrscheinlich in geringeren Maße von klimatischen Veränderungen betroffen sein als die Kupferproduktion. Da etwa 30 Prozent der globalen Kupferförderung und 30 Prozent der globalen Lithiumförderung in Chile stattfinden, könnten Produktionsstörungen in diesem Land die Versorgungssicherheit mit beiden Materialien weltweit beeinträchtigen.

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List of Abbreviations

AR4	Fourth Assessment Report of the Intergovernmental Panel on Climate Change
AR5	Fifth Assessment Report of the Intergovernmental Panel on Climate Change
DGA	Directorate General of Water
EEC	Environmental Evaluation Commission
EIA	Environmental Impact Assessment
ENSO	El Niño Southern Oscillation
GDP	Gross Domestic Product
GHG	Green House Gases
ILO	International Labour Organization
IWGIA	International Work Group for Indigenous Affairs
LCE	Lithium Carbonate Equivalent
NGO	Non-Governmental Organization
OECD	Organisation for Economic Co-operation and Development
ONEMI	Chilean National Emergency Bureau of the Interior Ministry (*Spanish: Oficina Nacional de Emergencia del Ministerio del Interior y Seguridad Pública*)
PM	Particulate Matter
RCP	Representative Concentration Pathways
SERNAGEOMIN	Chilean National Geological and Mining Service (*Spanish: Servicio Nacional de Geología y Minería*)
SING	Chilean Great North Interconnected System (*Spanish: Sistema Interconectado del Norte Grande*)
SQM	Sociedad Quimica y Minera de Chile S.A.
SRES	Special Report on Emissions Scenarios
UBA	German Federal Environment Agency (*German: Umweltbundesamt*)

1 Introduction

1.1 Project background

The following case study is one of five country case studies of the project 'Impacts of climate change on the environmental criticality of Germany's raw material demand' (KlimRess), commissioned by the German Federal Environment Agency (*Umweltbundesamt*, UBA). The project team comprised adelphi, ifeu Heidelberg and the Sustainable Minerals Institute of the University of Queensland. The aim of the project was to assess how climate change can potentially impact the environmental risks of mining and affect raw material supply chains.

Based on a systematic assessment of the case study results, the project team identified the most significant climate impacts across case studies. The project team also explored the links between climate change and a newly developed method to evaluate environmental hazard potentials as part of an environmental criticality assessment (OekoRess method) in order to inform the discussion of environmental criticality. Lastly, the project team combined data on current production and expected future production of nine raw materials with data on countries' vulnerability to climate change in order to identify patterns of particularly vulnerable raw materials and producing countries. The results are published in the final report of the project (see Rüttinger et al., 2019).

Based on these results, the project team developed recommendations on how to best adapt the mining sector, how to incentivise climate change adaptation measures in mining and how to foster effective mechanisms for the exchange of knowledge and expertise on the topic globally. These policy recommendations were published separately in the form of a recommendation paper (see van Ackern et al., 2019).

1.2 Selection of case studies

The case studies conducted as part of the project covered five different (climatic) regions:

1. Arid regions with water stress
2. Humid tropical regions
3. Polar or subpolar regions
4. Temperate regions
5. Coastal regions

In addition, the case studies covered nine raw materials that were identified and selected based on the following criteria:

- The importance of minerals and metals for future and environmental technologies
- Base metals, alloys and auxiliary materials important for the German economy

Other criteria that informed the case study selection were the climate change vulnerability of countries, their governance contexts and the prevalence of conflicts related to mining. The aim was to select a set of most different cases. Further selection criteria were the political relevance for Germany, the research institutions' partner networks and the availability of data.

The selected metals and minerals were: bauxite, coking coal, copper, iron ore, lithium, nickel, PGMs, tin and tungsten.

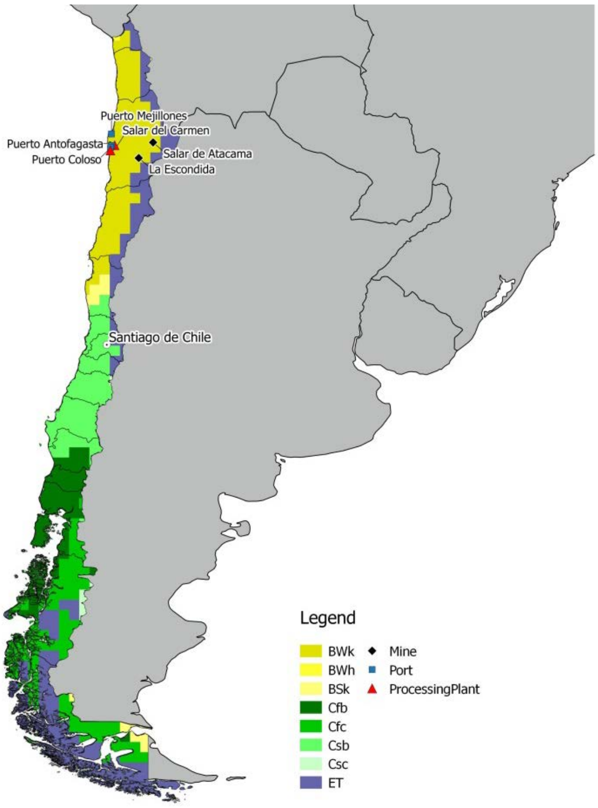
Each case study analysed a chosen mine site and the processing steps (to the extent these take place in the relevant country). The project team evaluated the environmental and supply risks potentially caused by climate stimuli and/or direct climate impacts for each of the mining and processing sites.

1.3 Content and structure of case studies

This study on Chile focuses on the following resources and mining sites (see Figure 1):

- BHP Billiton's Escondida mine: Copper mining in Antofagasta (cold desert climate, arid region with water stress)
- SQM's Salar de Atacama mine: Lithium mining in Antofagasta (cold desert climate, arid region with water stress)

Figure 1: Map of Chile indicating Köppen-Geiger climate classification and examined sites



Source: Maps prepared by adelphi using QGIS Geographic Information System (http://qgis.osgeo.org); climatic regions based on Rubel and Kottek, 2010.

The case studies are based on extensive secondary research, including the scientific literature, as well as reports and statements published by national government agencies, civil society organisations, mining and processing companies and the media.

First, the case studies provide a brief overview of the climatic conditions and projected climatic changes (in the case of this case study, for arid and coastal regions and for Chile as a whole). The studies then present an overview of the country's mining sector and its economic relevance as well as a summary of the country's mining governance (including disaster risk management, climate change adaptation, the environment, indigenous people and mining-related conflicts). In the case of Chile, water governance is also covered.

Second, we analyse the resources separately, covering the following topics:

- The global value chain of the respective resource

- Site-specific overview of the mine site
- Extraction and processing technologies
- Current environmental impacts and mitigation measures
- Current climate impacts and risks
- Climate change impact assessment:

The climate impact assessments are based on the *Guidelines for Climate Impact and Vulnerability Assessment*, published by the UBA (Buth et al., 2017). The Guidelines propose a combination of concepts outlined in the *Fourth Assessment Report* (AR4) (IPCC, 2007) and *Fifth Assessment Report* (AR5) (IPCC, 2014) of the Intergovernmental Panel on Climate Change. We use the terminology proposed by the Guidelines. To increase the compatibility across the Guidelines and the new AR5 approaches, we also indicate in the right margin the AR5 terminology in the climate impact chain diagrams (i.e. hazards, exposure and risks).

Finally, we summarise and discuss main findings of the case study.

2 Overview of climatic conditions and projected climatic changes

2.1 Arid regions

Arid climates have low mean annual precipitation rates, high year-to-year variability in precipitation and a relatively low humidity (Arnfield, 2016/Peel et al., 2007). This climatic zone has four subtypes: an arid desert climate, either of hotter[1] or cooler[2] nature, and a semi-arid steppe climate, also either of hotter or cooler nature. Arid climate is the world's dominant climate zone, covering over 30 per cent of the global land area (Peel et al., 2007).

Over the next century, precipitation in many arid regions is expected to decrease by at least 20 per cent (Arab Water Council, 2009). Although rainfall will likely be less frequent, it is expected to be more intense (Arab Water Council, 2009). Increasing temperatures will also result in higher evaporation and drier conditions, and this, combined with the decline in the frequency but increase in intensity of rainfall, will result in droughts and floods (Arab Water Council, 2009).

2.2 Coastal regions

Coastal regions lie in all climatic zones. Coastal systems and low-lying areas can be defined as areas close to the mean sea level (Wong et al., 2014).

According to the *Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (AR5), the global sea level is very likely to raise (Wong et al., 2014). There is high confidence that coasts will be impacted by submergence, flooding, coastal erosion and salt water intrusion caused by relative sea level rise which can vary substantially from the projected global mean sea level rise based on location (Wong et al., 2014). General sea level rise will also mean an increase in extreme sea levels[3] (Wong et al., 2014).

Coastal ecosystems will suffer from increasing ocean acidification and warming (Wong et al., 2014). In terms of extreme weather events, tropical cyclone frequency is likely to decrease or not to change; however, the intensity of tropical cyclones is likely to increase (Wong et al., 2014). The intensified impacts of cyclones (e.g. storm surges, storm waves, coastal flooding, erosion and consequently causing potential damage to coastal infrastructures) would be felt most strongly in coastal regions (Corlett, 2014). Projections for increased winds and waves have only low confidence (Wong et al., 2014).

Population growth, economic development and further urbanisation in coastal areas will put additional pressure on coastal systems. Furthermore, coastal populations, especially in tropical countries, are most vulnerable to sea level rise (Wong et al., 2014; Trewin, 2014). The *Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (AR5) states with high confidence: "Without adaptation, hundreds of millions of people will be affected by coastal flooding and will be displaced due to land loss by year 2100; the majority of those affected are from East, Southeast, and South Asia" (Wong et al., 2014: 364).

2.3 Chile

Due to the enormous geographical extend from north to south (18° S to 55° S) and its geographically inhomogeneous conditions, Chile can be divided into various climate zones, ranging from cold climate and Andean glaciers in the south to temperate climate and coastal rainforests in the central areas and deserts in the north (Rojas, 2012). According to the Köppen-Geiger climate types, Chile can be

[1] Average annual temperature is to or greater than 18°C.

[2] Average annual temperature is less than 18°C.

[3] Description of extreme sea levels: "Extreme sea levels are those that arise from combinations of factors including astronomical tides, storm surges, wind waves and swell, and interannual variability in sea levels. Storm surges are caused by the falling atmospheric pressures and surface wind stress associated with storms such as tropical and ETCs [extratropical cyclones] and therefore may change if storms are affected by climate change" (Wong et al. 2014: 370).

subdivided into three major climate zones: arid and semi-arid climates (group B), temperate and mesothermal climates (group C) and E (polar and alpine climates) (Peel et al., 2007, see Figure 1).

The mining facilities analysed in this case study, BHP Billiton's Escondida Copper mine and the Salar de Atacama lithium mine are located in Chile's North in the Atacama Desert, an area of extreme aridity. According to Köppen-Geiger, these areas are classified as cold desert climate (BWk), however, due to vertical drops in the Andes, the locations in the Atacama desert (the Escondida copper mine and the Salar de Atacama lithium mine) are adjoining regions of tundra climates (ET) (Peel et al., 2007).

The climate patterns of the Atacama Desert are complex. The region is one of the driest regions globally due to a number of interacting factors (Di Liberto, 2015). First, latitude: The region is located within the 20°S and 30°S, where air masses sink and stable high-pressure areas with dry air generally supress rainfall. Second, altitude: The desert is located between coastal mountains of over 2,000 meters and the Andes of over 6,000 meters height, which leads to a double rain shadow from both eastern and western sides and blocks the wind systems. Third, the proximity to the cold Humboldt Ocean currents hinder evaporation at the coast and thus the formation of rain clouds. In addition to these factors, the region is affected by the El Niño Southern Oscillation (ENSO). ENSO significantly affects the interannual variability of the climate, especially regarding coastal winds (Houston, 2006). It is responsible for significant weather extremes in Chile and the northern parts of the country regularly experience droughts, high temperature amplitudes and extreme heat, and heavy rain and storms (Houston, 2006).

When very specific and rare atmospheric conditions emerge, periodic rain events occur in the Atacama Desert (see section 5.5 on current climate in the region). In March 2015, for example, after ten years with nearly no rain, a cold front from the southwest channelled moist air into the desert region, leading to three days of intensive rain (see also section 5.5 on past weather extremes).

The mine products (copper cathodes and slurry, lithium products) are transported to the ports of Antofagasta (lithium processing plant and export of processed lithium and copper cathodes), Mejillones (export of copper cathodes) and Coloso (copper concentrate filter plant and export of copper concentrate), near the city of Antofagasta. The climate patterns here are also characterized by aridity. According to the Köppen-Geiger climate classification system, these areas are classified as cold desert climate (BWk) (Peel et al., 2007). The area is also affected by the cold Humboldt Ocean current which hinders precipitation, and the ENSO, which leads to a high variability in weather patterns.

Chile's Third National Communication on Climate Change to the United Nations Framework Convention on Climate Change, published by the Chilean Ministry of Environment gives an overview of observed current changes in Chile's climate and projections for future developments (MMA, 2016). The report states that the mean temperatures in the 20th and 21st century cooled at the coasts and warmed inland in the central valleys and the Andes. Rainfall trends differ depending on the region in focus, with significant inter-decadal variability in the Northern and Central parts of Chile, and decreases in the South.

Based on Rojas (2012), the Chilean Ministry of Environment furthermore outlines several projections (RCP 2.6, RCP 8.5, SRES A1B and PRECIS-ECHAM5 (A1B), for 2031-2050) of future climate change which all show similar warming patterns: A greater warming at the high plateau level and lower warming in the Chilean southern regions. With regard to precipitation patterns, a decrease of precipitation is foreseen between 5-15%, with a major decrease in the central parts of Chile (MMA, 2016).

Sea level is expected to rise along the Chilean coast by 34 to 52 cm for the RCP4.5 scenario and by 46 to 74 cm for the RCP8.5 scenario at the end of the 21st century (MMA, 2016, based on numerical models published by Albrecht and Shaffer, 2016).

Climate variability and extreme events in Chile are strongly interconnected with ENSO, the Pacific Decadal Oscillation and the Antarctic Oscillation. However, especially future trajectories of ENSO remain difficult to project, as it is expected to have a non-linear response to global warming (Power et al., 2013).

3 Overview mining sector

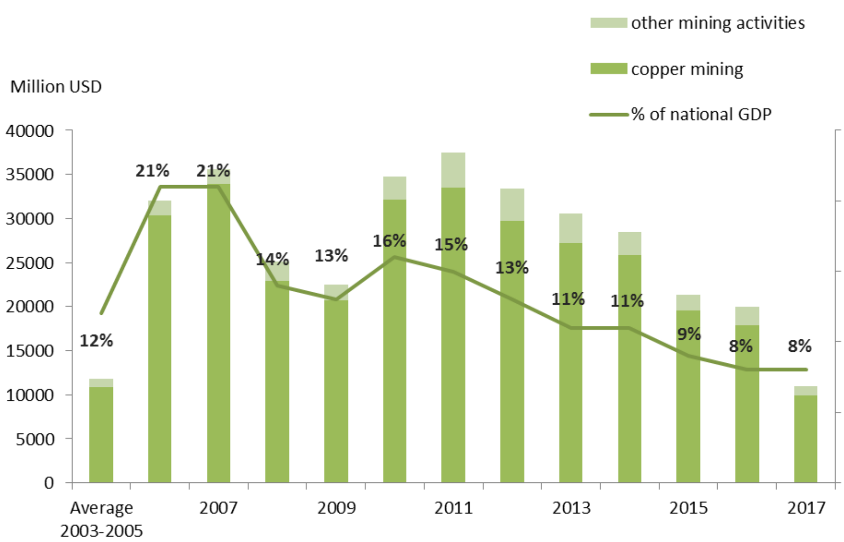
Chile has rich natural resource endowments. It has the world's largest reserves of copper (30 per cent of total reserves) and of lithium (more than half of total reserves) (USGS, 2017a; USGS, 2017b). In 2015, it accounted for 30 per cent of global copper production and 30 per cent of global lithium production (USGS, 2017a; USGS, 2017b). Additionally, Chile mines several other metallic and non-metallic resources such as molybdenum, rhenium, gold, silver and nitrates (Vasters and Sonnenberg, 2011).

Mining is considered a key pillar of Chile's economy with copper being its most important commodity, especially for export. Over the last decade, mining export represented between 50 and 63 per cent of total exports (Consejo Minero, 2017). In 2016, Chile's top exports were copper ore (21 per cent of total exports) and refined copper (20 per cent) (OEC, 2017). However, due to declining metal and mineral prices, the sector's contribution to the country's GDP decreased over the past 7 years (see Figure 2). While the mining sector contributed 21 per cent to Chile's GDP in the peak years 2006 and 2007, in 2016 the contribution of the sector to Chile's total GDP had decreased to 8 per cent (Consejo Minero, 2017). At the same time, the share of tax revenue from the mining sector dropped significantly from 34 per cent in 2006 to 2 per cent in 2016 (see Figure 3).

Chile's mining council estimated that in 2016 the sector employed 9 per cent of the Chilean workforce, including direct (208.850 persons) and indirect employment (533.000 persons) (Consejo Minero, 2017). Yet, the mining industry in Chile is facing a shortage of skilled labour with a projected need of an additional workforce of approximately 38,000 workers until 2020 (Simpson et al., 2014).

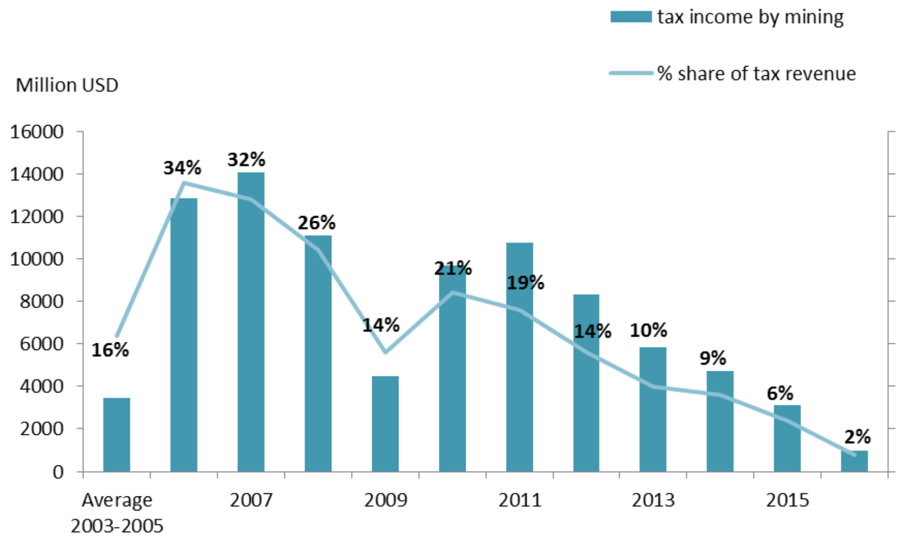
The world's largest international mining companies are operating in Chile (e.g. Anglo American, Barrick Gold, BHP Billiton, Freeport-McMoRan, Glencore, KGHM, Rio Tinto and Teck Resources) (EY, 2017). In addition, there are a number of Chilean private companies such as Compañía Minera del Pacífico, Antofagasta Minerals, Molibdenos y Metales and Sociedad Quimica y Minera de Chile (SQM) (EY, 2017). The state-owned mining company CODELCO is the biggest copper producer worldwide and a major producer of molybdenum (EY, 2017). There are also several medium-scale (up to 400 workers) and small-scale producers (up to 80 workers) which are supported by the state-owned ENAMI (national mining corporation) (EY, 2017; SONAMI, 2014).

Figure 2: GDP generated by mining (2003-2017)



Based on Consejo Minero, 2017: 316.

Figure 3: Tax income by mining and its tax share (2003-2016)



Based on Consejo Minero, 2017: 40.

4 Overview of mining governance

4.1 Disaster risk management and climate change adaptation

Chile is exposed to various geophysical (especially earthquakes, tsunamis and volcanic eruptions) as well as meteorological hazards (see section 2.3 on Chile's climate) (Valdivieso et al., 2017). Presumably because of its history of disasters, Chile developed early a variety of disaster risk management institutions and instruments (Sandoval and Voss, 2016). Already in 1974, the technical emergency agency (Oficina Nacional de Emergencia del Ministerio del Interior y Seguridad Pública (ONEMI)) was founded (Sandoval and Voss, 2016). ONEMI has the mandate "to plan, promote, coordinate, and implement preventive actions, response, and rehabilitation against collective risk situations, emergencies, and disasters caused by natural or human action" (Sandoval and Voss 2016: 109). Chile has an Early Warning Center which involves the National Seismological Center, the Hydrographic and Oceanographic Services, the National Geological and Mining Service (SERNAGEOMIN), the National Forest Corporation, the Directorate General of Water/Department of Health, and the Chilean Meteorological Office and is coordinated by ONEMI (CFE-DM, 2017). The Early Warning Center observes, monitors potential hazards and issues warnings when hazards occur (CFE-DM, 2017). The strategic plan for disaster risk management for 2015-2018 is the central framework for disaster risk management. In this plan, Chile pledges to further strengthen its monitoring and early warning system (ONEMI, 2016). The strategic plan for disaster risk management also stresses the importance of climate change as an additional risk factor (ONEMI, 2016).

The Chilean state has a leading role in preparing the country for climate change adaptation (Gobierno de Chile, 2016). Its Council of Ministers adopted a new national adaptation plan at the end of 2014 (Gobierno de Chile, 2016) that prioritizes several sectors for climate action: water, biodiversity, agriculture, livestock and forestry, energy, infrastructure, fisheries, health, cities and tourism (Gobierno de Chile, 2016). More detailed sectoral adaptation plans for biodiversity, forestry and agriculture, and health have already been developed; adaptation plans for the other sectors will be developed within the next years. Mining was not identified as a separate priority sector for adaptation, although the energy, infrastructure and biodiversity sector are relevant for mining. This is also reflected in the fact that the Mining Ministry is co-responsible for the adaption plan on biodiversity and water (Gobierno de Chile, 2016). The National adaptation plan has helped to shape Chile's adaptation policy, yet the OECD recommends in its 2016 Environmental Performance Review that Chile should "[c]ontinue improving the evidence base and capacity for mainstreaming climate change adaptation into public sector decision making; make the results of climate projections more accessible to end users (through a web portal, for example) to encourage adaptation by the private sector and other stakeholders" (OECD and ECLAC 2017: 40).

The Chilean mining industry is generally aware of climate change with some larger companies taking visible action: In 2015, BHP Billiton Chile held two planning workshops together with its environmental management staff on the topics "Resilience to Climate Change" and "Climate Change: Changing the ways in which we operate". The workshops resulted in action plans which will be implemented in all BHP Billiton mining operations in Chile until 2020 (BHP Billiton, 2015a). To adapt to reduced water availability and to an increased water demand, desalination plants supply the Escondida mine with water (see also section on environmental impacts) (BHP Billiton, 2015a). No further details on other adaptation measures at the Escondida mine are disclosed. There is no publicly available information on how SQM is reacting to climate change and whether they have adaptation plans in place.

4.2 Environmental governance

Since the 1990s, awareness for the environmental impacts of mining and other industries has increased. In 1994, the Environmental Framework Law came into force and laid the foundations for environmental regulation in Chile (Del Fávero, 1994). It also introduced the Environmental Impact Assessment (EIA) system. The EIA system requires that public or private investment projects which have a potentially significant environmental impact must be evaluated and permitted (Del Fávero, 1994). Small projects do not have to undergo a full EIA, but have to submit an Environmental Impact Declaration. The full EIA process requires public participation: the project proponent has to publish a short version of the EIA report to the local public which can submit comments to the regional Environmental Evaluation Commission (EEC) within a 60-day window. Municipalities need to ensure that there is community participation. However, the public participation during an EIA process allows only commenting regarding environmental mitigation measures of the proposed project but does not allow for the consideration of project alternatives. In case the EIA is approved by the EEC, a project receives a publicly available Resolution of Environmental Qualification which sets environmental impact mitigation measures and serves as an environmental permit[4] (OECD and ECLAC, 2017). In 2012, a Supreme Decree introduced, in accordance with ILO Convention 169, specific provisions for the participation of indigenous people in EIAs (see section on indigenous people) (Gajardo, 2014).

In 2010, Chile implemented several institutional and policy reforms, such as the establishment of the Ministry of Environment, the Council of Ministers for Sustainability, an environmental superintendence and an environmental assessment agency. These reforms can be rated as important improvements and have led to a significantly increased budget allocation to environmental authorities. With the creation of environmental courts in 2012, access to justice was strengthened as people or communities affected by environmental damages can claim compensation and any physical or natural person can file a lawsuit against environmental standards or regulatory decisions (e.g. EIA decisions). Further, Chile's air, water and waste management has improved over the past years. However, the regulatory framework for air emissions and wastewater discharge remains incomplete as not all pollutants are covered. Abandoned and inactive mining sites have been recognised as a major environmental problem by the state. The 2012 Mine Closure Law stipulates that all new mines need to present mine closure plans which need to be approved by SERNAGEOMIN. Yet, the more than 650 abandoned mining sites, many of which have been closed without adhering to state-of-the-art standards, are not subject to the new law (Weeks, 2015). Decontamination plans for already closed mines are not yet in place (OECD and ECLAC, 2017).

Although the OECD concludes in its Environmental Performance Review that the Chilean national environmental authorities – especially the environmental superintendence which is in charge of compliance monitoring – "still lack human and technical capacity to adequately perform their functions" (OECD and ECLAC 2017: 26), it is noticeable that the environmental superintendence imposed some major fines on several mining companies over the past years (e.g. Barrick Gold's Pascua Lama mine was fined US$16 million in 2013) (EY, 2017). In 2015, 60 per cent of all sanctioning processes for environmental breaches were directed towards mining companies (Minería Chilena, 2016).

4.3 Water governance

Chile generally has abundant water resources, yet they are very unevenly distributed: the north is very arid, while the south is mostly temperate and wet. Since 1996, water demand is greater than availability in Chile's north (Aitken et al., 2016). In Antofagasta, mining accounted for 64 per cent of the total water use, in all other regions agriculture is the main water consumer (Aitken et al., 2016).

The Chilean Water Code was enacted in 1981 under Pinochet's military regime. It defines water as a "national property for public use", but at the same time lays down a market approach for tradable water use rights. The Directorate General of Water (DGA) grants new water rights to petitioners (Bauer, 2015; Hearne and Donoso, 2004). Once a company or an individual holds water rights, they can trade their rights to others without the state intervening (Larrain, 2012). This has led to a high

[4] In addition, other permits might be required from sectoral authorities, such as a water or waste permit.

concentration of water ownership[5], to an overexploitation of some aquifers and conflicts over shared water resources (Larrain, 2012; OECD and CELAC, 2017). Water conflicts can be brought forward to administrative agencies, primarily to the DGA. If the agencies cannot resolve the conflict, the case goes to a court (Costumero et al., 2016).

The Code was reformed in 2005, but many problems remain unsolved (OECD and CELAC, 2017). According to Valdés-Pineda et al., "[i]t can be […] observed that the current water right allocation system may be inefficient and inequitable from a social and environmental perspective, in which those individuals or entities with more money tend to get such rights" (2014: 2562). The DGA has established five protective regulations for rivers and aquifers which stipulate that only temporary or no new water rights can be granted (Valdés-Pineda et al., 2014):

1. River Depletion Declaration
2. Environmental Flow Reserves
3. Protected Aquifers that sustain meadows and wetlands
4. Restricted Areas (risk of aquifer depletion)
5. Prohibited Areas (depleted aquifers)

In its Environmental Performance Review on Chile, the OECD recommends that the water resource management needs further reforms, e.g. addressing the issue of over-allocation and ensuring environmental and social requirements as well as the sustainable use of water (OECD and CELAC, 2017).

4.4 Indigenous people

According to the 2015 census, over 1.5 million people or 9 per cent of the Chilean population self-identify as indigenous (Ministerio de Desarrollo Social, 2017). In Antofagasta, the share of self-identified indigenous is 3 percent (Ministerio de Desarrollo Social, 2017). There are nine indigenous peoples with the Mapuche being the biggest group, representing 84 per cent of the total indigenous population in the region (Broch et al., 2017).

Although the situation of indigenous people in Chile has improved over the past years, social inequalities between indigenous and non-indigenous population remain. While 44 per cent of the indigenous population lived below the poverty line in 2006, 28 per cent of the non-indigenous population was registered as poor in the same year (Ministerio de Desarrollo Social, 2017). However, since then the share of poor indigenous people decreased significantly to 18.3 per cent in 2015 as did the share of non-indigenous which dropped to 11 per cent (Ministerio de Desarrollo Social, 2017).

The Chilean constitution, which came into force under the former dictator Pinochet in 1980, does not recognize the country's indigenous population (Broch et al., 2017; OECD, 2017). Yet, in 2015 President Bachelet launched a process to renew the current constitution, beginning with civic education about the process and public consultations. The new constitution is designated to acknowledge Chile's cultural diversity and indigenous rights (OECD, 2017). To date, indigenous groups expressed their discontent with the consultation process and a constitutional draft has yet to be presented (Broch et al., 2017).

Chile ratified the International Labour Organization's Indigenous and Tribal Peoples Convention (ILO Convention 169) in 2008 which stipulates the participation and other specific rights to indigenous people (Bustamente, 2015). The human rights organization IWGIA (International Work Group for Indigenous Affairs) remarks that the "application of ILO Convention 169 […] is still quite insufficient, in particular with respect to indigenous consultation rights when administrative measures on

[5] In the Chilean north groundwater rights have been over-granted (Valdés-Pineda et al., 2014). In Antofagasta, mining companies hold almost 100 per cent of groundwater rights (Larrain, 2012).

investment projects affect indigenous peoples" (Broch et al., 2017: 260). Nevertheless, several court decisions have led to sanctions for extractive projects over the past years because they did not consult with the indigenous community as stipulated in ILO Convention 169 (Bustamente, 2015).

Two institutional initiatives on state level promise to strengthen indigenous rights in Chile. In 2016, the Chilean sent legislative bills to the Congress for the creation of the Ministry of Indigenous Affairs and the National Indigenous Council (Broch et al., 2017). President Bachelet hailed these legislative bills as "the realization of a long-awaited and renewed dream: to elevate indigenous politics to the highest institutional rank through the ministry, improving the coordination necessary to do things correctly and to ensure the crosscutting presence of the indigenous approach in government" (Gobierno de Chile, 2017). However, the bills have yet to be enacted (Broch et al., 2017).

4.5 Mining-related conflicts

Chilean history is closely linked to natural resource conflicts. During the War of the Pacific (1879-1884), the Atacama Desert was subject to boundary and territorial disputes between Chile on the one side and Bolivia and Peru on the other side (St John, 1994). The discovery of nitrate deposits fuelled already existing regional rivalries (St John, 1994). During the time of military rule (1973-1990), the Chilean copper miners' confederation was part of the opposition against Pinochet's regime and faced violent oppression during strikes and protests (Miller Klubock, 1997).

Similar to the situation in other Latin American countries, large-scale mining projects and processing industries still play a central role in environmental conflicts in Chile. Currently, the Instituto Nacional de Derechos Humanos (National Human Rights Institute) lists 102 so-called socio-environmental conflicts in Chile, of which 35 have a direct link to the mining sector with about half of them involving indigenous lands and territories (17 cases) (Instituto Nacional de Derechos Humanos, 2017).

The main issues in these conflicts are community rights, negative environmental impacts of mining operations, water and energy use, the sharing of mining benefits and labour conditions at mining sites.

There are several conflicts related to the Escondida copper mine. One of them dates back to 2006, when Escondida intended to expand its operations with the Pampa Colorada project. The company planned to extract groundwater in the vicinity of several indigenous communities 190 kilometres away from the mining site. The inhabitants of these localities opposed the project as they feared the depletion of water sources and the destruction of archaeological sites and objected the project's EIA report (Environmental Justice Atlas, 2014; Coordinadora por la Defensa del Agua y la Vida, 2017). As a consequence the regional environmental commission declined the environmental permit for the project in 2007 (Environmental Justice Atlas, 2014; Coordinadora por la Defensa del Agua y la Vida, 2017). The expansion project Pampa Colorado is one of the rare cases in which the Chilean state rejected a mining project because of environmental and cultural concerns (Environmental Justice Atlas, 2014; Coordinadora por la Defensa del Agua y la Vida, 2017). Another, more recent case related to a water extraction conflict evolved around the Salar de Punta Negra. Local environmental organisations claimed that the water extraction is harming the region's biodiversity and submitted two complaints to the environmental superintendence in 2016 (Fuentes, 2016). In June 2017, the Escondida mine announced to stop water extraction from Punta Negra and to change its water strategy (Minería Chilena, 2017; for further details see section 5.4.1. on environmental impacts).

In February and March 2017, a six-week strike at the Escondida Mine gained public attention. 2,500 workers of the union stopped working as negotiations over new wage and benefit contracts failed. They engaged in the „longest private-sector mining strike in Chile's history" (Jamasmie, 2017). At times, the strike turned violent when disguised protesters barricaded connecting roads by burning tires. Rocks were thrown at policemen who reacted by using tear-gas (Ricardo, 2017). The striking workers and the majority owner and operator BHP Billiton could not reach a final deal. In consequence, the main union chose to end the strike and the workers returned to work after 43 day of labour action (Jamasmie, 2017). The strike led to a production shortfall of 120,000 tonnes of copper and a loss of almost 1 billion USD, followed by downwards revision of this year's production volumes (Sanderson and Hume, 2017; Jamasmie, 2017).

In Antofagasta, air pollution stemming from the transport of copper concentrates in Antofagasta stirred up protests. The local population complains about the black dust originating from the loading of copper concentrate at the Antofagasta Terminal International (not linked to the Escondida mine, it ships copper concentrate produced by KGHM's Minera Sierra Gorda) (Environmental Justice Atlas, 2017; OCMAL, 2015). Mostly because of health concerns, local organisations formed the movement "Este Polvo Te Mata" ("This dust kills you") and engaged in public campaigns and protests (Environmental Justice Atlas, 2017; OCMAL, 2015; El Nortero, 2015). In August 2015, the environmental superintendence imposed a fine on Antofagasta Terminal International and ordered a clean-up in the port area of Antofagasta. In October 2016, a court decision confirmed that the sanctioning process was fully in accordance with the law (El Diario de Antofagasta, 2016).

Various issues linked to the lithium producer SQM led to discontent of the public. In early 2015, SQM was involved in a corruption scandal, which became part of a larger series of political scandals in Chile. SQM was accused of having bribed several politicians (including many family members and employees of high rank politicians such as then-incumbent president Michelle Bachelet and former and re-elected president Sebastian Piñera) and financing political campaigns of several parties with almost 7 million USD over the years (Radwin, 2016; Montes, 2015; Fox, 2017). In addition, SQM is currently in arbitration with the Chilean government over royalty payments and faces charges of the environmental superintendence for various environmental breaches at its iodine and nitrate operations in the Salar de Llamara (O'Brien, 2016; González, 2017).

5 Case study: copper mining

5.1 The global value chain of primary copper

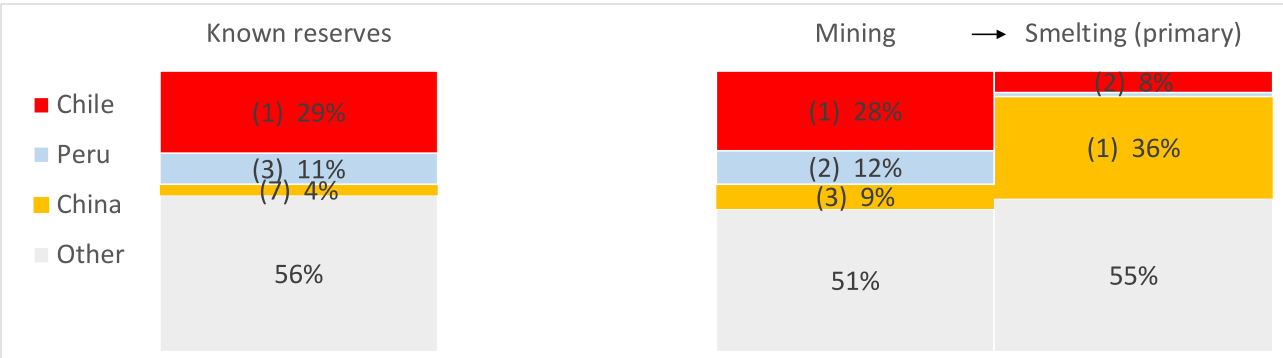
Copper is one of the most important metals in modern economy. High thermal and electrical conductivity, high ductility and malleability, resistance to corrosion, and abundance in nature have made copper indispensable in electrical and electronic applications, as well as in construction, transportation, machinery and general consumer products.

Porphyry copper deposits are the single largest source of copper in the world, accounting for about 60% of total copper output (and almost all copper production in Chile) (ICSG, 2016), and about 85% of total identified copper resources (USGS, 2017a). These deposits, despite lower average grades, can be mined at low-cost through bulk mining methods such as open-pit or underground block-caving. Other important sources of copper are sediment hosted deposits and volcanogenic massive sulphides.

The main ore mineral of copper is chalcopyrite ($CuFeS_2$). Other copper sulphide minerals include bornite (Cu_5FeS_4), covellite (CuS) and chalcocite (Cu_2S). The sulphide minerals yield most of the copper produced in the world (Geoscience Australia, 2015). Generally, they occur in the deeper part of the deposit, which is not exposed to weathering, while near the surface they are altered by oxidation resulting in secondary copper minerals (i.e. oxides and carbonates). The latter forms rich (mixed) ore in the upper parts of many deposits in Chile.

The world copper reserves are currently estimated at 720 Mt; the total identified resources are about 2,100 Mt while undiscovered resources are represented by additional 3,500 Mt (USGS, 2017a). The world copper mine production has been estimated at about 20 Mt in 2016, with Chile being the leading producer (28 per cent), followed by Peru (12 per cent) and China (9 per cent). In the next stage of supply chain – metal smelting – China dominates the world accounting for more than one third (36 per cent) of copper (primary) smelting, followed by Chile (8 per cent) (Figure 4).

Figure 4: Copper global value chain and ranking for selected countries (2016)



Note: figures in brackets show the country's global ranking. Data sources: USGS, 2017a; ICSG, 2017.

Produced via smelting copper metal is shipped for fabrication, mainly as cathode, wire rod, billet, cake (slab) or ingot. Copper and its alloys can be further transformed by downstream industries for use in final products such as automobiles, appliances, electronics, and other (ICSG, 2016).

5.2 Site-specific overview – Escondida mine in Atacama Desert

Copper mining in Chile is primarily based on large scale open-cut or underground mines, spread along the Andes Mountains, particularly concentrated in the Antofagasta region located in the arid northern Atacama Desert of Chile, about 1,100 km north of Santiago. It is the major mining hub in Chile and one of the most important mining regions in the world.

The Escondida copper-(gold)-(silver) mine, located in the Atacama Desert at an altitude of 3,100 meters above sea level, and about 160 km southeast of the port of Antofagasta, is the world's largest copper mine, accounting for about 5 per cent of the total world production and 20 per cent of copper production in Chile (USGS, 2017c). The mine (Minera Escondida Limitada) is a joint venture between BHP (57.5 per cent), Rio Tinto (30 per cent), and a Japanese consortium (12.5 per cent) (BHP Billiton, 2017a). It produces copper concentrate and cathodes through the operation of two open pits – Escondida (started in 1990) and Escondida Norte (2005) and the associated beneficiation and processing plants.

Primary sulphide mineralisation at Escondida includes pyrite, chalcopyrite and bornite, with covellite and chalcocite in the enriched zone. Primary hydrothermal sulphide ore grades are between 0.2 per cent and 1 per cent copper. Escondida's measured resource is currently 5,870 Mt at 0.64 per cent copper (equal to 37.6 Mt of copper) (Rode, 2015), which allows mining operations to continue for about 30 years at the current scale of production. Although, the estimated total mineral resource base (indicated, measured and inferred) of about 27,000 Mt at 0.52 per cent Cu could extend operations to more than 100 years (Rode, 2015).

Ore mineral grade has averaged approximately 2.7 per cent copper since start-up (1990) through fiscal 1997, in the period of mining the enriched cap overlying the primary sulphides (BHP, 2000). The concentrator' average head-grade has declined through the development of deeper parts of the deposit, and stabilised at around 0.8-1 per cent (Rode, 2015). To maintain production volumes and mine's capacity, there were several expansions, including introduction of heap bioleaching for low grade sulphide ore (0.6 per cent copper).

In 2016, Escondida produced 1,002 kt of copper in total, including 690 kt in the form of copper concentrate and 312 kt in cathodes (BHP Billiton, 2017a). This represented a decrease if compared to previous years, primarily explained by lower ore grades. The record high copper production at the Escondida mine was achieved in 2007 at 1.6 Mt of copper from 90.7 Mt of ore with a head grade of 1.8 per cent (USGS, 2016). The company's forecast indicates production volumes at about 1.2 Mt per year until 2025 (Rode, 2015).

5.2.1 Overview of transportation systems and routes

Escondida mine produces two major products – copper cathodes (metal) and copper concentrate. Copper cathodes are transported via railway to the ports of Antofagasta and Mejillones, primarily for export. The railway system in Chile is operated by the State. Mining companies have private local connections within the mine site boundaries. The concentrate is transported through slurry pipelines to filtration and port facilities located at Coloso, south of Antofagasta, where concentrates are dewatered and dried for export (BHP, 2000; Rode, 2015). The slurry pipelines were renewed in 2014 and placed inside a tunnel (BHP Billiton, 2014).

5.3 Extraction and processing technologies

5.3.1 Extraction and processing technologies at Escondida

Escondida copper mine is a conventional open-pit operation processing sulphide and oxide ores (Figure 5). The average daily total material moved rate is about 1.4 Mt, including waste rock, major high-grade sulphide ore, low-grade sulphide ore, oxide ore, and mixed ore (Rode, 2015). Oxide ore is currently produced as a 'by-product' of sulphide mining.

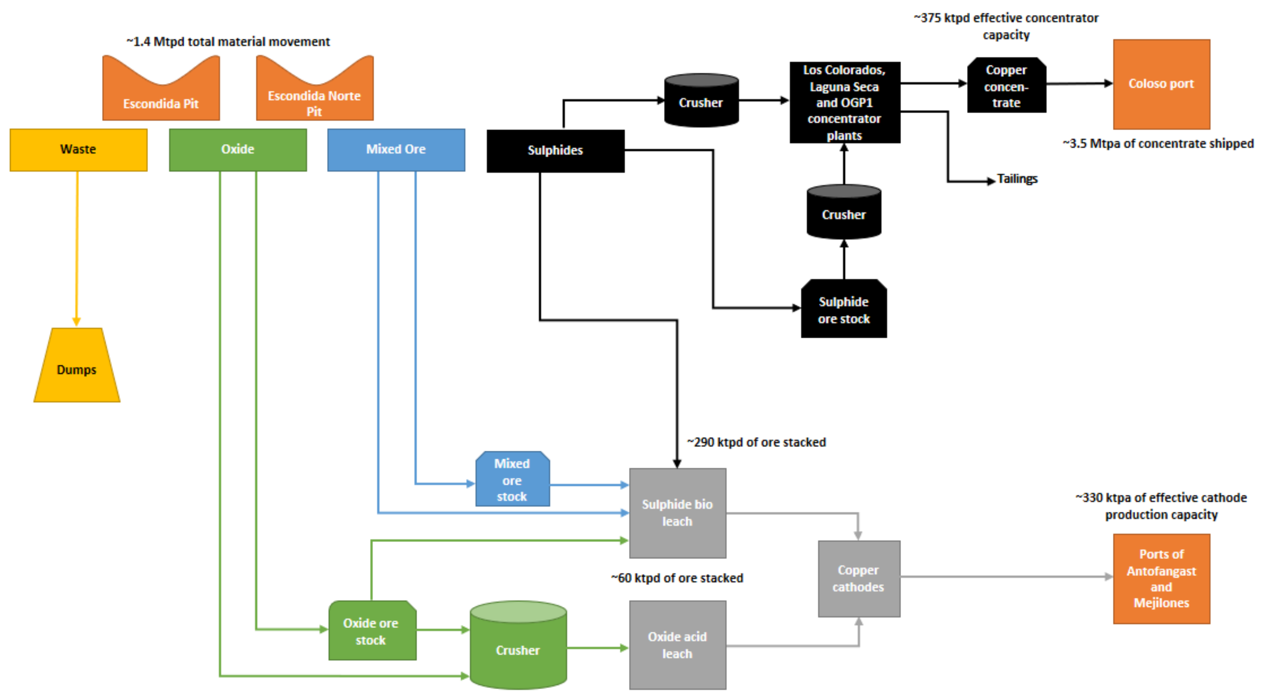
Mining infrastructure at Escondida includes crushing and transportation systems, two leach pads (one for oxide ore, and one for low-grade sulphide ore), three concentrator plants, two solvent extraction plants (oxides and sulphides), and electrowinning plant. There are also two seawater desalination plants at the coast in Puerto Coloso, which provide additional water supply to the mine through a 170 km long pipeline (BHP Billiton, 2017a).

Copper ore is blasted on benches in the pit and loaded by shovel into large off-road trucks for haulage to concentrators. To separate copper sulphide minerals from the rock, the concentrators employ crushing, milling and flotation circuits. Oxide ore is crushed and sized and then heap leached with dilute sulphuric acid the dissolved copper is recovered at the solvent extraction plant through electrowinning. The sulphuric acid is recycled from the solvent extraction plant and is re-used.

The low-grade sulphide ores are treated with crushing, agglomeration, stacking, and bacteria assisted bioleaching flowsheet (Demergasso et al., 2010). The designed heap dimensions at Escondida are 2 km wide by 5 km long (divided into 40 leaching strips), currently operated with the third lift loaded (each lift is 18 m high). Each leaching strip has its own individual irrigation and forced aeration system (Soto et al., 2013). The declining average copper ore grades make the bioleaching flowsheet an important part of copper mining in Chile and worldwide. The amount of copper produced in Chile by bioleaching has increased from about 5% in 2002 to more than 10% (Demergasso et al., 2010).

Copper concentrates from Escondida mine are pumped through a 170 km long, nine-inch-diameter pipeline to the coastal port of Coloso where concentrates are dewatered and dried for export (Gundewar et al., 2011).

Figure 5: Schematic of mining and processing at Escondida mine



Source: Own graphic, based on Rode, 2015.

5.4 Environmental impacts and mitigation measures

5.4.1 Escondida mining area

Land use

Land use at the Escondida mine is typical for a large copper mine of this nature – namely a very large open pit (3.9 km long, 2.7 km wide and 645 m deep (Mining-technology.com, 2017)), a large scale mineral processing and hydrometallurgy infrastructure and very large tailings storage facility. A key infrastructure difference between Escondida and other copper mines, which affects land use, is the seawater desalination plant and associated infrastructure from the coast to the mine site.

While there are few local stakeholders in the vicinity of the mine reducing potential for competition over land use, there is about 1 million people who live across the Atacama desert (over 100,000 km^2), and there are groups that conduct informal mining which do not have direct impact on Escondida but are nevertheless part of the mining landscape.

Water use

Water is a very scarce and expensive commodity in Chile, leading to high importance of increased water efficiency. In the period 2000-2014, the specific water consumption in the Chilean copper industry decreased from 1.1 to 0.7 m^3 per ton of ore (Cerda, 2015).

Water is a crucial input to copper mining and processing, including water use in the beneficiation processes (such as grinding, flotation, and leaching), tailings deposition, transportation of copper concentrates through pipelines to other parts of the site and/or to export terminals near the coast, as well as for dust control on roads and waste dumps. The mine's total water consumption in 2016 was 83,472 ML (BHP Billiton, 2017a). In 2014, fresh water represented about 60% of the total water balance at the mine site, followed by recovered (recycled) water (26%) and water from the desalination plant (11%) (Rode, 2015). Freshwater is mainly extracted at the mining site as well as from the Punta Negra and Monturaqui aquifers (138 water wells) and pumped via aqueducts to the mining site (DGA, 2016). The existing water recovery programs and an additional desalination plant are expected to further significantly reduce fresh (underground) water withdrawal. By 2018 it is projected that (desalinated) seawater participation will increase to 43% at Escondida (Rode, 2015), and by 2025 it will account for about 40% in the Chilean copper industry overall (Cerda, 2015). However, Escondida is currently seeking to obtain the right to expand the extraction of freshwater from the nearby Monturaqui aquifer (Golder Associates, 2017).

Escondida's second seawater desalination plant in Puerto Coloso was commissioned in December 2016. Its design capacity of 2,500 litres per second is one of the largest in the world (the first plant's capacity is 525 litres per second, which has been in operation since 2006) (BHP Billiton, 2017a).

Extraction of water from the Salt Basin Punta Negra (1,800 liters per second) has been viewed as a serious impact to the fauna and the environment, and local stakeholders and NGOs lodged a complaint in 2016 for serious socio-environmental damages. According to the report presented in conjunction with the complaint, the socio-environmental impacts express damages such as that the watershed of the Salar, specifically the Brava lagoon, has reduced its water capacity by 44.7%. In the field of flora and fauna, 47 species of birds, 51 plants, 13 mammals and 7 reptiles are at risk. The altered hydrological conditions and its impact on the land and its appearance was also seen to have socio-cultural consequences (Elciudadano.com, 2016). The Escondida mine announced in 2017 to halt extraction of (brine) water from the salt lake by introducing a long-term water strategy excluding the use of aquiferous natural reservoirs, and relying on desalinated seawater (E&MJ News, 2017).

Energy use

The high energy costs in Chile are driving most future mining projects towards producing copper concentrates rather than copper metal (Cerda, 2015). The total estimated energy consumed directly and indirectly at Escondida was 25,8 million GJ in 2016, with about 45% attributed to diesel use and 55% to (indirect) electricity use (BHP Billiton, 2017a). To ensure current and future electricity supply to the Escondida mine and other BHP mines in northern Chile, BHP – through an international tender for long-term electricity supply – initiated the construction of new gas-fired power plant by Kelar S.A. consortium which was launched in 2016. Details regarding how much energy is used for water desalination are not disclosed, but based on a typical reserve osmosis energy consumption (up to 5.5 kWh/m^3 (Desware, 2017)), the desalination plants could use up to 2 million GJ for producing over 3,000 litres per second, as mentioned in the previous section. In addition, there would be significant energy demands for pumping the desalinated water from the coast to the site, which is at 3,100 metres above sea level.

Mine waste

The open-pit copper mining generates massive mining waste, mainly in the form of waste rock, spent ore (residue from leaching process) and tailings (from concentrator). Each type of waste materials requires specific control methods to ensure the stability of storage facilities and protection of the environment (BHP Billiton, 2017a). As water efficiency is one major issues (and operational bottlenecks) at Escondida mine, water reuse at concentrators and from leach pads, and water recovery from tailings are crucial to mine operation (Chambers et al., 2003). Therefore, mining operations produce no significant waste water or water emissions. As shown in Table 1, the extremely low rainfall means that there is minimal risk related to the generation of acid mine drainage.

There are two tailings facilities at Escondida mine – the old Hamburgo facility and the relatively new Laguna Seca facility, which is designed to receive 3,300 Mt of tailings over 40 years of operations (Chambers et al., 2003). Water is recovered from tailings by thickening in the concentrator, and through initial release of transport water and long-term seepage from tailings consolidation in the tailings facility. The water recovery from tailings has been incorporated into the design of the Laguna Seca facility, which represents a horseshoe shaped bowl of approximately 50 km^2, with a dry clay lake bed at the centre at an elevation of 2876 m above sea level. The rim of the bowl rises to elevations above 3000 m above sea level. The facility comprises the tailings pumping system from the Los Colorados concentrator, a gravity discharge system for the tailings from the Laguna Seca and OGP1 concentrators, a water recovery system returning water to concentrators and the Starter Dam (which will be raised by the downstream construction method along with growing tailings deposition). At the end of the mine operations, the tailings dam is expected to be approximately 3 km long with a maximum depth of 80 m (Chambers et al., 2003).

Maintaining high tailings deposition rates is a key to maximize water recovery from the consolidating tailings. The maximum ratio is 0.30 (30% recovery) at tailings deposition rates greater than 4 meters per year, while at the rate of 1 meter per year the runoff ratio approaches zero (Chambers et al., 2003).

The Laguna Seca dam has been built following the downstream method[6] to exclude dam breaching or leakage. In an arid region like Antofagasta this would not be considered an issue due to low precipitation rates, however taking into account the impact from potential seismic activities in the area the downstream method is highly preferred. In general, breaching of a dam wall due to a seismic event would be the major hazardous risk related to mine waste.

Emissions

Escondida's total annual GHG emissions were 3,695 kt of CO_2 eq. (including 881 kt of direct emissions) in 2015, and 4,283 kt (1,043 kt) in 2016 (BHP Billiton, 2017a). The main sources of GHG emissions in copper mining are associated with the use of fuels to power machinery (mainly diesel), the use of explosives, from land clearing, and electricity for processing and especially smelting operations, as well as for the seawater desalination plant. There is a particular focus on minimizing emissions of particulate matter (PM) at the mine site and respirable crystalline silica which results from mine blasting processes (BHP Billiton, 2017a).

[6] Engels describes the downstream method as follows: "Downstream embankment design starts with an impervious starter dyke. The tailings are at first deposited behind the dyke and as the embankment is raised the new wall is constructed and supported on top of the downstream slope of the previous section" (Engels, 2017).

Biodiversity

Escondida's operations take place in the ecosystem of the High Andean Plateau, and the marine environment of the coast of northern Chile (BHP Billiton, 2017a). There are no protected areas within the mine site and its facilities, nevertheless the Escondida mine qualifies some areas (Punta Negra and Tilopozo wetland as well as the coastline of Coloso) of its operations as zones rich in biodiversity, and works together with local authorities to monitor these zones for negative impacts. Specifically, monitoring of the potential effects of water withdrawal by the mine on the fauna and flora is required (BHP Billiton, 2014).

Rehabilitation

The Escondida mine has a closure plan approved by the SERNAGEOMIN. It complies with the Chilean legislation on the Closure of Mines and Mining Installations, the company's sustainability framework and Health, Safety, Environment and Community requirements to address the whole life cycle of its mining projects (BHP Billiton, 2017a).

Health

The major health concern for workers at the Escondida mine site relates to potential exposure to air-borne carcinogens and contaminants, such as silica (primarily from ore blasting and crushing) and acid mist (from heap leaching process). The ongoing preventive measures include technological process improvements, installation of atomisers and water tanks to spray water directly over the source of dust, and using polymer additives reducing dust generation in the ore crushing and stockpiling (BHP Billiton, 2017a).

Seismic risks

Chile is heavily affected by tectonic activities. Major earthquakes occur frequently throughout the region. While higher intensity earthquakes occur closer to the subduction zone located towards the cost, the impact of seismic activity reaches across the region and has the potential of damaging mine infrastructure. The risk of tailings dam breakage during such events is increased. However, seismic risks are not directly influenced by climate change and are therefore not further examined in the climate change impact assessment.

5.4.2 Copper concentrate filter plant at the port of Coloso

Copper concentrates from Escondida mine are pumped through a 170 km long, nine-inch-diameter pipeline to the filter plant at the coastal port of Coloso, in the far south area of the city of Antofagasta, where concentrates are dewatered and dried for export (Gundewar et al., 2011). This practice allows to significantly reduce and the associated environmental impacts, such as the use of heavy trucks and avoidance of dust emissions as well as transportation costs.

Land use

The copper concentrate filter plant has an insignificant land use.

Water use

There is no information available on the plant's water use.

Energy use

There is no information available on the plant's energy use.

Waste

Effluent from the filter plant is treated (to recover suspended solid particles) before discharge deep into the Pacific Ocean (Gundewar et al., 2011). A detailed physical oceanographic study and mathematical models for effluent circulation and dispersion confirmed that marine ecosystem at Coloso would not be measurably altered (Croce et al., 1995).

Emissions

The final product – copper concentrate powder – is sent via a conveyor belt system to a closed storage facility and further loaded on ships. The strong winds observed in the area required additional engineering solutions to minimize dust generation during copper concentrate storage and conveying (Croce et al., 1995).

Rehabilitation

Rehabilitation measures are not applicable.

Biodiversity

The marine ecosystem in the Coloso bay is highly diverse. Yet, it is not expected to be measurable altered by the filter plant's waste which is discharged into the ocean (see section on waste). There is a monitoring programme in place that controls the plant's productions activities and aims at preventing impacts on the marine environment (BHP Billiton, 2014).

Health

No health related impacts from the filter plant has been reported to date.

5.5 Current climate impacts and risks

Current climate

The climate of the Escondida mining area is extremely arid with annual average precipitation estimated at 5 mm/year (Chambers et al., 2003). Köppen-Geiger classifies the climate as cold desert climate (BWk). As most of the surface water in the region is ephemeral[7] , relatively few animal species live in this arid environment, and faunal diversity and density is extremely low (WWF, 2017). The average monthly potential evaporation ranges from 4 mm/day to 11 mm/day, with an annual average of 7 mm/day or over 2.5 m/annum (Chambers et al., 2003). The monthly average temperature ranges between 4.5°C (July) and 11.5°C (January) (data for Estación Zaldivar situated within mine site).

[7] Ephemeral is defined as a "stream or portion of a stream which flows briefly in direct response to precipitation in the immediate vicinity, and whose channel is at all times above the groundwater reservoir"(Levick et al., 2008).

Table 1: Estación Zaldivar – monthly mean rainfall

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean [mm]	5	1	0	0	1	0	1	0	1	1	0	0

Source: Climate-Data, 2017a.

Past weather extremes

During the past decades drought has affected the mining production in Chile. Officially imposed water restrictions because of drought conditions led to a 2 per cent reduction of copper production in the second half of 2014 (Alliance News, 2015; La Tercera, 2015).

At the end of March 2015, torrential rains led to severe flash floods in the usually very arid Chilean north (regions of Antofagasta, Atacama and Coquimbo). After almost 10 years of drought, a cold front moved in at the end of an extremely hot summer and caused three days of very heavy rain (in comparison to average levels) (Munich RE, 2016). The flash floods led to mudflows and debris avalanches which caused damage to towns and settlements, infrastructures, and mining sites (Munich RE, 2016). Several companies had to close their mines temporarily (Munich RE, 2016). Codelco's El Salvador copper mine had to halt its operation for 30 days which cause a production loss of 6,500 tons of copper (Selaive et al., 2015). Codelco also closed various transport routes and other mines (Selaive et al., 2015). The Escondida mine was also affected and had to reduce its productivity (BHP Billiton, 2015b). In June 2017, the Escondida mine had to halt operations due to heavy rain and snow. This led to a production loss of 12,000 tons of cooper (BHP Billiton, 2017c).

There is no information available whether these wet weather extremes caused negative environmental impacts at the copper mining sites, such as washed out heavy metals or the generation of acid waters.

In the past years, newspapers reported that several copper-exporting ports along the northern Chilean coast had to be closed temporarily because of bad water and heavy waves, e.g. in May 2017 for four days (Azzopardi, 2017).

5.6 Climate change impact assessment[8]

Like all mountain regions, the Andes are a major challenge for climate modelling due to the complex topography and steep and sharp climatic gradients ranging from tropical to arctic climate (Beniston, 2003; Urrutia and Vuille, 2009). In mountain areas, rapid changes in climate parameters like temperature and precipitation within kilometres are characteristic. The same is true for sudden changes in runoff and erosion, and soils and vegetation (Beniston, 2003). Global climate models are "[n]ot capable of adequately resolving these climatic [and environmental] gradients" (Urrutia and Vuille, 2009: 2). This poses a major challenge for climate impact studies. Nevertheless, regional climate models can provide some approximations of future climate; even if their significance in mountain areas is not as high as in non-mountainous regions (see e.g. Beniston, 2003).

The Escondida mine, the SQM Salar de Atacama lithium mine, processing facilities as well as transport routes/pipelines and the ports are expected to face some climate change-related impacts in the future, caused mainly by changes in precipitation regimes such as even less precipitation in combination with very rare but intense precipitation events.

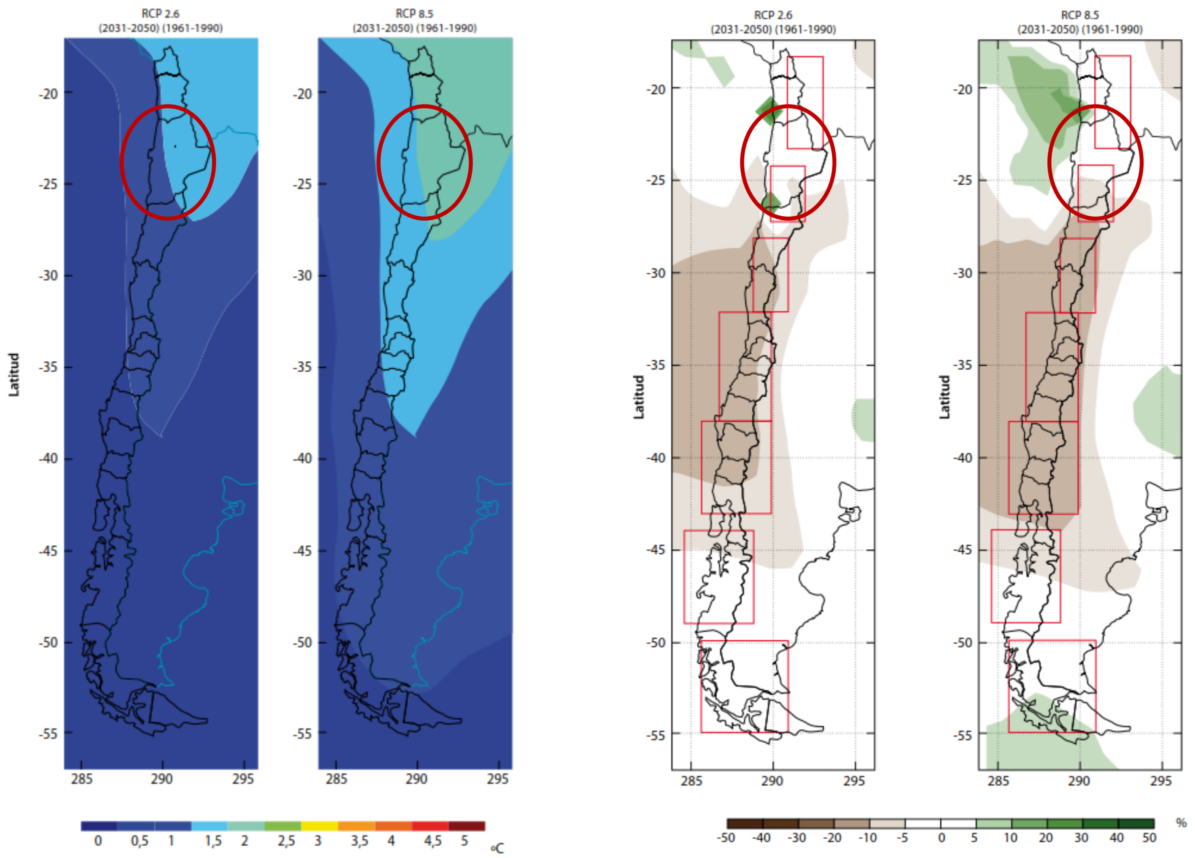
Although the projected warming for Chile is lower than the average warming for the world, temperatures are projected to rise over the next centuries in all parts of Chile (Gobierno de Chile, 2016). According to the RCP2.6 scenario (Global Climate Model), an increase in mean temperature by 1.5°C is projected for the locations of the Escondida mine and the SQM Salar de Atacama lithium mine for the period between 2031-2050 in comparison to 1961-1990 (see Figure 6; Gobierno de Chile,

[8] For an overview see Figure 7.

2016). For the location of the lithium processing plant the mean temperature and for the city of Antofagasta an increase of 1°C is expected. Under the RCP 8.5 scenario (Global Climate Model) for the period between 2031-2050, the projected mean temperature increase is 2°C for both mining locations and 1.5°C for the lithium processing plant's location and the city of Antofagasta (see Figure 6; Gobierno de Chile, 2016).

These increases are underlined by the results of regional climate model, which show changes of mean summer temperature, downscaled for the region of the Antofagasta port, from 20.7 to 22.8°C till 2050 (+2.1 degrees) under RCP8.5 (no information for RCP 2.6 available), and changes of winter temperatures from 13.7 to 15.9°C (+ 2.2 degrees) (INFODEP, 2016). Furthermore, these models show changes of mean summer temperature, downscaled for the location of the Escondida mine, from 4.7 to 7.3°C (+2.6 degrees) till 2050 under RCP 8.5, and changes of winter temperatures from -1.6 to 1.1°C (+2.7 degrees) (INFODEP, 2016).

Figure 6: Climate projections[9] for temperature (left) and precipitation (right)



Source: Gobierno de Chile, 2016: 16-17; the Antofagasta region is encircled in red.

The annual mean precipitation is projected to remain unchanged or decrease slightly by 5 to 10 per cent for the locations of the mines for the period between 2031-2050 in comparison to the 1961-1990 average precipitation under the RCP 2.6 scenario (Global Climate Model, see Figure 6; Gobierno de Chile, 2016). According to the RCP 8.5 scenario, precipitation projections are similar to the RCP 2.5 scenario, although the area where precipitation is larger (see Figure 6; Gobierno de Chile, 2016).

These results are again underlined by the results of the regional climate model, which show also no or only very small changes of annual precipitation, downscaled for the zones of the mines, with no changes in mean annual values (6 mm per year for the baseline 1980-2010 and the scenario 2050) and

[9] These climate projections are based on a Global Climate Model.

mean minimal annual values (0 mm per year for the baseline 1980-2010 and the scenario 2050), and only very small changes of mean maximal annual values (from 31 mm per year for the baseline 1980-2010 to 29 mm for the scenario 2050) (INFODEP, 2016).

With regard to the locations at the coast, annual mean precipitation is projected to remain unchanged under the RCP 2.6 scenario for the period between 2031-2050 in comparison to the 1961-1990 average precipitation (Global Climate Model, see Figure 6; Gobierno de Chile, 2016). According to the RCP 8.5 scenario, precipitation projections are similar to the RCP 2.5 scenario, although there might be some minor decreases in precipitation (see Figure 6; Gobierno de Chile, 2016).

This picture is underlined by the results of regional climate model, which show a slight decrease of annual precipitation, downscaled for the locations at the coast, from 58 mm to 54mm (INFODEP, 2016). However, it is important to note that the regional projections show that areas with increasing precipitation are located side by side to areas with decreasing precipitation.-

For extreme weather events, there are no downscaled projections publicly available. Especially future trajectories of ENSO remain difficult to project, as it is expected to have a non-linear response to global warming (Power et al., 2013). With regard to extreme rain events, data of past events is very rare as they do not occur often in Chile's northern cost and the Atacama Desert. Due to this lack of baseline data, there is no "sufficient template against which to predict changes in the precipitation regime under future climate scenarios" (Jordan et al., 2015: 4). However, some projections for the northern parts of South America indicate a higher probability for drought events and despite an overall trend of decreasing precipitation, intensifying wet and extreme precipitation events (Aguilar et al., 2005; MMA, 2010). This might – particularly in combination – lead to severe flooding events. Furthermore, some argue that the precipitation event 2015 "might serve as an example of what could be more common in the future, if winter temperatures rise" (Jordan et al., 2015: 4).

There are no regional projections for droughts available, but projections for water stress exist. According to the World Resources Institute, based on the RCP 8.5 scenario, water stress[10] is estimated to increase significantly over the next decades in Chile. While Chile's water stress score was 2.89 (medium-high water stress) in 2010, it is projected to be 3.69 (high water stress) in 2020, 4.09 (extremely high water stress) in 2030 and 4.45 (also extremely high water stress) in 2040 (WRI, 2015b). These figures relate to Chile as a whole and not only to the region of Antofagasta. Yet, according to other studies, the north of Chile is projected to experience most water stress (Valdés-Pineda, 2014).

Sea level change projections are available for the end of the 21th century (Albrecht and Shaffer, 2016). The coastal town Antofagasta is estimated to experience a total sea-level rise of approximately 40 cm to 50 cm for the time period 2081-2100 in comparison to 1986-2005 under the RCP 4.5 scenario. According to the RCP 8.5 scenario, estimations indicate a sea level rise of approximately 55 cm to 75 cm for the time period 2081-2100 in comparison to 1986-2005.

5.6.1 Potential climate impacts on the Escondida mine

The projected climatic changes and extremes could impact the Escondida mining operations, in particular a further decline in water availability and long dry periods followed by wet weather extremes.

The extremely arid region in which the Escondida mine operates is projected to become even drier. Due to the general absence of water, there is usually no potential for the generation of acid rock drainage (Wiertz, 1999). Only if a heavy rain fall event occurs, eventually accompanied by the flooding of mine pits, leach pads and other tailing facilities, soluble accumulated constituents could be flushed

[10] "Water stress is defined as the ratio between total water withdrawals and available renewable surface water at a sub-catchment level. Higher scores on the scale from 0 to 5 correspond to greater competition among water users relative to available surface water resources" (WRI, 2015a).

out (Nordstrom, 2009). The contact of sulfur-bearing rock and tailings with water can possibly lead to the production of sulfuric acid which in turn can dissolve other metals from rock and tailings. Also the sulfuric acid used for the leaching could leak in time of water excess. The flooding of the mining site could not only cause acid mine drainage, but also lead to a decreased or interrupted copper production through preventive closure, damages at the mining site or transport routes. As mass movements depend on various factors (e.g. geological and geomorphological conditions, surface texture, surface coverage with vegetation, etc.), it is not possible to evaluate the potential for erosion and landslides of the pit, leach pads and tailing facilities during rain and flood events.

As the mining and processing require large inputs of water, drier conditions can further exacerbate the current water shortage, either in terms of physical availably or due to officially imposed water restrictions. The withdrawal of freshwater from highly biodiverse places in the mine's vicinity or groundwater sources might be limited or prohibited under such conditions. Thus, the mine is expected to face a substantially reduced freshwater supply, which potentially could decrease its productivity. Further, less water might be available for particulate matter and silica dust suppression, which would increase the negative health impacts for mine workers. Such water shortages might be circumvented if the use of desalinated sea water and recycled water is increased as planned by the mining company.[11]

Increased mean temperatures as well as decreased precipitation are not expected to exacerbate environmental impacts or the security of supply as the projected changes are marginal.

5.6.2 Potential climate impacts on the pipeline and railway connecting the mining site and the port

Flooding and landslides that are caused by extreme weather are the most relevant direct climate impacts on the railway which connects the mine to the port. As shown in the past, flooding and landslides could cause damages to the railway, leading to decreased or interrupted transportation of copper cathodes to the ports of Antofagasta and Mejillones. The slurry pipelines are not expected to be affected by flooding or landslides as new pipelines were built in 2014 that run inside a tunnel. Therefore, the transportation of copper concentrate from the mine to the filter plant and port is not expected to be affected by climate change impacts.

The projected climate changes are not expected to increase the minor environmental impacts and hazards of the slurry pipelines or railways.

5.6.3 Potential climate impacts on the copper concentrate filter plant at Puerto Coloso and the desalination plant

The main potential climate change impacts expected at the copper concentrate filter plant are related to flooding and wind. However, these extreme events are hard to project, especially in areas which are affected by factors such as ENSO which are expected to have non-linear response to global warming. In the case of Chile, no regional projection for wind and extreme rain events was publicly available.

Water excess or flooding caused by heavy rain or sea water could lead to a spill of copper concentrates into the sea which would be toxic for aquatic life which is highly biodiverse at Coloso port (Irwin, 1997). Copper sulphide compounds have been classified by several mining companies as environmentally hazardous, although they have low solubility in water (e.g. cf. Prominent Hill Material Safety Data Sheet, 2011). Increased winds could intensify dust fallout from the copper concentrate storage and conveying.

The production at the copper concentrate filter plant could be decreased or interrupted by flooding and wind and therefore negatively impact the supply.

[11] However, by using desalinated sea water, the energy use of the mining project might increase.

5.6.4 Potential climate impacts on the ports in Antofagasta, Mejillones and Coloso

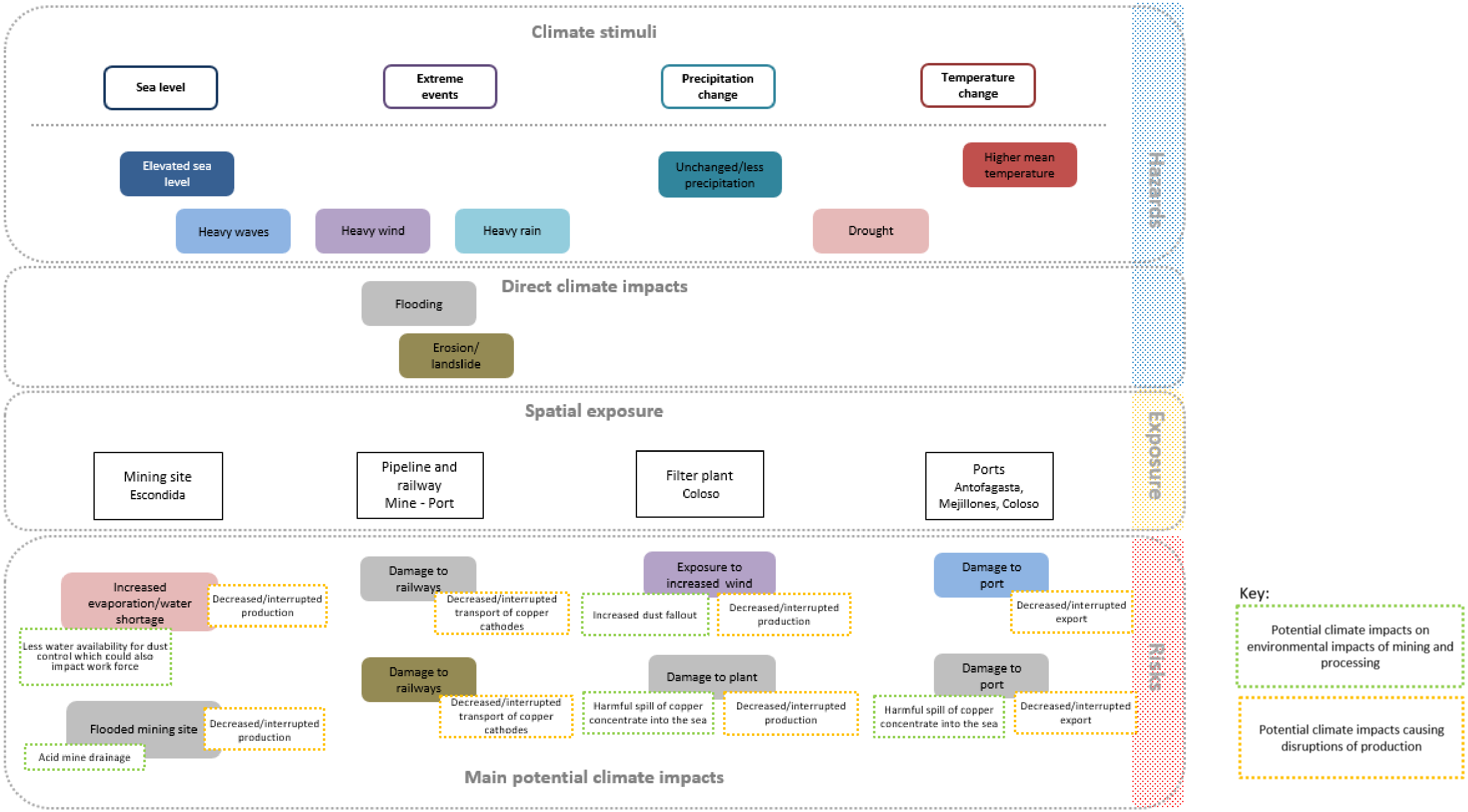
The main potential climate impacts for the ports of Antofagasta, Mejillones and Coloso could be caused by more intense extreme weather events, in particular heavy wind and rain, which can cause heavy waves, leading to the flooding of coastal areas. However, these extreme events are hard to project, especially in areas which are affected by factors such as ENSO which are expected to have non-linear response to global warming. In the case of Chile, there are also no regional projections for wind and extreme rain events publicly available.

The risk of coastal flooding is exacerbated by elevated sea levels. As described in foregoing section on climate impacts on the filter plant, water excess or flooding caused by heavy rain or sea water could lead to an environmentally harmful spill of copper concentrates. A spill at the ports where copper cathodes are shipped is not expected to have adverse environmental impacts. Furthermore, flooding could lead to damages to the ports which might result in decreased or interrupted exports.

As precautionary measure, ports can be instructed by the Maritime Authorities to halt operations when there is warning for bad weather, including heavy waves (OECD and ITF, 2016). This minimises the risk of damage but leads to an interruption of exports.

Based on the sea level projections for 2080 to 2100 under a higher emission scenario, sea level rise could harm the ports operations, unless adaptive measures are taken. The port of Antofagasta is currently building a breakwater for 6-meter high waves (standard biggest wave in 100 years), primarily as protection from tsunamis caused by earthquakes (OECD and ITF 2016). Yet, this measure can also help to adapt to rising sea levels.

Figure 7: Climate impact chain for copper



The diagram illustrates the specific climate stimuli, the spatial exposure, the direct climate impacts and the potential climate impacts. In order to visualise the links between these components of the climate impact chain, the colours of the frames of the potential climate impacts are used accordant to the corresponding climate stimuli and direct climate impacts.

6 Case study: lithium mining

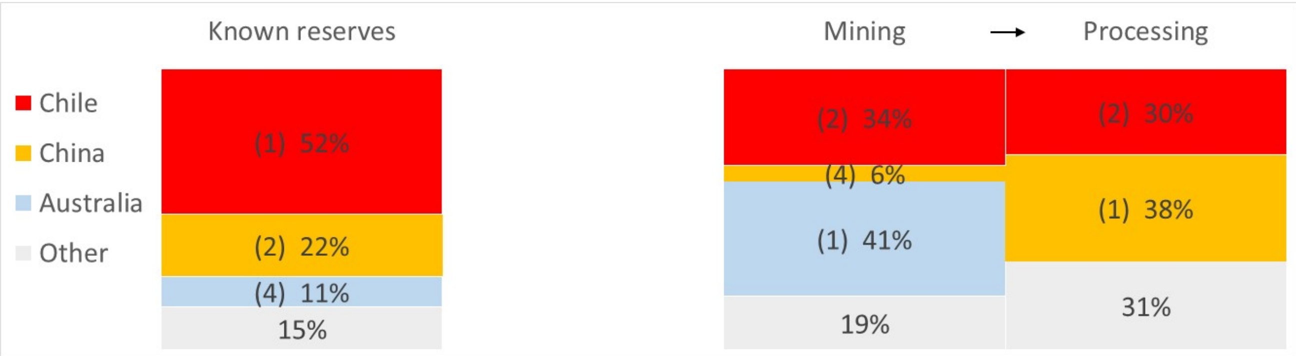
6.1 The global value chain of lithium

Lithium is an alkali metal that under standard conditions is the lightest of all metals. Being the most electronegative metal with excellent electrical conductivity, lithium is ideal for use in batteries. As lithium-ion batteries store more energy per weight and volume (SQM, 2017c) than other metals they have a higher energy density than traditional batteries. The lithium-ion battery global market is growing rapidly due to new technological developments, particularly for application in electric vehicles and as energy storage for industrial and domestic use (USGS, 2017b). It is forecasted that battery consumption will grow more than five times from 2015 to 2025, and triple the global demand for lithium (an equivalent of more than 11 per cent of annual growth rate) (Deutsche Bank, 2016). Application in batteries was estimated as the major industrial use of lithium and its compounds in 2016 (39 per cent), followed by more traditional applications such as heat-resistant glass and ceramics (30 per cent), grease lubricants, flux additives for iron, steel and aluminium production, and others (USGS, 2017a).

Lithium is recovered from both mineral deposits (mainly from pegmatites or hard rock) and from salts, largely from lithium-rich brines in salt lakes (Geoscience Australia, 2014). According to the US Geological Survey, the world reserves of lithium exceed 14 Mt, with Chile accounting for 52%, followed by China (22 per cent), Argentina (14 per cent), and Australia (11 per cent) (USGS, 2017b). Most of the known brine deposits are located in Chile, China, Argentina, and Bolivia, while hard rock deposits are found in Australia and Canada.

With increasing demand for lithium, exploration for lithium deposits continues worldwide, and the current identified world's lithium resources are close to 50 Mt, with leading positions being held by Argentina and Bolivia – about 9 Mt each, followed by Chile (7.5 Mt) and China (7 Mt) (USGS, 2017b).

Figure 8: Lithium global value chain and ranking for selected countries (2016)



Note: figures in brackets show the country's global ranking. Data sources: USGS, 2017b.

In the case of hard rock mining, lithium is often produced in the form of (spodumene) concentrate which requires further processing (Geoscience Australia, 2014). In the salt brines case, concentrated lithium brine is extracted from salt pans ('salar') first, followed by lithium carbonate production. The latter is the major lithium semi-product, also used for comparative purposes in industry statistics as lithium carbonate equivalent (LCE). Lithium carbonate can be directly used in industrial applications such as additives to glass and ceramics and production of lithium cathode materials for batteries, or can be processed further into other products.

6.2 Site-specific overview – Salar de Atacama in Atacama Desert

The Salar de Atacama is the largest salt flat in Chile, surrounded by mountains with no drainage outlets, covering about 3000 km^2 at an average elevation of about 2,300 m above sea level. It contains one of the largest and best quality reserves of lithium from brines. These brines were formed through natural leaching from the Andes Mountains, containing elevated concentrations of several minerals including those of potassium and lithium. The Salar de Atacama has several advantages for minerals extraction: high lithium concentration in the brine (0.1-0.3 per cent); reduced magnesium content to minimize processing costs; higher evaporation rates than other salt plains in the world (3,500 mm/year); and the opportunity to operate all year round due to favourable weather conditions (SQM, 2017b).

The Salar de Atacama currently hosts the world's largest lithium brine mining operations, owned by SQM. The extracted lithium brine is transported to SQM's Salar del Carmen lithium processing plant, near Antofagasta. The annual production capacity of the lithium carbonate plant is 48,000 t/year (increasing to 63,000 t/year in 2018); part of this output is processed further into lithium hydroxide (a higher value added product), with current capacity of 6,000 t/year (13,000 t/year since 2018) (USGS, 2017b). With the current level of production, the reserves of the salar that belong to SQM will last for at least 30 more years (SQM, 2017b).

6.2.1 Overview of transportation systems and routes

At the Salar de Atacama operations, SQM produces concentrated lithium brine, which is transported on trucks to the Salar del Carmen Lithium processing plant, near the city of Antofagasta. The final products – lithium carbonate and hydroxide – are exported worldwide from the port of Antofagasta.

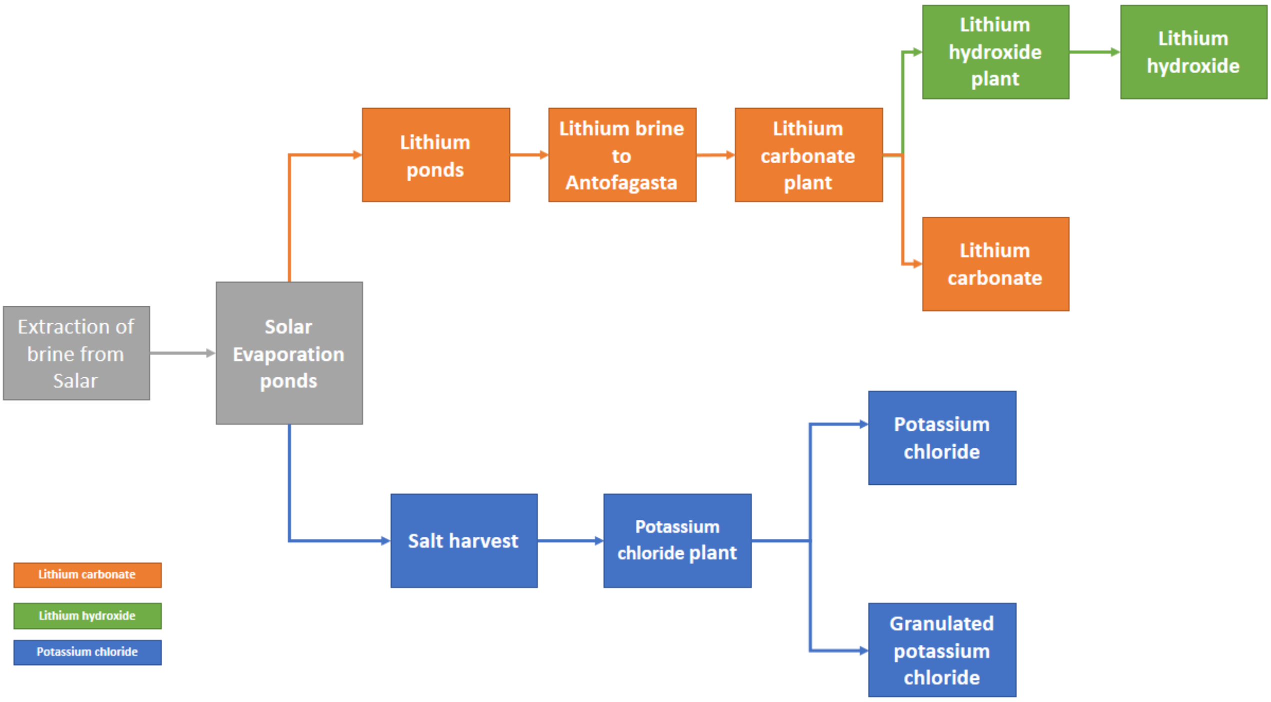
6.3 Extraction and processing technologies

6.3.1 Extraction and processing technologies at Salar de Atacama

The underground lithium brines are typically accessed through brine wells drilled into the brine aquifers, and the first step in processing is to concentrate the brine. At SQM, lithium production is based on lithium chloride solutions obtained as a by-product of the production of potassium chloride. The lithium and potassium rich salar brines are pumped into solar evaporation ponds, which cover an area of about 1,700 ha (SQM, 2017b). There are 384 wells which pump between 0.3 to 200 litres of brine per second (SQM, 2017d). The size of these ponds, high evaporation rates, amount of solar radiation, wind, humidity and temperature are essential for the economically effective operation. Located at the Salar de Atacama, one of the driest places on earth, SQM has an extremely efficient evaporation process compared to other lithium processors.

Lithium is more soluble than other elements found in the brine, therefore other salts will precipitate first leaving the brine enriched in lithium. The brine is pumped through a series of evaporation ponds: the sodium chloride precipitates first, then a mixture of sodium chloride and potassium chloride is precipitated and harvested for further separation. The remaining lithium rich concentrated solution is transported to the SQM's Salar del Carmen processing plant near Antofagasta, while the unused brines are re-injected back into the salt flats (SQM, 2017b). At the processing plant, the brine is treated with sodium carbonate to precipitate a lithium carbonate slurry, which is then filtered and washed to remove residual sodium chloride, and finally dried to a pure lithium carbonate product.

Figure 9: Schematic of lithium and potassium mining at Salar de Atacama



Source: Own graphic, based on SQM, 2017b.

6.4 Environmental impacts and mitigation measures

6.4.1 Salar de Atacama lithium mining area

Land use

One of the most significant environmental impacts of lithium production is land use. In the case of a desert environment, land clearing usually results in a minimal loss to ecosystem compared to mining in other types of environment. The major land use at lithium brine mining operations is associated with evaporation ponds which are lined with PVC geomembranes (Berube et al., 2007). High lithium concentrations in the brine, which are sourced from underground, as well as high evaporation and low precipitation rates all improve the efficiency of the process. As all these conditions are favourable at SQM's operations in the Salar de Atacama, the size of the evaporation ponds are highly effective for the levels of production.

Water use

Water is a very scarce resource in the desert climate where SQM operates. The total water consumption (mainly as underground water from a large number of extraction points in the area) at SQM's Salar de Atacama production facilities (for both lithium brine and potassium chloride) was 5,860 ML in 2016 (SQM, 2017c). Most of this water is used for potassium chloride production. To maximize water efficiency, all water treated in SQM sewage treatment plants is incorporated into its production processes, while process solutions are reutilized to reduce fresh water use (SQM, 2017a).

Most of the valuable ecosystems are located in the peripheral zone of the salt flat, mainly upstream, north from SQM's mining operations. According to a peer reviewed study financed by SQM, there is no scientific evidence that the extraction of fresh water and brines in the Salar de Atacama basin have greatly affected the ecosystems in the area (Ortiz et al., 2014). However, the study also states that brine and groundwater extraction is considered the major potential risk to the unique flora and fauna in the area, thus it requires thorough monitoring and further research (Ortiz et al., 2014). In addition, local communities and organisations raise concerns that flamingo populations in the area are adversely affected by reduced water levels in the salt flats as well as an altered mineral content in the water caused by the fresh water and brine extraction (Millan Lombrana, 2016; Butcher, 2017). This underlines that more research at the local level is needed to fully understand the scope of the impact of brine and freshwater extraction for the ecosystems and local communities.

Energy use

The SQM's energy use include solar energy, electricity obtained from the Chilean Great North Interconnected System (SING), and fuels such as oil and natural gas (SQM, 2017a). Solar energy plays the most important role in lithium production from brines. High radiation and high rates of water evaporation in the Atacama desert makes SQM's lithium operations the most cost effective and efficient in the world (SQM, 2017a). It is estimated that solar energy accounts for more than 90% of all energy consumed in SQM's facilities (87,625 TJ), followed by electricity (1,867 TJ) and diesel use (1,456 TJ) (SQM, 2017c).

Mine waste

Lithium recovery from brines allows a nearly zero-waste mining compared with mining from hard rock deposits (Lithiummine.com, 2017). There is no overburden produced during brine extraction, and after the recovery of potassium and lithium salts, the remaining brines – a sodium chloride solution – can be re-injected back into the salt flats (SQM, 2017b).

Emissions

Mining and mineral processing operations can generate significant dust emissions creating a health hazard for workers as well as potentially affecting local communities. The underground extraction of lithium in the form of brine prevents a direct cause of dust, however the use of evaporation ponds to harvest salt products as well as transportation on trucks still may contribute to dust generation. The SQM's emissions control measures include covering trucks with tarps during transport of bulk products, installing abatement equipment at plants for particulate matter and gases, and wetting roads for dust control at mine sites (SQM, 2017c). The company also regularly discloses its emissions and air quality monitoring information to authorities (SQM, 2017c).

Relying on solar energy based processes, the SQM's GHG emissions are relatively low. The company estimates its total aggregated carbon footprint, without disclosing information for specific products. For all mineral extraction and processing operations, including domestic and international transport, SQM's GHG emissions were estimated at less than 1 Mt of CO_2 eq. per year over 2014-2016, including 618,341 tons of CO_2 eq. in 2016 (SQM, 2017c).

Biodiversity

The activities of SQM's operations in the Salar de Atacama do not result in significant impacts on biodiversity because of the geographic and climatic conditions. The environmental protected areas, Soncor and Aguas de Quelana sectors of the National Flamingo Reserve, which are closest to the mine site are several dozen kilometres away.

There are several claims that brine and freshwater extraction harm the flamingo populations living in the protected areas (see section on water use). However, it is difficult to attribute the impacts to SQM's operations and further research is needed.

The company has developed environmental monitoring and contingency plans for the safeguarding of these protected areas (SQM, 2017a). This includes on-going hydro-geological monitoring and biotic monitoring for flora and fauna, soil moisture and aquatic life in lake systems at the Salar de Atacama, using direct on-site measurements and high-resolution satellite images (SQM, 2017a).

Rehabilitation

The SQM mine closure plans are based on criteria and measures according to Chilean environmental regulations, and have been approved by the respective authorities (SQM, 2017c). Based on the value of these closure plans, the company provides performance bonds (i.e. financial assurances) to the SERNAGEOMIN (SQM, 2017c).

Health

No health related impacts from lithium mining in the Salar de Atacama have been reported to date.

6.4.2 SQM's Salar del Carmen processing plant (lithium carbonate and hydroxide production)

The lithium carbonate and lithium hydroxide operations generate relatively small environmental impacts compared to the mining stage.

Land use

The processing plant includes several lithium brine reservoirs. Compared to the land use linked to the evaporation ponds at the Salar de Atacama operations, the land use of the processing plant is insignificant.

Water use

Importantly, as a source of industrial water supply, the Salar del Carmen operations use treated domestic liquid waste from the city of Antofagasta. The total reported water use in 2016 was 590 ML.

Energy use

The energy use is primarily associated with electricity and natural gas (SQM, 2017c). SQM does not disclose information on energy use for individual facilities and/or products.

Waste and emissions

This includes minimal solid waste (with a potential to be reused as construction materials), minor water effluents and dust emissions. The residual liquid waste is disposed into the public sewer system (SQM, 2017c).

Biodiversity

No information available.

Rehabilitation

Not applicable.

Health

No information available.

6.5 Current climate impacts and risks

Current climate

The Salar de Atacama is a salt flat covered with sparkling salt-encrusted rocks. The annual rainfall in the area is only a few mm a year, while evaporation rates are about 3,500 mm/year (Lithiummine.com, 2017).

Table 2: San Pedro de Atacama[12] - monthly mean rainfall

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	22	5	2	2	1	0	0	0	3	3	1	3

Source: Climate-Data, 2017b.

Past weather extremes

Also lithium mining was affected by the extreme wet weather event in March 2015 (see also chapter 5.6). SQM Salar de Atacama lithium operations were halted as a preventative measure. After transport roads and electrical damage were repaired, the operations resumed (Moores, 2015).

6.6 Climate change impact assessment[13]

For current and projected climate changes, please see chapter 5.6. As the positions of the Escondida mine and the SQM Salar de Atacama lithium mine are very close to each other (same is true for the processing facilities and ports), climate change projections are similar.

6.6.1 Potential climate change impacts on lithium mining

The projected climatic changes could impact the SQM lithium operations, in particular a further decline in water availability, increased mean temperatures, flooding events and strong wind. However, these extreme events are hard to project, especially in areas which are affected by factors such as ENSO which are expected to have non-linear response to global warming. In the case of Chile, no regional projections for wind and extreme rain events were publicly available. While drought and flooding could potentially have negative impacts on environmental impacts and security of supply, an increased mean temperature as well as more wind could impact the mining operations positively.

Drier conditions can further exacerbate the current water shortage, either in terms of physical availably or due to officially imposed water restrictions. The withdrawal of fresh water[14] and the extraction of brine in combination with increasing water stress could negatively impact the environmentally protected areas in the mine's vicinity, as ground water aquifers are generally connected. Yet, the link between brine extraction, freshwater extraction and the ecosystems in the area is highly complex, not well understood and requires further research (Ortiz et al., 2014; Butcher, 2017).

Flooding could wash out minerals from the evaporation ponds, yet this is not expected to have adverse environmental impacts as the soil and groundwater show high mineral contents anyway. However, a flooding of evaporation ponds can lead to a slowing of the evaporation process or could disturb the production process through damages at the site.

An increased mean temperature and stronger winds could potentially accelerate the evaporation process and therefore positively impact lithium processing (see Garrett 2004).

[12] San Pedro de Atacama is the nearest town to the edge of the Salar de Atacama (about 10 km to the northern boundary).

[13] For an overview see Figure 10.

[14] Mostly required for potassium production.

6.6.2 Potential climate change impacts on transport routes

Extreme wet events which could lead to flooding and mass movements (erosion and landslides) are expected to be the main potential climate impact on the transport routes which connect the mining site to the Salar del Carmen processing plant. As shown in the past, flooding and landslides could cause damages to the route, leading to decreased or interrupted transportation of lithium brine to the plant.

6.6.3 Potential climate change impacts on the processing plant

There are no potential negative climate impacts expected at the Salar del Carmen processing plant.

As all water used at the processing plant is recycled domestic water, drought is not expected to impact the plant's supply with water. Flooding of lithium brine reservoirs and a potential spill of lithium brine is not expected to have severe adverse environmental impacts as its environmental toxicity is low and does therefore not pose a large threat to flora and fauna (Aral and Vecchio-Sadus, 2007).

6.6.4 Potential climate change impacts on the port of Antofagasta

As described in foregoing section on climate impacts on copper shipping (chapter 5.6), the main potential climate impacts for the port of Antofagasta could be caused by more intense extreme weather events, in particular heavy wind and rain, which can cause heavy waves, leading to the flooding of coastal areas. However, there are no regional projections for wind and extreme rain events publicly available.

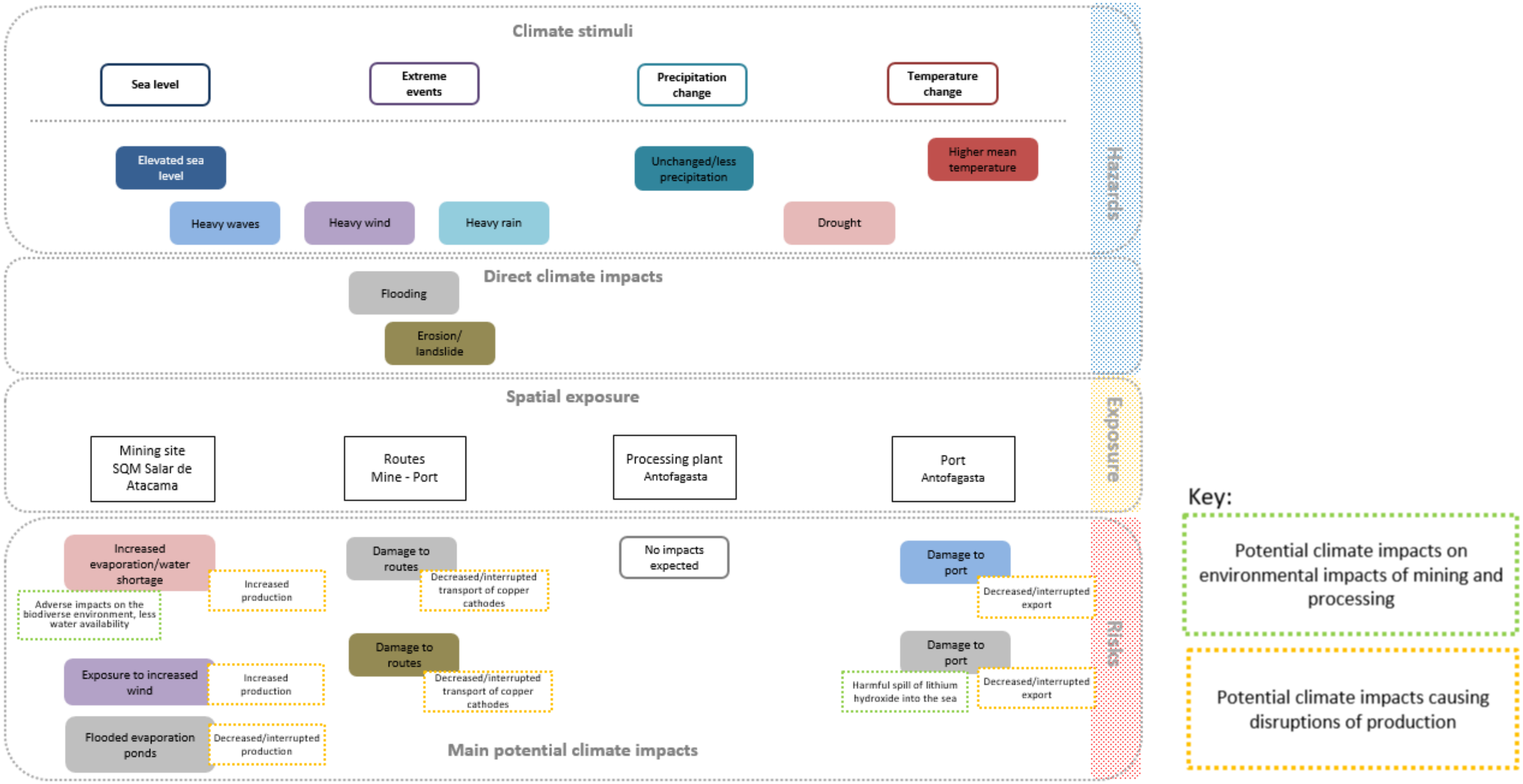
The risk of coastal flooding is exacerbated by elevated sea levels. Water excess or flooding caused by heavy rain or sea water could lead to a spill of lithium products. A spill of lithium hydroxide into the sea would be harmful for aquatic life (PubChem, 2017b), whereas lithium carbonate is not reported to be environmentally hazardous (PubChem, 2017a).

Furthermore, flooding could lead to damages to the ports which might result in decreased or interrupted exports.

As precautionary measure, ports can be instructed by the Maritime Authorities to halt operations when there is warning for bad weather, including heavy waves (OECD and ITF, 2016). This minimises the risk of damage but leads to an interruption of exports.

Based on the sea level projections for 2080 to 2100 under a higher emission scenario, sea level rise could harm the ports operations, unless adaptive measures are taken. The port of Antofagasta is currently building a breakwater for 6-meter high waves (standard biggest wave in 100 years), primarily as protection from tsunamis caused by earthquakes (OECD and ITF 2016). Yet, this measure can also help to adapt to rising sea levels

Figure 10: Climate impact chain for lithium



The diagram illustrates the specific climate stimuli, the spatial exposure, the direct climate impacts and the potential climate impacts. In order to visualise the links between these components of the climate impact chain, the colours of the frames of the potential climate impacts are used accordant to the corresponding climate stimuli and direct climate impacts.

7 Summary and conclusions

Chile extends over several climate zones and often faces weather extremes and geological hazards. The Atacama Desert, where the copper and lithium production sites assessed in this study are located, is characterized by extreme aridity. Yet, climate patterns in the Atacama are complex and under specific conditions periodic rain events can take place. March 2015 was marked by such an unusual climatic event. After almost ten years with hardly any rain, Chile's north – including the Atacama – experienced three days of heavy rain, causing severe flash floods which also impacted the copper and lithium production, mainly by interrupting production and damaging transport routes.

Because of various geographical and meteorological characteristics, the accurateness of the climate projections available for the Atacama is limited. Nevertheless, a number of potential climate change impacts for the mining and processing sites as well as transport infrastructure can be identified. Based on the available climate projections, the region is expected to experience an increase in the mean temperature in the future. Mean precipitation is projected to remain unchanged or to decrease slightly. There are no downscaled projections for extreme weather events. Yet, based on larger scale projections, higher water stress and intensifying wet weather extremes can be expected. However, the exact likelihood of extreme weather events and temperature and precipitation changes remain uncertain.

Environmental impacts of mining and processing

The case study identified the following central environmental impacts resulting from copper and lithium mining and processing operations:

Copper: The Escondida copper mining operations have a very large land footprint. Yet, the region is sparsely populated and therefore competition over land use is not prevalent.

As water is a very scarce resource in the arid Atacama and at the same time a crucial input for the mining operations, freshwater extraction from the surrounding aquifers has a significant environmental impact, potentially affecting the local biodiversity. The use of desalinated seawater attempts to address this issue, yet it does only partly replace the use of freshwater.

The mining operations further require extensive energy inputs, not only for ore extraction and processing, but also for seawater desalination and the pumping of desalinated water from the coast to the mining site.

The copper mining and processing generates large amounts of mining wastes (waste rock, spent ore and tailings). The tailings facilities are relatively new and constructed to prevent breaching or leakage. As most water is recovered, the mining operations and processing do not produce significant waste water. The potential for acid mine drainage is generally low, due to the arid conditions at the mining site. Major health impacts for workers derive from respirable silica (generated during blasting) and acid mist (generated during heap leaching). The mining company seeks to minimize the adverse health impacts through technical prevention measures.

The copper concentrate filter plant at Puerto Coloso has less environmental impacts than mining and processing operation at the Escondida mining site. The waste water at the filter plant is discharged deep into the Pacific Ocean, yet this is not expected to negatively affect the marine ecosystem and biodiversity. The handling and loading of copper concentrate into ships entails dust generation. However, there are no reported health impacts.

Lithium: The environmental impacts of lithium mining and processing are much smaller compared to the impacts of copper mining and processing. The major land use of lithium production is associated with the large fields of solar evaporation ponds.

The lithium operations are located in a wide salt flat (Salar de Atacama) which is, similar to the area around the Escondida copper operations, sparsely populated. Water scarcity is also prevalent at the lithium operation site. The lithium processing itself does not consume groundwater (the Salar del Carmen lithium processing plant uses treated domestic liquid waste). However, the lithium production is currently a by-product of potassium chloride production which requires large water inputs, sourced from groundwater extraction points in the area. The water extraction takes place in a biodiverse and water scarce environment. Yet, data and studies are lacking to understand the complex hydrological system of the Salar and to fully assess the impacts of groundwater extraction and/or the extraction of brine by mining operations on local ecosystems and water availability for local communities.

Energy use is significantly lower for lithium mining and processing and almost all energy is generated by solar power. The lithium mining and processing does not generate significant waste. Emissions are mostly related to dust from evaporation ponds and transport. Yet, there are no reported health impacts for workers.

Climatic changes potentially aggravate environmental impacts of mining and processing

In the Atacama, climatic changes, especially projected water stress, are expected to aggravate current environmental impacts of copper mining and processing. Wet weather extremes are also expected to exacerbate or cause some environmentally adverse impacts. Lithium mining and processing is expected to be less affected by climatic changes.

Copper and lithium[15] mining operations extract large quantities of fresh water and brine from unique biodiverse places. Therefore, a further decline in water availability increases the risk of negative impacts of groundwater and brine extraction for the surrounding sensitive ecosystems and local populations. Further, less water might be available for dust suppression and therefore increase the negative health impacts for workers.

If a very dry period is followed by an extreme wet event, this can have environmentally adverse consequences for copper mining operations in the Atacama. The generally low potential of acid mine drainage at the Escondida copper operations is expected to increase in case of an extreme wet event. A flooding of the lithium evaporation ponds is not expected to have adverse environmental impacts.

The environmental consequences of flooding, leading to a spill of copper and lithium products, are estimated to vary, depending on the product. While a spill of copper cathodes into the water is not expected to be environmentally harmful, spilled copper sulphide compounds are classified as environmentally hazardous. A spill of lithium hydroxide into the sea is expected to be harmful for aquatic life, whereas spilled lithium carbonate is not reported to be environmentally hazardous.

Water scarcity and wet weather extremes adversely impact security of supply

Water scarcity and extreme wet events are also expected to have an impact on the production of copper and lithium in Chile. As 30 per cent of the global copper production and 30 per cent of the global lithium production currently originates from Chile, this could impact the global security of supply of both materials.

As the copper mining and processing require large inputs of water, drier conditions can further exacerbate current water shortages, either in terms of physical availably or due to officially imposed water restrictions. As production processes might have to be slowed or halted, a significant reduction of water availability could lead to a reduced supply of copper. As not much freshwater is required for lithium production, a decoupling from water-intensive potassium chloride production would reduce the supply risks of water shortages on lithium supply. The feasibility of decoupling lithium from potassium chloride production remains to be studied. A further increase in desalinated water production might be

[15] Fresh water is mostly required for the production of potassium chloride and not for the lithium processing.

required to overcome shortages of extracted freshwater with potentially negative impacts in terms of GHG emissions (unless renewable energies are used to fulfil the significant energy demand of desalination).

Flooding and associated mass movements can partly interrupt the production and transport of copper and lithium products. Such events could hinder copper mining operations, slow down the evaporation process of lithium brine, cause damages at both mining sites as well as to railways and transport routes. The pipelines which carry copper concentrate to the port are not expected to be negatively affected by flooding or mass movements.

An increased mean temperature and stronger winds could potentially have positive impacts on the production of lithium, as the evaporation process might accelerate.

Bad weather or strong waves could lead to halted operations or damages at ports which might result in decreased or interrupted exports. The specific impacts of sea level rise on ports or mining sites that are near the coast are uncertain for the near future. Yet, at the end of the century ports are expected to face elevated sea levels, which will require new protection measures. As protection from tsunamis, the port of Antofagasta is currently building a high breakwater which also helps to adapt to rising sea levels.

Challenges ahead in mining sector governance

Chile's disaster risk management and climate change adaptation policies, and environmental and water governance and with it several important government institutions have developed substantially over the last decades. However, especially the environmental authorities lack capacities to adequately regulate the sector, while the water management system needs reforms to improve the sustainable use of water. This is particularly important in the face of the aggravating water scarcity in the north of Chile.

Although the mining sector contributes significantly to the country's national economy, the sector is regularly provoking conflicts around the infringement of community rights, negative environmental impacts of mining operations, water and energy use, the sharing of mining benefits and labour conditions. The mining companies assessed in this study were both involved in various disputes, ranging from opposition to water extraction (Escondida) and environmental breaches (SQM), to labour disputes (Escondida) and corruption (SQM).

In the context of this strained relationship with the civil society, both mining companies engage in community activities and contribute to environmental monitoring. Furthermore, BHP Billiton seeks to implement technical innovations to improve their environmental conduct and prepare for adverse climatic impacts in the future, e.g. through increasing the use of desalinated water and developing a climate adaptation action plan. Yet, the scrutiny of the public as well as of government authorities remains of outmost importance to increase the sustainability of mining operations in the Atacama.

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