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Economic Effects of planetary boundaries on metal mining: CO2 emissions case study

Ana Maria Gomez

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Master Thesis

Economic Effects of planetary boundaries on metal mining: CO_2 emissions case study

Ana María Gómez Cuartas

Supervisor: Dr. Peter Moser

Co-Supervisor: Ing. Michael Tost

Date(02/10/2019)

Chair of Mining Engineering and Mineral Economics
Department Mineral Resources Engineering
Montanuniversitaet Leoben

A-8700 LEOBEN, Franz Josef Straße 18
Phone: +43 3842-402-2001
Fax: +43 3842-402-2002
bergbau@unileoben.ac.at

Declaration of Authorship

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Signature Author
Ana Maria, Gomez
Matriculation Number: 11722919

Preface, Dedication, Acknowledgement

First of all, I wish to express my gratitude to God who is my reason, my guide and my most wonderful provider. Thanks, are also extended to Michael Tost for his advice, time, guidance, patience and always positive attitude in the preparation of this thesis. I would also like to give a special recognition to Richard Biastoch who took the time to review this master thesis and gave very valuable suggestions.

This was a great experience that made me grow as a professional by giving me a holistic view of mining and its whole life cycle. I was able to learn about the extractive industry in different countries and to build up an international network across my peers. I specially dedicate this achievement to my mother and sister who are my biggest support. I also strongly appreciate the prayers from my family and friends from Colombia.

Thanks to the AMRD group 2017 who I consider now as my family too. Thank you to each one of you for making this a breath-taking experience, wherever I'll be you have a home. I wish to highlight the priceless friendship that grew up with Linda, Juan Carlos, Felipe, Panashe, Kudzai and Sahan Gül. My gratitude is also extended to Dianita, Dieguito, Edwin, Ozan, Berkay and Vanessa, for their friendship and support.

Abstract

This master thesis calculates the hypothetical economic impacts on revenues and profits of 16 of the largest producers of copper, aluminium (bauxite ore), gold, and iron ore, if some key planetary boundaries were appropriately costed. For this, the author conducted literature research in order to compile prices of water, land-use change and CO_2 that are given under global constraints. Firm's annual and sustainability reports were also assessed in order to extract information about the emissions and other environmental pressures associated with their activity. Due to the difficulties to define planetary boundaries and prices for land use and water, the author uses CO_2 as a study case. Nevertheless, regional examples for water and land use valuation are given.

The results show, that costs of CO_2 emissions per ton of copper, aluminium (bauxite ore), iron ore and gold vary highly; mainly due to the wide range of prices per ton of CO_2 across the different studies. It becomes apparent that an appropriate costing of released carbon emissions would significantly diminish certain companies' revenues. The applied methodology may allow for a more in-depth analysis within the mining industry or other industries and can inform targeted environmental policymaking and taxation in the future.

Keywords: Planetary boundaries; emissions; valuation; CO_2 pricing.

Zusammenfassung

In dieser Masterthesis wird der hypothetische, ökonomische Effekt einer angemessenen Einbeziehung der planetaren Grenzen auf Umsätze und Profit von sechzehn der weltweit größten Produzenten von Kupfer, Aluminium, Gold und Eisen analysiert. Hierfür führte die Autorin eine umfassende Literaturrecherche durch um die Preise von Wasser, Landnutzung, und CO_2 zu ermitteln. Informationen bezüglich der Emissionen und der adversen Umwelteinflüsse wurden aus Jahres- sowie Nachhaltigkeitsberichten der Bergbaufirmen entnommen.

Aufgrund des, in dieser Arbeit illustrierten, Mangels einer anerkannten Definition der planetarischen Grenzen und den damit verbundenen Preisen für Wasser- und Landnutzung, führt die Autorin eine ausführliche Fallstudie für CO_2 durch. Es werden dennoch einige Studien für die regionale Land- und Wassernutzung aufgeführt.

Die Ergebnisse der Analyse zeigen, dass die Kosten für CO_2 Emissionen pro Tonne Kupfer, Aluminium, Eisen und Gold stark variieren; einerseits Aufgrund der Unterschiede im Abbauverfahren, aber im Besonderen aufgrund der in der Literatur aufgeführten Bandbreite von Preisschemata pro Tonne CO_2 Emission. Eine angemessene Anrechnung der Kosten der Kohlendioxidemissionen würde somit die Umsätze einiger Firmen signifikant beeinträchtigen. Die für diese Arbeit entwickelte Methodologie ermöglicht eine tiefgreifendere Analyse für den Bergbau oder anderer Industrien und kann gezielte Umweltpolitik und Besteuerung informieren.

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1 Introduction

The disturbance of Earth System Processes by human activity has brought serious consequences for the environment such as mass extinction of plants and animal species, ocean pollution and alteration of the atmosphere (Stern, 2007). Some scientists suggest that the *"Anthropocene"* has replaced the Holocene geological epoch in which we were living in for the last 11,700 years (Stromberg, 2013). Steffen et al. (2007) defines the Anthropocene as *"the current epoch in which humans and our societies have become a global geophysical force".* The beginning of that period of time is placed in the industrial revolution, in which the use of fossil fuels significantly increased, adding considerable CO_2 emissions to the atmosphere (Steffen et al., 2007; Grubler et al., 2014).

Regardless of the progress in scientific knowledge and consensus about resources depletion and major environmental threats, humanity has not made significant changes in their lifestyle (Wikjman et al., 2012). Rockström et al. (2009), analyse the levels of anthropogenic perturbation with the purpose to identify thresholds that shall not be trespassed in order to prevent undesirable shifts in environment dynamics. The authors define nine planetary boundaries, seven of them are able to be quantified. The level of uncertainty of each planetary boundary compromises the Earth Systems stability, thus the capacity to remain *"- a safe operating space for a societal development"* (Steffen et al., 2015).

The implementation of planetary boundaries represents a challenge for policy makers and industry. Clift et al. (2017) manifest the difficulties on the identification of limit levels for different geographical scales. According to the authors, the fair shares allocation across the value chain is also a concern, as well as the requirement of international organizations to work on the formulation and implementation of the necessary tools to maintain within the planetary boundaries.

Implementation challenges are intended to be approached by international agreements such as the Sustainable Development Goals (SDGs) (Planetary

Boundaries Initiative, 2015), launched by the United Nations and adopted by world leaders in the year 2015, introducing the planetary boundaries into the world's agenda (Planetary Boundaries Initiative, 2015). This concept has been also introduced in the United Nations High-Level Panel on Global Sustainability and World Wildlife Fund for Nature (Heistermann, 2017). The author of this master thesis conducted a literature review in order to identify implemented global thresholds for climate change, land use and water use. Only climate change, from the assessed planetary boundaries, offers an international threshold. The Paris Agreement has as target to prevent Earth's temperature to rise above 2 ºC, from pre-industrial levels, and to make further efforts to stay within 1.5 ºC.

Firms and industry also play an important role concerning the achievement of planetary boundaries. The link between firms and boundaries are represented by the impact of global limits to business, in terms of supply chain disruption, increase in operation costs due to more strict policies compliance, resources scarcity and raw materials availability (University of Cambridge, 2019). There is a growing tendency for firms and companies to undertake corporate sustainability studies and voluntarily report about the environmental and social impact of their economic activity (Whiteman et al., 2012). Whiteman et al. (2012) recognized that companies are moving beyond reputation as a reason to integrate sustainability. According to the authors, firms are also acting to reduce their ecological footprint by reducing energy, emissions and waste from operations. This is the case for the mining sector, which has a dominant position in terms of possibilities to mitigate global environmental threats (Whiteman et al., 2012). For this master thesis, the annual and sustainability reports of 16 large-scale metals mining companies that produce iron ore, gold, copper and aluminium (bauxite ore) are assessed, and information about their emissions, environmental demand of land and water as well as economic indicators such as revenues and profits is extracted.

The firm's revenues and profits can be assessed from an environmental approach. Efforts have been made by economist in order to include appropriate methods for valuation and monetization of environmental services associated to human's activity. According to (Stern, 2007), climate change is not only a challenge for economics, but also a *“serious global threat, and it demands an urgent global response’’*. Economists are increasingly considering economic growth in a setting driven by climate change, collapsing biodiversity and global inequality.

In literature there are monetary valuation approaches for CO_2 emissions in the atmosphere at a global scale under planetary constraints. This is not the case for water-use and land-use system change, where pricing efforts have been made mainly in a regional or local scale. The author of the current study, uses CO_2 emissions as case study in order to analyse the economic impact CO_2 prices under global thresholds, to metals mining.

1.1 Objectives

The current thesis aims to conduct a literature review in order to identify and analyse the hypothetical economic impacts of planetary boundaries to metals mining.

With the purpose to prove the hypothesis that *‘’planetary boundaries, when appropriately costed, imply an economic impact to metal’s mining’’,* there are developed the following tasks*:*

- Identify the most relevant planetary boundaries for metal’s mining.
- Determine appropriate limit values for each planetary boundary.
- Identify prices for each assessed planetary boundary.
- Conduct quantitative analysis on the impact of planetary boundaries prices to the profits and revenues of 16 of the largest producers of copper, aluminium, gold, and iron ore.

2 Literature Review

This master thesis uses as baseline the paper developed by Tost et al., (2018), in which the authors make an analysis of the metal's extraction environmental pressure for the year 2016. They consider three planetary boundaries: CO_2 emissions, land use and fresh water use, and estimate their demand by 18 of the largest companies that produce iron ore, gold, copper, and aluminium. According to the authors, these four metals represent more than 68% of industrial value, and excluding gold they are accountable for over 96% of all the metals mined worldwide in terms of bulk tonnage.

The author of this master thesis, aims to continue to assess the three planetary boundaries and the four metals selected by Tost et al., (2018), but focusing on their economic impact to the metal's mining. For each of the global constraints, literature research is conducted in order to find limit values officially adopted in an international environment, like for instance through policies or agreements. Regardless Röckstrom et al., (2009) proposal of thresholds, their implementation is not yet official or mandatory. The global limit values considered in this study are those that has been enforced in international accords as defined targets.

Prices that consider the designated global constraints are compiled, and self-reported information from 16 of the largest companies that produce copper, iron ore, gold and aluminium (bauxite ore) are assessed. CO_2 emissions, land use and water withdrawals are obtained from the firm's sustainability reports and papers, and from the companies' annual reports there are collected their revenues and profits.

2.1 Planetary Boundaries

This chapter is divided into three sections. They provide a general background on climate change, fresh-water use and land system change individually. The objective of the conducted literature research is to identify a global limit value for each of these planetary boundaries. There are only compiled those prices that in their valuation methodology consider the selected global threshold.

2.1.1 Climate Change

Climate change is related to the greenhouse effect and consequently global warming. The greenhouse effect is a natural process, which keeps the Earth warm enough in order to sustain life as we know it today (Johnson, 2017). Naturally, the Earth is heated by solar short-wave radiation that is then reflected back to the space as long-wave radiation (Mitchell, 1989). The atmosphere contains gases such as carbon dioxide, methane, and water vapor, known as greenhouse gases (GHG), that retain part of the solar heat producing an additional warming (Mitchell, 1989). When GHG concentrations increase, the absorption of wave radiation also rises, which leads to a logarithmically heat increment responsible for global warming (Mac, 2017).

Climate change is a topic that has been under international discussion (United Nations, 2019). Many agencies and research units have concluded that the Earth’s temperature is rising (Figure 1). According to NASA data, the year 2016 has been the warmest in 1880-2016 period record (NASA, 2016). Research of a significant group of scientists have revealed that the major problem is the excessive concentration of greenhouse gases in the atmosphere, such as carbon dioxide (AMS, 2012). It is believed that today’s atmospheric concentrations of this critical greenhouse gas are higher than it has been for the last 65,000 years (AAAS, 2007). Findings show that the main reason for rapid climate change since the year 1950 is human-induced (AMS, 2012).

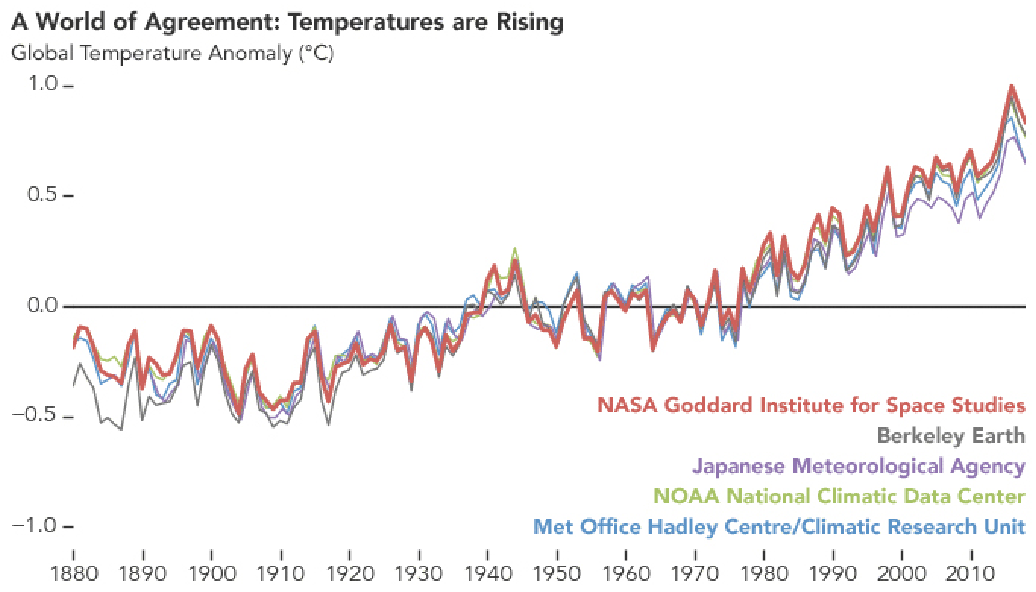

Figure 1. Global temperature anomalies (NASA, 2016).

The Global Carbon Budget is an international assessment of anthropogenic carbon dioxide emissions, which synthesizes several data sets and analyses the results of individual research groups (Le Quéré et al., 2018). The authors estimate fossil CO_2 emissions by including fossil fuels as a result of activities such as transportation, heating and cooling and gas flaring amongst others. They also consider fossil CO_2 emissions from cement, chemicals and fertilisers production. The studies have concluded that burning of fossil fuels (coal) is responsible for ca. 14.57 billion tons of CO_2 emissions in the year 2017, while oil and gas have a share of ca. 20 billion tons (Global Carbon Budget, 2018). Consequently, electricity and heat production are the largest contributors of carbon dioxide emissions with 49% of the total emissions in the year 2014, followed by the transportation sector, manufacturing industries and construction that emit ca. 20% each (Figure 2) (Ritchie et al., 2017).

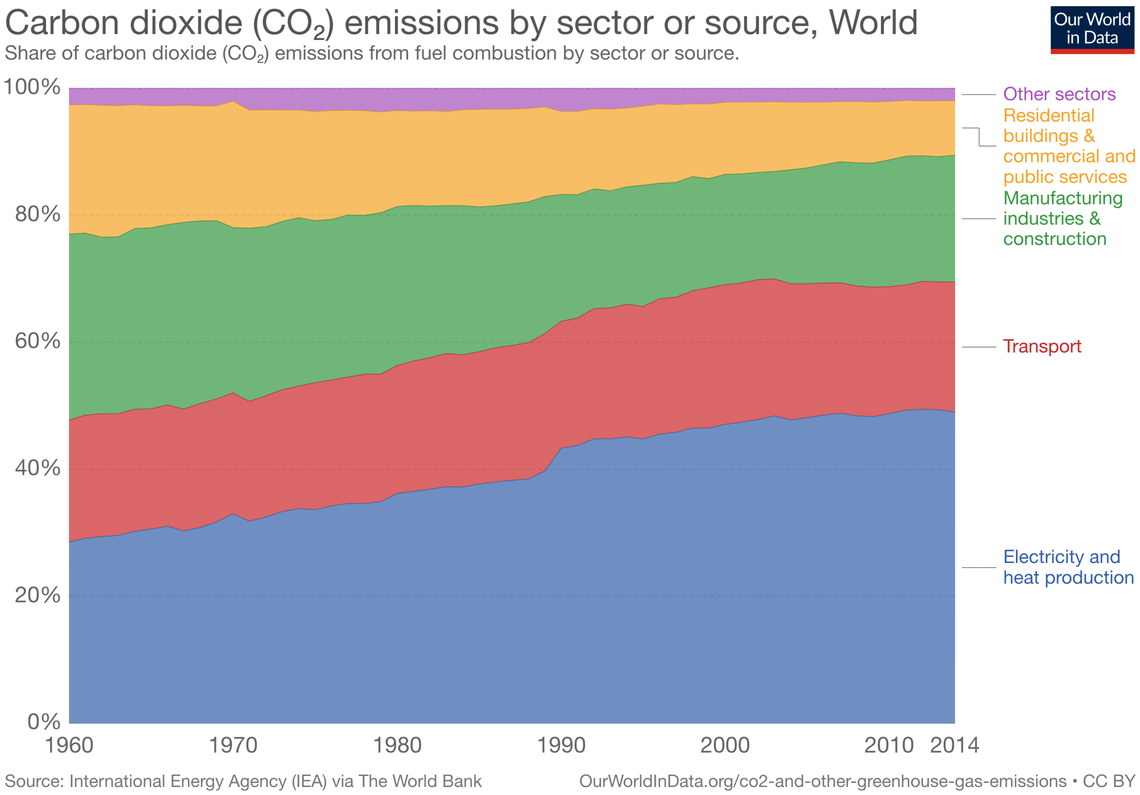

Figure 2. CO_2 emissions by economic sector (OECD-IEA, 2014 In: Ritchie et al., 2017).

Regarding CO_2 emissions from land use, land use change and forestry, the global Carbon Budget includes in its analysis CO_2 fluxes from forest degradation, deforestation, changes in land use from cultivation to agriculture and agriculture abandonment (Le Quéré et al., 2018). In the year 2010, agriculture, land use and forestry had a CO_2 emission share of 2.2 billion tons, approximately 10% of the energy sector (FAO, 2017 In: Ritchie et al., 2017).

Tost et al., (2018), made a deeper mining industry approach by calculating the specific metal's extraction environmental pressure. Their study is based on literature review were minimum, average and maximum values were compiled and updated to the year 2016. The authors concluded that the mining of bauxite, copper, gold and iron ore emit 190.5 Mt of CO_2, which corresponds to ca. 0.5 to 0.7% of the total global CO_2 emissions from fossil fuels and industry, and between 1.3 to 2% of all industrial emissions for the year 2016 (Tost et al., 2018).

Stern (2007) emphasizes the importance of preventing the global mean temperature to rise by more than 2 ºC above pre-industrial levels (1750-1850). The ‘pre-industrial levels’ is a very broad constraint that remains poorly defined, and different baselines have diverse impacts in the probability to exceed 2 ºC and further 1.5 ºC (Schurer et al., 2017). Rockström et al., (2009) don’t provide an exact time period, they only refer to the relatively stable environment in the Holocene, that has been clearly disturb by humans after the industrial revolution. It is well known that the concentrations of GHG emissions have rapidly increase since the industrial revolution that began approximately in the year 1750 (Schurer et al., 2017). Nevertheless, it is challenging to set a clear ‘’pre-industrial’’ time horizon since there are important gaps in the estimates of temperature prior this period, and calculations mainly focus on the northern hemisphere (Schurer et al., 2017).

The IPCC in the Fifth Assessment report conceives as pre-industrial the period between 1850-1900. In their research it is expected that global surface temperature by 2081-2100 will exceed the 1.5 ºC threshold when compared to 1850-1900, while the 2 ºC limit value is likely to be surpassed unless there are stringent mitigation policies adopted (IPCC, 2014)

Stern (2007) concludes that the 2 ºC global limit value could be achieved by stabilizing carbon emissions between 450-550 ppm CO_2 in a timeline of 100 years[1]. Rockström et al. (2009) adjusted the range of emissions to 350 ppm, based on scientific knowledge regarding measures to be taken in order to avoid critical climate systems changes. The IPCC in its 5th assessment report announced that, in order to achieve the 2 ºC goal, concentrations of CO_2 in the atmosphere must remain below 450 ppm. This identified thresholds are first evaluated by Hare et al., (2006), who conducted a feasible scenario of warming commitment. They made a computation of global mean climate indicators through simple climate models. Carbon dioxide along with other GHG are modelled for

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[1] By the year 2018 the global CO_2 atmospheric concentrations have reached ca. 409 ppm (NOAA-ESRL, 2018)

each scenario and the ‘pre-industrial’ levels are set between 1861-1890. Considering the stabilization of emissions in the atmosphere of 350 ppm, temperature is likely to rise 1.5-1.7 ºC by 2100 that is below the 2 ºC target (Hare et al., 2006).

Human-induced warming has already reached 1 ºC above pre-industrial levels in the year 2017 (Allen et al., 2018). This has led to i) melting of ice and rising of sea level that floods and erodes coastal areas, ii) extreme weather like heavy rainfall that results in floods, iii) frequent heat waves in certain regions, such as southern and central Europe, iv) wildfires, and v) wildlife emigration and increased risk of extinction (European Commission, n.da) The alerts given by scientists regarding evidence of global warming and its negative impact have increasingly gained traction in media, governments, and the broader public[2]. Policies have been made in order to reduce greenhouse gases emissions into the atmosphere by changing the way energy is produced and by reducing the demand for it (ESS, 2018).

At the beginning of the 1990s, the rising concern about the global impacts of climate change led to the United Nations Framework Convention on Climate Change (UNFCCC), adopted at the Rio Earth Summit in the year 1992 (UNFCCC, n.d.). By the mid-1990s, the Convention noticed the need to strengthen policies to reduce emissions. In 1997 the Kyoto Protocol was launched, which introduced legally-binding mitigation commitments for greenhouse gases emissions reduction targets in developed countries until the year 2020. The member states, 195 countries to date, have the obligation to take all the required measures to meet their defined targets (Council of the European Union, 2015). The December 2015 Paris Climate Conference constitutes a new global agreement on climate change with a clear action plan which shall curb global warming below the 2 ºC of pre-industrial levels and pursue efforts to limit it to 1.5 ºC (UNFCCC, n.d.), as scientists such as Stern (2007) have suggested before.

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[2] In a US survey on people’s attitude towards climate change and global warming, less than 25% of the sample believed warming was naturally occurring, while more than 60% agreed that global warming is caused by humans (Revkin, 2019)

The Paris Agreement entered into force with the ratification of 55 countries, responsible for 55% of global emissions, it covers the period from the year 2020 onward. Till date, 185 of the 197 participating member countries have ratified the agreement (United Nations, 2015). Russia, one of the largest pollutant nations, has not yet ratified the accord but has indicated its intentions of doing so by September 2019 (Climate Home News, 2019). Regardless the global attempts to preserve the Earth's environment, mitigate and improve its conditions within a sustainable perspective, the United States have announced their withdrawal from the Paris Agreement (The White House, 2017). Albeit such setbacks, the volume of voluntary offsets increased (Hamrick et al., 2018) and carbon prices fluctuated widely in 2016, when the agreement was entering into force, as a result of accelerated technology changes (World Bank Group, 2018).

This master thesis considers the global average temperatures targets of the Paris Agreement (2 and 1.5 ºC) as the thresholds or limit values form the climate change planetary boundary. The author focuses only on the prices of CO_2, that take into consideration the accord as a variable in the valuation model.

2.1.2 Fresh Water Use

Although water goes through a closed hydrological cycle, there is a global concern about its scarcity. 96.5% of the water on earth is stored in oceans, 0.9% in other saline water and only 2.5% is fresh water. 68.7% of the freshwater is in glaciers and ice caps, 30.1% can be found as groundwater and only 1.2% in surface and other freshwater reservoirs such as ground ice and permafrost (69%), lakes (20.9%) and soil, atmosphere, swamps rivers and living things (Shiklomanov, 1993 In: USGS, 2019). The recharge of water aquifers, occurs very slowly, and the mean residential time is hundreds or thousands of years. In contrast, rivers not affected by human intervention, have a mean residential time below three weeks (Oki et al., 2006).

Water scarcity is closely related to overconsumption and groundwater withdrawal (Postel, 1992). According to the author, there are evident signs of water stress, such as falling water tables and shrinking lakes and wetlands. She alerts for the urgent need to balance humans demands with natural cycles. To achieve this, new ways of resources management are required. Regions such as the Arabian Peninsula and Northern Africa have reached overexploitation of water resources of levels of up to 500% and 175% respectively (FAO, 2014). The total water withdrawal on Earth has increased during the last 40 years (Huang et al., 2018).

According to the database of the FAO (2016), from the 1990s to the year 2017, the world's total freshwater withdrawal, including surface and groundwater, was ca. 14,200 (Gm^3), which means an average of ca. 525 (Gm^3/year). Only China in the year 2015 surpassed that average with a total freshwater withdrawal of ca. 595 (Gm^3/year), while the United States have had a level of ca. 444 (Gm^3/year) (FAO, 2016).

During the years 2013-2017, the regions with the highest water consumption were Asia and Africa, used mainly for agriculture, which is closely related to their rapid growth in population (FAO, 2014). 69% of the world's water withdrawal is linked to agriculture, 19% to industries and 12% to municipalities.

It is estimated that mining is responsible for less than 5% of the total global water withdrawal share (Huang et al., 2018). While precise estimates are only sparsely available, a study suggests that the United States have withdrawn ca. 15 Mm^3/d for mining in 2015, approximately 1% of the country's total withdrawals, out of which 77% were freshwater (USGS, 2015). In Europe, mining is accountable for 18% of total water use (EEA, 2019). A significant correlation exists between regions with high water withdrawal and their mineral production rate.

Statistics show that Asia is the largest mineral producer. In the year 2016, the continent produced 58.2% of the world's total, followed by North America with

14.1% and Europe with 8.5% (World Mining Data, 2018). The average water withdrawal in the year 2016 of bauxite, copper, gold and iron ore mining was ca. 7,656 Mm^3, which represents from 0.09% to 0.15% of the global total (Tost et al., 2018). Africa holds a relatively small share in minerals production (World Mining Data, 2018), however it is one of the regions with highest global agricultural production, along with Asia, North America and Western Europe, (OECD-FAO, 2018).

Throughout history, there have been several agreements on transboundary water resources, most of them related to hydropower and water utilization (UNDP, 2006). According to the UNDESA (2014) *''the world's transboundary lake and river basins cover nearly half of the Earth's land surface''*. The organization identified that there are basins that are shared within two countries while others such as the Congo, Niger, Nile, Rhine, and the Zambezi are shared between 9 and 11 countries. The Danube travels within 18 different nations. The more than 3,600 agreements and treaties signed related to water bodies are an indicator for the international importance and efforts regarding sustainable use of water, nevertheless it also represents the lack of success to achieve multilateral agreements regarding clear measures and boundaries (UNDESA, 2014).

In the year 2009, a threshold value of 4-6 Mm^3 yr^{-1} for global freshwater use was proposed (Rockström et al., 2009). This range, according to the authors, was based on fragmented and incomplete scientific evidence of ecosystems response. Nevertheless, the researchers concluded that surpassing those limits would affect regional climate patterns, biomass production, carbon uptake, and consequently the risk of reduction of biodiversity. Authors such as Heistermann (2017) disagree with these limit values and suggest that a planetary boundary on freshwater is misleading since the arguments to define those thresholds are speculative and arbitrary. Nordhaus et al. (2012), concur with Heistermann by arguing that six of the planetary boundaries, out of which one is freshwater use, *''do not have planetary biophysical thresholds in themselves.''* This implies that there is a lack of conclusive evidence regarding the global impacts triggered by freshwater use on ecological processes (Nordhaus et al., 2012).

Gerten et al. (2013) made a revision to the conceptual and mathematical model behind the freshwater-use planetary boundary. They revised the limit value to 2,800 km^3 yr^{-1} with a range of uncertainty of 1.1-4.5 Mm^3 yr^{-1}. The authors admitted that these thresholds are temporary and that further research has to be conducted in order to be able to define constraints on a global scale. Destouni et al. (2013) conducted a hydro-climatic change analysis in nine of the major Swedish basins. The results were compared with regional and global changes by irrigation and deforestation. The research suggests that human water use was about 4.5 Mm^3 yr^{-1}, which surpassed the proposed planetary boundaries. This new value was calculated by interpolations, from a regional to a global scale, considering the components that shift the evapotranspiration processes.

Steffen et al. (2015) also acknowledge the difficulties to precise a planetary boundary for fresh water use, since *''not all earth-system processes included in the PB approach have singular thresholds at the global/continental /ocean basin level''*. Nevertheless, the authors highlighted the importance to establish limit values in which society should operate. Steffen et al. (2015) provided a different assessment to complement the work of Rockström et al. (2009), in which they suggest 2.6 Mm^3 yr^{-1} as updated current control variable. Despite these revised assessments, no substantial changes to the methodology are made to the original study which would, in turn, allow for a better understanding of the earth system as a whole (Heistermann, 2017).

Accordingly, international water governance is difficult to enforce due to the lack of an uncontested threshold and derived from this, uncertainty on how much freshwater is safe to consume. The Sustainable Development Goals (SDGs) introduced clean water and sanitation as one of the 17 goals with the aim to achieve clean and accessible water around the world by the year 2030. The United Nations and its member states intend to improve sanitation and drinking water through investment in management of freshwater ecosystems at the local level in developing countries (United Nations, n.d). The UNESCO (2019) recognises that good water governance should be local, and it must include a structure to facilitate multi-stakeholder dialogue. In their World Water Development Report 2019, planetary boundaries are introduced as a basis for the definition of goals and principles for policy-making, however, no concrete threshold is included into this work.

Due to the lack of international consensus regarding limit values for freshwater use, the author is not able to define a global limit value. For this master thesis, a literature research is conducted on regional or local freshwater prices for delimited catchment areas in order to proof how the concept of pricing could work for water.

2.1.3 Land System Change

About 71% of the earth is covered by water, which leaves less than 30% of dry land surface (USGS, n.d.). Albeit the limited body of knowledge on the historical development of land use, sustainability approaches and policy-making rely on it (Yang et al., 2017). Land-use change is described by Bimal et al. (2016) as *''a process in which human activities transform the natural landscape, referring to how land has been used, usually emphasizing the functional role of land for economic activities"*. As long as humans have been living on earth, undisturbed ecosystems have been modified into cropland and pasture and to a lesser extent into urban areas (Kaplan et al., 2011).

Shifts in land-cover and land-use, when aggregated globally, can have a considerable effect on the functioning of earth systems (Lambin et al., 2001). It has been discovered that the biotic diversity can be severely affected. For instance, endemism in the European Alps, Himalayan Alpine region and the Arctic, will be highly impacted by land-use change (Sala et al., 2000). The authors concluded that *"land-use change is the driver with the largest impact on biodiversity.''* This planetary boundary is also strongly related to climate change since it releases carbon to the atmosphere when forests are transformed into agricultural fields, contributing to global warming (Houghton et al., 1999).

More than one-third of the earth’s land surface supports agriculture (Goldewijk et al., 2017). Over 70% of the agricultural land is used for livestock, which represents 40 million km^2, and ca. 20% for crops (Ritche, 2017). These activities have triggered anthropogenic environmental pressure that compromises the stability of the Planet’s biomes (Rockström et al., 2009). Local decisions regarding land-use change are often driven by regional and international trends (Heck et al., 2018). Historically, not all countries share the same experience regarding land-use, but differences accrue mainly due to variety in population density and the selection of agricultural methods (Goldewijk et al., 2017).

Article 5 of the Paris Agreement highlights the importance of controlling land-use since it is a key process that impacts climate change. There are countries such as Japan, France, United Kingdom, United States and Germany which, in accordance to the Paris Agreement, have included their will to facilitate appropriate forest and land management, and to promote urban vegetation with the aim to remove CO_2 from the atmosphere (Bundesministerium, 2016; HM Government, 2017; Republique Française, 2017, The Government of Japan, 2019; The White House, 2016).

Implementing sustainable approaches for land-use is typically associated with agriculture instead of mining. As a control variable for the measurement of land system change, Rockström et al. (2009) note that the identified planetary boundary is a global aggregate which is subject to high ambiguity. Despite this shortcoming, the authors proposed limit values based on local and regional evidence on the impact of land-cover change on ecosystems. According to the research, less than 15% of the global ice-free land surface should be converted to cropland, with a range of uncertainty between 15-20%. The thresholds suggested by Rockström et al. (2009), or any other global limit value for land use, have not yet been implemented at a governmental level.

Murguía (2015) analyses the disturbed area by large scale mining of iron ore, bauxite, copper, gold and silver in the year 2011. He uses a global inventory of large-scale metal mines, in which there are registered ca. 2,700 mines that produce metals worldwide. The methodology applied is based on random sampling for iron ore and bauxite without any distinction from mining method, since the author concluded a significant predominance in open pit mining. For copper, gold and silver mines there is made a classification between open pit and underground mining. A regression model is applied to calculate specific land requirements with a total sample of 106 mines.

The author selected 13 bauxite and 27 iron ore open pit mines, along with 66 mines that produce copper, gold and silver. In this sample, 45 sites are mined by open pit mining method, the remaining ones are underground extraction. For the 106 large-scale mines it is stablished the annual production per mine for the five metals assessed. Murguía (2017), calculated a weighted disturbance rate per metal, in order to identify the annual amount of newly disturbed land per millions of tons of extracted ore (Table 1). His findings suggest that bauxite and gold demand more land per ton of ore extracted than silver, copper, and iron ore.

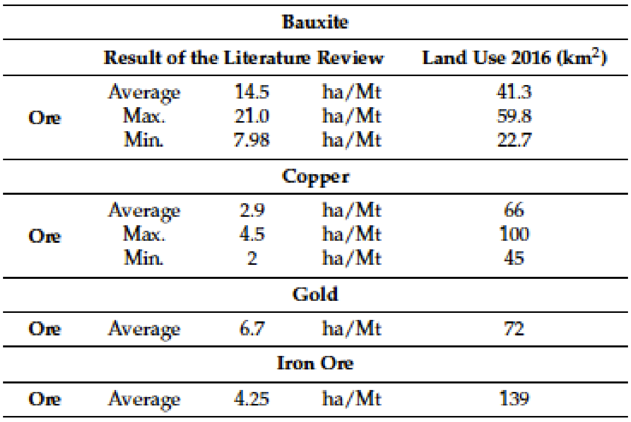
In his research he also determines the cumulative net disturbed area for the year 2011. The results show that for the assessed mines that are globally widely distributed, the cumulative net disturbed area due to large-scale mining is ca. 1.2 million hectares (ca. half of Belgium).

Ore	Land Use ha/Mt
Bauxite	7.98
Gold	6.70
Silver	5.53
Copper	4.50
Iron	4.25

Table 1. Annual amount of newly disturbed land of ore extracted (Murguía, 2015)

The documentation of global plant species patterns has allowed for a classification of homogeneous diversity zones (Barthlott et al., 2007). Plant diversity zones have been used in order to determine thresholds (Röckstrom et al., 2009). Murguía (2015) crosschecked the global distribution of 2,860 mines and 2,055 ore deposits around the globe and was able to identify that 23% of mines and 20% of ore deposits are located in areas of high diversity. While the sample only included bauxite, gold, silver and copper mines, the findings suggest that large scale mining is one of the important adverse impact factors on land use and to this extent to the broader ecological system.

Tost et al., (2018) update the information regarding global land use for bauxite, copper, gold and iron ore mining to the year 2016. The authors conducted a literature research in order to find different sources of hectares used per million ton of ore extracted (Table 2). The values obtained are even higher than those presented by Murguía (2015).



	Bauxite			
	Result of the Literature Review			**Land Use 2016 (km^2)**
Ore	Average	14.5	ha/Mt	41.3
	Max.	21.0	ha/Mt	59.8
	Min.	7.98	ha/Mt	22.7
	Copper			
Ore	Average	2.9	ha/Mt	66
	Max.	4.5	ha/Mt	100
	Min.	2	ha/Mt	45
	Gold			
Ore	Average	6.7	ha/Mt	72
	Iron Ore			
Ore	Average	4.25	ha/Mt	139

Table 2. Global land use for bauxite, copper, gold and iron ore mining (Tost et al., 2018).

The author of the current study, was not able to identify a limit value that is internationally adopted in policies or agreements. Instead, it is noted that the efforts to quantify the impacts of land-use change in a global scale have as base regional cases from which information is extrapolated. In the case of Murguía (2015), the disturbed area by large-scale mining is calculated by a small sample of productive mines around the world. Due to the gaps in information this master thesis has to focus on land-use prices without considering global thresholds.

2.2 Prices

These sub-chapter has as objective to show the prices for CO_2 emissions, fresh-water use and land system-change, along with the related valuation methodologies. The information is divided in three sections. The first section addresses the prices of CO_2/t under the Paris agreements constraints. Since the author was not able to identify implemented global limit values for water and land use, the second and third section present prices for these boundaries at a local and international scale, without considering global constraints.

2.2.1 Carbon Dioxide

Literature review and data compilation are conducted to identify costs of CO_2/ton under the Paris Agreement planetary boundaries. No commonly accepted carbon valuation methodology exists yet, therefore the author compiles different costs of CO_2 from 11 influential studies that consider the limit rise of global temperature (2 ºC and 1.5 ºC) in their models. Most of the sources provide a minimum and a maximum price for CO_2 per ton under the Paris Agreement scenario.

Different models have been applied in order to quantify the economic feasibility of reducing GHG emissions, with the goal of monetizing their environmental impact. Gillingham et al. (2018), believe that the most efficient way to address the problem of rising GHG emissions is to *''reduce emissions to the point that the marginal benefits of the reduction are equal to its marginal cost''*. At this point, the polluter would not be incentivized to further reduce its pollution. A carbon tax would therefore encourage the reduction of emissions, the tax rate behaves as the marginal benefit of the emission reduction, which is *''the monetized damages for emitting an additional ton of carbon dioxide''* (Gillingham et al., 2018).

McKinsey (2009) took a sample of more than 200 GHG emission reductions opportunities in ten of the most important economic sectors, and from 21 world regions, between the years 2014 to 2030. They concluded that the investment needed to achieve the Paris Agreement is manageable at a global level but challenging for individual sectors. The study also highlights that a delay of 10 years for applying the appropriate measures will render the 2 ºC limit value unattainable.

Nordhaus (2007) creates the Dynamic Integrated Model of Climate and Economy (DICE), as an alternative from social cost of carbon[3]. He modifies the economic growth theory of the Ramsey Model, which suggests that *''society invests in capital goods, thereby reducing consumption today, to increase consumption in the future''*, by including investment in capital education and technology. His model considers *''GHGs as a negative natural capital, and emission reductions as investments that raise the quantity of natural capital''* (Nordhaus, 2007). The author uses an abatement cost function for his model, recalibrated to other integrated models' abatement cost functions. He also calculated a damage function that describes the economic impact or damages of climate change, which is an important input to calculate the social cost of carbon. The DICE incorporates the declination of CO_2 in order to observe the rates of decarbonization and assesses 12 regions with data of 71 countries that are accountable for 97% of emissions, 94% of world output and 86% of population.

With a temperature constraint of 2 ºC, Nordhaus (2007) proposes a price of USD_{2005} 71.82/tC, which is equal to USD_{2005} 19.56/tCO_2[4]. The author also estimated a price of USD_{2005} 174.68 per t of carbon, or USD_{2005} 47.60/tCO_2, under a 1.5 ºC in the year 2015. These values were updated in the year 2013 by

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[3] Social Cost of Carbon: ''is a measure, in dollars, of the long-term damage done by a ton of carbon dioxide (CO2) emissions in a given year. This dollar figure also represents the value of damages avoided for a small emission reduction.'' EPA (2016)

[4] In order to project this cost in tCO_2 it has to be considered that the atomic mass of Carbon is 12 and the atomic mass of oxygen is 16 (Royal Society of Chemistry, n. d), which means that the total atomic weight for CO_2 is 12+16(2) =44. If there is given a quantity of CO_2, its relation to an amount of carbon can be expressed by multiplying the amount of CO_2 by 0.27 (12/44) (Brander et al., n.d), which will be the same to divide the amount of carbon by 3.67 (44/12).

Nordhaus et al., (2013), to USD_{2005} 50/tCO_2 for 2 ºC, which they describe as an ambitious target that will impose a significant economic penalty.

The Department of Energy and Climate Change (2009) made a carbon valuation for the United Kingdom policy. They recognize the importance of an appropriate emission valuation for decision making regarding climate change impacts. Similar to Nordhaus (2007), they criticize the uncertainty of the Social Costs of Carbon (SCC) estimates. Their proposed model evaluates the Abatement Costs (AC) that will be needed in order to achieve specific emission reduction targets. Nevertheless, as well as in the DICE model, the SCC still is considered an important input, since *''the optimal stabilization goal is found where the MAC[5]=SCC''* as shown in Figure 3. In order to reach the global stabilization goal to which the UK had committed as part of the Kyoto Protocol, and later the Paris Agreement, the Department of Energy and Climate Change (2009) estimates the prices for CO_2/t that can be seen in Table 3.

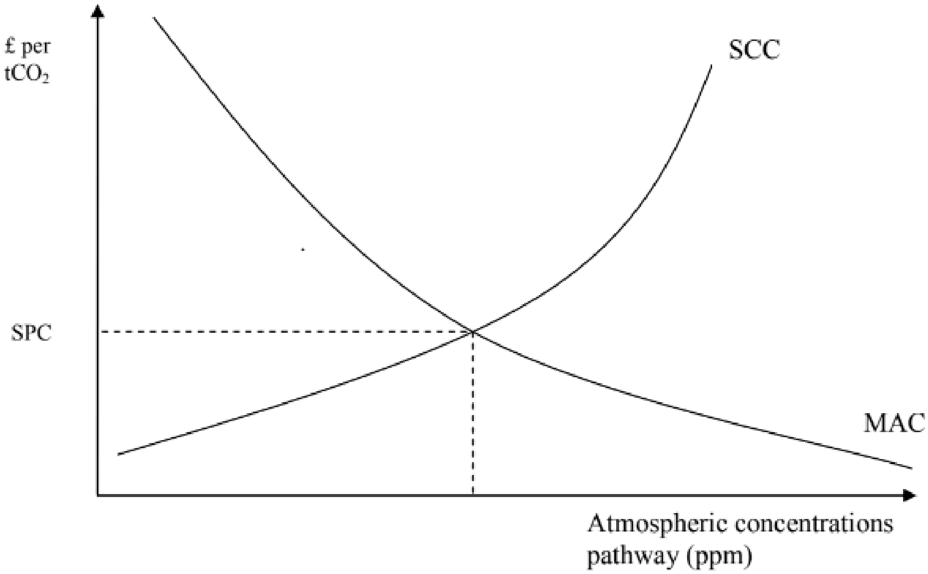

Figure 3 Diagram that describes the optimal stabilization goal Marginal Abatement Costs MAC=SCC. Source: The Department of Energy and Climate Change (2009).

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[5] Marginal Abatement Costs: ''reflects the cost of one additional unit or ton of pollution that is abated, or not emitted'' (EconPort, 2006)

		Min	Max	Year
Short term traded price of CO2	25	14	31	2020
Short term non-traded price of CO2	60	30	90	2020
Long term traded price of carbon	70	35	105	2030
	200	100	300	2050

Table 3. Prices for carbon in GBP using linear interpolation to form price series between 2020 and 2030, and 2030 to 2050 (The Department of Energy and Climate Change, 2009)

In the year 2010, 16 countries were accountable for 74% of the global GHG emissions (DDPP, 2017). According to the author, in order to meet the 2 ºC scenario until the year 2050 at a national scale, early incentives for innovation to achieve long-term decarbonization must be provided and investments into mitigation made. In that sense, rapid increase in the short-term of carbon shadow pricing[6] would be appropriate (DDPP, 2017). The study suggests a global value per ton of CO_2, obtained from an Integrated Assessment Model (IAM) developed for India under a 2 ºC scenario. It provides prices under a conventional setting but additionally includes a sustainable framework which considers extra measures such as local pollution, energy security, urban planning, decentralized energy for rural areas and water management amongst others. It is concluded that in the year 2020, the conventional global price is USD 40 per ton of CO_2. For the sustainable scenario, in which the aggregate final consumption is lower due to less pollution and diversified energy supply, the price is set on USD 5 per ton of CO_2. Integration Assessment Model is also used by Edenhofer et al., (2014) in the 5th assessment report for the IPCC. They estimated ranges from USD_{2010} 18/tCO_2 to USD_{2010} 250/tCO_2 in the year 2020, corresponding to emissions of 430 – 480 ppm COeq. The authors suggest that the broad ranges are due to the difference in mitigation efforts within countries.

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[6] Shadow Price: *‘’ The assignment of a dollar value to an abstract commodity that is not ordinarily quantifiable as having a market price but needs to be assigned a valuation to conduct a cost-benefit analysis’’.* (Investopedia, 2019

The International Energy Agency (IEA, 2015) analyses the innovation and investments needed in order to limit global temperature to rise above 2 ºC. The agency considers a scenario in which the energy share of the global Gross Domestic Product (GDP), and the carbon demand for primary energy have to decrease close to 60% by the year 2050. To achieve these targets, they have estimated that additional investments of ca. USD 40 trillion will have to be due between 2015 to 2050. In their study, the IEA concludes that carbon pricing is one of the key factors to incentive decarbonization. They estimated, through global marginal abatement costs, that under a 2 ºC scenario, the tCO_2 should cost between USD 30 - 50 in the year 2020. This range will be 50% higher in the year 2030, the period after which the growth rate of tCO_2 will decrease due to the increase of experience and innovation (IEA, 2015).

Canfin et al. (2016) suggest a carbon price floor on the electricity market, a minimum price on carbon emissions, in order to encourage the decarbonization in France. He conducted more than 80 expert interviews in France, Brussels, and Berlin regarding the inconsistencies between the European carbon market, the Paris Agreement and the European climate objectives. They suggest a minimum and maximum soft price collar. The minimum for the soft price collar can be set between EUR 20-30/tCO_2 in the year 2020, with an annual increase of 5 to 10% in order to reach EUR 50/tCO_2 in the year 2030. The authors also propose solutions that could help the European Trading Scheme (ETS)[7] to deliver efficient carbon prices. The ETS is the first international emissions trading market based on the 'Cap Trade' principle[8] (European Commission, n.db.). This means that a carbon market was created by issuing a limited number of available emission allowances that companies can buy and trade.

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[7] *During the years 2005 to 2012 most allowances were given for free to the participating companies: GHG- intensive sectors in the power and manufacturing industry. From the year 2012 to 2020 a default auctioning period started, nevertheless free allowances still being allocated mainly to the industry sector (European Union, 2015).*

[8] *'the overall of greenhouse gases that can be emitted by the power plants, factories and other fixed installations covered by the EU emission trading system (EU ETS) is limited by a 'cap' on the number of emission allowances''* (European Commission, n.db.)

By the year 2016, the EU ETS price for tCO_2 varied between EUR 4 to EUR 8 (Sandbag, 2019). The ETS contributes to the achievement of the EU's climate policy goals that are aligned with the Paris Agreements (European Union, 2015). Mitigation allocation in each member state depends on the gross domestic product (GDP) per capita (European Commission, n. dc).

This master thesis does not consider the EU ETS or carbon taxes, since the market prices are not specifically aimed to prevent global temperature to rise above 1.5 to 2 ºC . For instance, the European Commission in the year 2015 presented a legislative proposal that ambitions to reduce greenhouse gas emissions by 43%, compared to 2005, from 2021-2030 period (European Union, 2016).

The Organisation for Economic Co-operation (OECD) in partnership with the IEA, developed a valuation scenario with a 66% probability to achieve the targets of the Paris Agreement over the course of the 21st century. In their study, they assume that the CO_2 budget between 2015 to 2100 is 880 gigatons (Gt). They assess only the CO_2 budget from the energy sector, and subtract from their model the CO_2 emissions that are derived from land use, land-use change, and forestry. The assumption that the emissions form these sources fall from 3.3 Gt in 2015 to zero by the mid-century, shows a cumulative CO_2 emission close to zero. The challenges for their proposed model are that it requires an important energy transition and an ambitious reduction on energy emissions in a context where negative-emissions technologies might not be available on time. On the other hand, according to the National Determined Contributions, the energy sector would emit ca. 1,260 Gt by the year 2050, which surpasses the allowed budget by far (OECD-IEA, 2017).

The IEA found that to accomplish the 66% probability to prevent temperatures to rise by more than 2 ºC, it would be required that the CO_2 emissions related to the energy sector have to fall by more than 70% of the levels of 2017 by the year 2050. This implies that the fossil fuels consumption must decrease by 50% from 2017 to 2050 and renewables should triple at a global scale. It is estimated that under this scenario, the price of tCO_2 will reach USD 190 by 2050 (OECD-IEA, 2017). The study warns that carbon prices can affect future reorientation energy investment. In accordance with Canfin et al. (2016), it is suggested that by the year 2020 all the OECD countries will need to achieve a price of USD 20 per ton of CO_2. They also note that for emerging market economies USD 10 should suffice, and for certain regions USD 5 should be enough. In all regions these prices must however escalate significantly until the year 2050 (Table 4).

	2020	**2030**	**2040**	**2050**
OECD Countries	20	120	170	190
Major emerging countries	10	90	150	170
Other regions	5	30	60	80

Table 4. tCO_2 prices in USD for a 66% probability scenario to achieve 2 ºC limit value. Source: OECD-IEA, 2017.

While both the Carbon Pricing Corridor Initiative and the OECD-IEA (2017) consider industry such as power and energy sector in their pricing models, the costs per tCO_2 differ. The Carbon Pricing Corridor enables the most important companies and economic sectors in the world to define the needed carbon prices to comply with the Paris Agreement. Panel members calculate that the chemical and power sector would have to be burdened until 2020 with ranges between USD 24 to USD 50/tCO_2. These prices will allow them to plan the required investment to reduce carbon emissions against a temperature increment of 2 ºC (CDP, 2018). Canfin et al. (2016) suggests that the carbon price for the power sector should be EUR 30/tCO_2.

Guivarch & Rogelj (2017) agree to the climate constraints as suggested by the OECD-IEA (2017) and the estimated price ranges for tCO_2 are similar although they seem to use different valuation methodologies. Guivarch & Rogelj (2017) use quantitative projections of the Shared Socioeconomic Pathways (SSPs). Their aim is to assess carbon prices variations in a 66% probability scenario to limit global temperature increases to above 2 ºC of pre-industrial levels. The authors found that variations in prices occur because of the different frameworks used in modelling, as well as because of the diverse policy decisions and socio-economic factors. In order to address those variables, Guivarch & Rogelj (2017), made systematic literature research in databases that compiles quantitative projections of the SSPs (Table 5). They used an online dataset that provides quantification of SSPs by using the most updated IAMs.

There are several IAMs developed per SSP, hence there are different interpretations per socioeconomic pathway (Guivarch & Rogelj 2017). The authors identified that a climate limit value is not enough to achieve Paris Agreement 1,5 and 2 ºC thresholds. Additionally, there is a need to implement mitigation policies that must be considered in each SSP as Share Policy Assumptions (SPAs). In literature, Guivarch & Rogelj (2017) were able to find very broad ranges of prices per tCO_2 (USD/tCO_2e), according to the authors, this is mainly due to the structural modelling differences, as well as the distinctive socio-economic scenarios. They estimated that the costs tCO_2 for the SSPs overall, assessed by the available 6 different IAMs, are USD_{2010} $5/tCO_2e$ to USD_{2010} $15/tCO_2e$ by the year 2020. Indirectly this study also provides prices for a 1.5 ºC scenario, since the authors found that in that context prices are 2 to 3 times higher than those of the 2 ºC approach. Accordingly, the cost per tCO_2 in order to reach the 1.5 ºC threshold is ca. USD_{2010} 15-45.

SSP1	Development under a green-growth paradigm
SSP2	A middle-of-the-road development along with historical patterns
SSP3	A Regionally heterogeneous development
SSP4	A development that results in both geographical and social inequalities
SSP5	A development path is dominated by high energy demand supplied by extensive fossil-fuel use

Table 5. Shared Socioeconomic Pathways considered by Guivarch & Rogelj, 2017.

Rogelj et al., (2018a) used the same methodology as Guivarch & Rogelj (2017), in order to propose different scenarios that will restrict the global median warming below 1.5 ºC. They estimated average discounted carbon prices of USD_{2010} 50-

165/tCO2e over a 2020-2100 period for a SSP2 context. In the same year Rogelj et al., (2018b) made an economic assessment for the IPCC on the implications of 1.5 ºC pathways. They estimated undiscounted values of USD_{2010} 135-6050/tCO_2eq for the year 2030. Despite the used methodology in both studies is IAM, the prices vary significantly. The available data used for the IPCC report is highly divergent across models and scenarios and the prices are strongly impacted by mitigation efforts (Rogelj et al., 2018b).

It is challenging to compare the wide ranges in prices of CO_2 per ton since there is not a uniform methodology. Each assessment use different approaches regarding scenarios, allocation across sectors and countries, policies and included economic sectors amongst others. In general, costs per tCO_2 obtained from marginal abatement costs- and social cost of carbon methodologies display more conservative ranges than the values which result from integrated models.

All the pricing methodologies have as common goal to incentivize decarbonization in order to achieve the Paris Agreements thresholds. There appears to be a consensus, that in the short-term (2020-2030), the prices per ton of CO_2 will have to increase significantly since important investment will be required for mitigation and adaptation. After the year 2030, it is expected that the growth rate of prices tCO_2 will decelerate, when compared to 2020-2030, in response to the growing experience and technology transition (OECD-IEA, 2017). While research for a 2 ºC scenario is taking place, there need to be further efforts for a 1.5 ºC approach. Currently there are few studies about the prices per ton of CO_2 for the latter threshold, the preferred methodology to assess this scenario is IAM. A summary of the compiled prices is shown in Annex I and II.

2.2.2 Fresh Water Use

Fresh-water use global prices are not sufficiently documented in the scientific literature. The author of this thesis compiles prices of water-use calculated in a regional scale and delimited catchment areas, in addition the valuation methodologies used are described. The majority of the available information refers to the operation costs of providing water as a service. However, attempts have been made in order to estimate regional monetary values of externalities such as water quality, referring to the usability (navigable, swimming, fishable) or to suspended solids. (Daniels et al., (2012), compile data regarding existing valuation estimates, and they concluded that the most popular valuation methodology for this specific externality is contingent valuation (CV), followed by contingent valuation surveys. According to their study, CV is a methodology that is based on hypothetical market scenarios. The surveys help to determine the willingness of people to pay or received certain amount of compensation for a fixed quality of an environmental good. It is one of the only tools capable to assign monetary values to ecosystems that are not involve in market trades (Daniels et al., 2012). However, the study identifies that the interview process might be a source of possible bias, while the reliability of the answers from the people that are interviewed is also an important constraint of the methodology.

Hellegers et al., (2010), use the residual method[9] that aims to calculate the disaggregated economic value of irrigation water. The area of interest is the Musi sub-basin located in India, where there is a wide variety of crops and different agriculture methods are applied. The author's methodology is based on the belief that *''the value to a producer from producing a good is exhausted by the summation of the values of the inputs required to produce it.''* The residual method, according to the authors, estimates average values instead of marginal values, since the total value is divided by the quantity of water applied. The model has as input the following variables:

- Quantity of output of crops
- Price received for crops
- The input used to produce a certain crop
- The average value of inputs

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[9] *''The residual method calculates the value of water as the reminder of net income after all the other relevant costs are accounted for*'' (Young & Loomis, 2017). The most conventional approach involves the estimation of the Value Marginal Product through the product extraction theorem or theory of economic rents (Young & Loomis, 2017).

Considering those variables, Hellegers et al., (2010) calculate the net return to water of the assessed crop, which is also known as the residual value. According to the authors, once the value of irrigation water is known for a determined crop, it is possible to calculate the water used in a certain zone and during a defined season, if multiple crops are produced. For their study they assess five agricultural zones in the basin, as well as 8 different crops: rice, vegetables, chili, fruits, groundnuts, maize, cotton and gram, during the years 2001-2002[10]. The crops are assembled into a single category in order to balance water demands. They also include all the input and output prices such as labour, fertilizer and pesticides, as well as social prices that reflect the value of water to the society. For output prices, the data is obtained from the FAO and the District's Handbook. The study estimates that the weighted average prices for irrigation water overall are ca. Rs. 3.31/m^3 for the rainy season and ca. Rs. 2.4/m^3 for dry season[11].

Lionboui et al., (2014), also use a disaggregated model and the CV concept, in order to find the optimum prices for irrigation water in the Tadla sub-basin, located in Morocco. In the year 2009, official policies for the Tadla sub-basin, determined that *''the equilibrium rate of irrigation water must achieve 0.40 Moroccan Dirham (MAD) per cubic meter in 2011[12]''* (Official Journal, 2009 In: Lionboui et al., 2014). However, the study mentions that the target price has not been yet implemented, since the government has doubts on the farmers acceptability.

According to Lionboui et al., (2014), the Tadla sub-basin receives annually an average of 330 mm of rainfall. The study area is delimited by 30,000 ha that

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[10] The study cover a whole dry and raining season cycle in the year (2001-2002) (Hellegers et al., 2010).

[11] Considering an Exchange rate of 1 USD = 71 Rs, the weighted average prices of irrigation water are ca. USD 0.04/m^3 for dry season and USD 0.03/m^3 for rainy season.

[12] The set equilibrium rate of irrigation water for 2011 is ca. USD 4 cents per cubic meter with an exchange rate of 1 USD = 9.65 MAD. The currency exchange is taken from OANDA currency converter.

represents the overall agriculture zone, from which 126,000 ha are irrigated areas. According to the authors, the water used for irrigation purposes in Tdla sub-basin is fresh water that comes mainly from surface water bodies. In order to obtain a price for irrigation water, Lionboui et al., (2014), first create two hypothetical scenarios that have as baseline the years 2009-2010. The first simulation suggests an increase of 25% in the equilibrium rate (ca. USD 4 cents per cubic meter). The second one refers to a dry season scenario in which the equilibrium rate of irrigation water varies and the water supply is reduced in 40%. Considering the reactions of the farmers towards each model scenario in their model, the authors were able to calculate an average water shadow price[13], for the irrigated area of Tdla sub-basin, of ca. MAD 0.78/m^3. The shadow prices are adjusted depending on the availability of water supply from September to August in a one-year basis (2009-2010) (Table 6).

	average price (MAD/m3)	**Approximate price in US dollars**
Farmlands with easy access to ground water	0.6	0.06
Farmlands with easy access to surface water	1.26	0.13
Farmlands with easy access to ground and surface water	1.4	0.15

Table 6. Average shadow prices of irrigation water in three agricultural sites within the Tdla sub-basin. It is assumed an exchange rate of 1 USD = 9.65 MAD. Adapted from: (Lionboui et., 2014). The currency exchange is taken from OANDA currency converter.

Bierkens et al., (2019), like Lionboui et al., (2014), calculated the shadow price of irrigation water or the marginal value of water. However, they propose a more global approach by assessing 11 countries: China, Egypt, India, Iran, Italy, Mexico, Pakistan, South Africa, Spain, Turkey and United Sates. According to the authors, these are the major groundwater depleting nations. The prices are calculated for 5 commodities: wheat, maize, rice, potato and citrus, which excluding citrus, are

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[13] The shadow Price of water represents the value of a commodity that can be produce by the marginal unit water consumed, given the quantity of other inputs such as labour, supplies etc. (Bierkens et al., 2019).

globally four of the most important crops in terms of production (FAOSTAT In: Bierkens et al., 2019). The authors in their study, define the relationship between the output and water input by production functions. These functions are parametrized by country and crop using globally available data on country-specific yields and prices. Global ground and surface water consumption obtained from a global hydrological model was also included. For each crop there are used the following parameters extracted from the Food and Agriculture Organization of United Nations (FAO) database:

- Information on yield
- Total area
- Crop prices for the years 1991-2010
- Sources of water: For each identified water sources there is calculated waste consumption.

Anthropogenic water is also considered by Bierkens et al., (2019), since the global hydrological model used includes more than 6,000 man-made reservoirs. After the estimation of the production function, the authors, calculated the average irrigation shadow prices for the periods 2006-2010 and 1991-2010. The average shadow prices obtained for the overall sample is ca. USD 0,0669/m^3 for 2006-2010 and ca. USD 0,0684/m^3 for 1991-2010.

Williams et al., (2017) calculate the social costs related to an additional unit of groundwater that is extracted from the southern part of Ogallala Aquifer, located in USA. They also define the shadow price per unit of water that remains in the aquifer during the year 2004. In order to evaluate the relationship between the Marginal Abatement Costs (MAC) and the optimal extraction rate they use production functions, alike Bierkens et al., (2019). The authors in their model use the following parameters:

- The area of the aquifer: Using GIS data
- The specific yield
- The total average saturated thickness
- The total recharge of the aquifer

- The return-flow coefficient
- The natural recharge
- Farmers total revenues per commodity (cotton, corn, sorghum, wheat and peanuts) in the counties that are within the study area.
- Estimates of the marginal product
- Water pumping costs
- The total irrigated acreage

Williams et al., (2017), calculated a shadow price and current MAC per county, however in their paper they only show the current shadow price for Bailey County which is ca. USD 0.026/m^3. The minimum MAC obtained across the sample is USD 0.005/m^3, maximum USD 0.17/m^3[14]. The estimated average value overall is ca. USD 0.09/m^3. Knowing the area of the aquifer in each county, the authors were able to estimate that the social cost of an additional unit withdrawn from a study area of ca. 31,444 km^2, is ca. USD 77,934,000,000. Table 7, shows the minimum, maximum and average social costs per county.

Total County MAC (Thousand USD)	
Minimum	269
Maximum	12,734
Average	5,600

Table 7. Minimum, average and maximum value of total county MAC. Adapted from: Williams et al., (2017).

The author of the current study was not able to find prices for water-use under planetary boundaries constraints. Instead, in the available literature there are valuation efforts towards estimating prices for irrigation water, mainly in a regional and local scale. Most of the studies use as preferred methodology Shadow Price or Marginal Value of Water. Residual methodology is not widely used (Hellegers et

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[14] The values in the study are given in acre-inch units, in this master thesis they are converted to USD by considering that 1 acre-inch is equivalent to 102.79 m^3, 1 inch = 0.0254 m and 1 acre = 4,046.86 m^2

al., 2010). It is difficult to compare between studies, since the samples and input data are different, however all of them have the aim to incentive a sustainable use of water. In the methodology of all the assessed studies, there are given prices for irrigation water, they all choose a geographic are of interest (basin, sub-basin) and select a defined number of commodities to be evaluated (e.g. Crops) in a given period of time (regularly in a one-year basis that covers seasons). All of the authors considered in this chapter include in their models the social value of water. The ranges across the studies for irrigation water prices are USD 0.004-0.17/m^3. Table 8, shows a summary of the compiled costs.

Price USD per m^3			Time Horizon	Valuation Methodology	Source
Min	**Average**	**Max**			
0	0.04	0.31	2001-2002	Residual Method (Rainy Season)	Hellegers et al., 2010
0	0.03	0.31	2001-2002	Residual Method (Dry Season)	
0.06	0.08	0.15	2009-2010	Shadow Price	Lionboui et al., 2014
0.005	0.09	0.17	2004	Social Costs	Williams et al., 2017
-	0.00669	-	2006-2010	Shadow Price	Bierkens et al., 2019
-	0.0684	-	1991-2010	Shadow Price	

Table 8. Summary of compiled prices of irrigation water in USD per m^3.

2.2.3 Land Use

There are global initiatives implemented in order to create awareness on the need for sustainable land use. For instance, the Economics of Land Degradation (ELD) was created in the year 2011 in order to provide guidelines for land degradation valuation processes (ELD Initiative, n.d). The ELD also aims to help nations around the world to achieve the target number 15 (Life on land) of the Sustainable Development Goals (ELD Initiative, 2015). The ELD Initiative, in the year 2017, assessed the costs of land degradation in Africa. The study analyses a cropland area of 105 million hectares, in over 42 countries of the continent during the years 2016-2031. The research is based on an empirical approach align with economic valuation (cost-benefit). The results for the overall sample show that the cost of inaction against nutrients depletion, induced by soil erosion, is ca. USD 127 billion per year, while the cost of action is ca. USD 9.4 billion.

Land-use valuation is an incentive for appropriate land management, and the results are determining for policymaking. The cost-benefit analysis includes the factors that triggers land degradation such as topography, land cover, poverty, and access to commodity market amongst others (Lambin et al., 2011 In: Turner et al., 2015). According to Costanza et al., (2007 In: Turner et al., 2015), the analysis of processes involved in land use degradation and restoration, must have a sustainable and holistic approach, in which human, built, natural and social capitals are considered.

De Groot et al., (2012), assess the average monetary value of 10 biomes that includes tropical and temperate forest, woodlands and grass. The authors conducted a literature review of local studies around the world, alike databases, academic publications and case studies for 22 ecosystem services considered per biome. The authors costed each service by using different methodologies, depending on the purpose of the valuation, socio-economic and environmental background. The compiled data is stored in a database in which values are normalized in a common set of units ($/ha/yr). Table 9, shows the total monetary values of the ecosystem services per biome relevant to land use.

	Min	Median	Max
Tropical forest	1,581	2,355	20,851
Temperate forest	278	1,127	16,406
Woodlands	1,373	1,522	21,88
Grasslands	124	2,698	5,930

Table 9. Total monetary volume of ecosystem services per biome on USD_{2007}/ha/yr. Adapted from: De Groot et al., (2012).

Shadow pricing has also been an alternative to estimate land use monetary value. Arslan (2008) assesses land allocation decisions for modern and traditional maize crops in the Mexican rural area. She compares the effectiveness of shadow and market prices to better reflect the value of farmers' product or output. For this purpose, the author develops a theoretical model, feed with survey data form the Mexican National Rural Household Survey and the National Institute of Statistics, Geography and Informatics. The sample includes 1782 households and 16 villages, which according to the author, is representative of Mexican rural area. Arslan (2008) concluded that the shadow prices, for her study case, reflect non-market values of subsistence farming of traditional maize varieties, while market values fail to do so. According to the author, market prices are not representative when farmers have attached an important amount of non-market values to their crops.

Lighart & Van Harmelen (2019), assess the costs of land use through abatement-based and damage-base shadow prices. The methodology uses Soil Organic Carbon (SOC) depletion as main parameter to calculate abatement initiatives, such as adding organic matter to agricultural soil. Damage-based shadow price is calculated by considering the reaction of crops production to SOC. The results estimate the following prices for SOC depletion: EUR 0.10/kg^{-1} for abatement-based shadow price and EUR 0.0286/kg^{-1} for damage-base shadow price.

The available information regarding land use prices mainly provides guidelines and theoretical model that can be apply depending on specific needs. The prices found correspond to different econometric analysis, models, parameters and variables, which makes it difficult to compare between them. De Groot et al., 2012 contribute with global prices of ecosystem services, which can be a baseline to know the economic impact of land demand of a certain commodity or industry in the assess biomes.

3 Case Study: Carbon Dioxide

This chapter is divided in two sections. The first section describes the methodology used to calculate the economic impact of CO_2 planetary boundaries to metal's mining. The second section shows the results of the applied methodology.

For this case study there are assessed 16 large-scale mining companies that produce copper, iron ore, aluminium (bauxite ore) and gold. The aluminium (bauxite ore) producers considered in this study account for approximately 39% of global outputs for the year 2016. The assessed mining companies for Copper have a share of ca. 33%, gold 19% and Iron ore approximately 33% (Tost et al, 2018).

The CO_2 emissions per firm are costed using the estimated prices of USD_{2016} CO_2/t that derive out of the applied methodology for this master thesis. The results are subtracted to the company's revenues in order to identify the hypothetical impact in their finances.

3.1 Methodology

The prices compiled in literature research for CO_2, are shown in Annex I and II. All the values for CO_2/t are exchanged to the same currency (USD/tCO_2), using World Bank exchange rates (The World Bank, 2019b). The Annex III shows the calculations only for a 2 ºC scenario, since all the values for 1.5 ºC were obtained in USD. Considering the opportunity to give knowledge value to this master thesis, 2016 is chosen as base year. On the one hand the results can complement other studies such as Tost et al., (2018). On the other hand, important commodity's economic indicators, such as those from the World Mining Data Report (2018), are updated until the year 2016.

The prices are converted to 2016 base year prices by using the US inflation rates (IMF, 2019). For this process there are selected only those costs that have year horizon up to 2020, since Inflation forecasts are not accurate or even available above the year 2025. Unless specified different by the sources, the value of money for prices of CO_2/t, is assumed to be the time horizon of the study. To convert the prices to 2016 base year, first there are compiled the US annual inflation rates, given by the International Monetary Fund (IMF, 2019). Each rate is divided by 100 in order to obtain a conversion factor per unit. These factors are used to calculate the cumulative inflation rate factor from the date of origin to the base year. From the cumulative values, 1 unit is subtracted in order to estimate the rate (%) (Table 10). For more detail information regarding the calculation of the inflation rates see Annex IV and V.

Year	Inflation rate
2005	**19%**
2006	16%
2007	12%
2008	12%
2009	10%
2010	**7%**
2011	5%
2012	3%
2013	1%
2014	1%
2015	0%
2016	1%
2017	3%
2018	6%
2019	7%
2020	**11%**

Table 10. Inflation rates used to convert all the prices to 2016 base year. Calculation based on: (IMF, 2019)

After the inflation rates are calculated, the author converted all the prices for CO_2/t compiled in the literature review (Table 11 and 12 to the year 2016). Average minimum and maximum values for CO_2/t are derived out of the converted prices. It is estimated for a 2 ºC constraint a minimum average cost per ton of CO_2 of USD_{2016} 23 and maximum USD_{2016} 67/tCO_2. For a 1.5 ºC scenario the estimated values are USD_{2016} 35/tCO_2 minimum and maximum USD_{2016} 93/tCO_2. These price ranges are used to calculate the costs of CO_2 emissions per assessed mining company.

Price USD CO_2/ton		**Value of money base year**	**Inflation Rate**	**Price USD_{2016} CO_2/t**	
Min	**Max**			**Min**	**Max**
5	40	2020	11%	6	44
5	15	2010	7%	5	16
5	20	2020	11%	6	22
19	41	2020	11%	21	46
18	250	2010	7%	19	268
24	50	2020	11%	27	56
18	27	2020	11%	20	30
40	120	2020	11%	44	133
30	50	2020	11%	33	56
40	80	2020	11%	44	89
-	30	2020	11%	-	33
-	20	2005	19%	-	24
-	45	2020	11%	-	50

Table 11. Prices of CO_2/t, in a 2 ºC scenario, converted to base year 2016

Price USD CO_2/ton		**Value of money base year**	**Inflation Rate**	**Price USD_{2016} CO_2/t**	
Min	**Max**			**Min**	**Max**
15	45	2010	7%	16	48
50	165	2010	7%	54	177
	50	2005	11%		56

Table 12. Prices of CO_2/t, in a 1.5 ºC scenario, converted to base year 2016

The 2016 sustainability reports of 16 of the largest firms that produce gold, iron ore, copper and aluminium (bauxite ore) are reviewed in order to obtain the emissions (tons of CO_2) related to their activity. In parallel, data on their revenues and profits is extracted from their annual reports (Table 13). The impact on revenues is assessed by multiplying the corresponding average of the obtained minimum and maximum prices of CO_2/ton to the amount of companies' self-reported emissions in the year 2016. Such theoretical costs are subtracted from revenues of each company, in order to identify the relative additional costs of CO_2 emissions.

Companies	Revenues (USD)	Emission (t)	Source
	Aluminium		
Alcoa	$ 9,318,000,000	21,800,000	Alcoa, 2016
Chalco	$ 25,616,038,410	68,620,000	Chalco, 2017
Hydro	$ 9,756,309,524	13,000,000	Hydro, 2016
	Copper		
Codelco	$ 11,537,000,000	5,000,000	Codelco, 2016
Freeport-McMoRan	$ 14,830,000,000	10,400,000	Freeport-McMoRan, 2016
Glencore	$ 42,142,000,000	3,510,000	Glencore, 2016
BHP	$ 30,900,000,000	6,900,000	BHP, 2016
Southern Copper	$ 5,379,000,000	5,390,000	Southern Copper Corp, 2016
	Gold		
Barrick	$ 8,558,000,000	3,646,671	Barrick, 2016
Newmont	$ 6,711,000,000	4,300,000	Newmont, 2016
Anglo Gold Ashanti	$ 4,254,000,000	4,062,000	Anglo Gold Ashanti, 2016
Goldcorp	$ 3,510,000,000	1,143,616	Goldcorp, 2016
Kinross	$ 3,472,000,000	1,568,000	kinross, 2016
	Iron ore		
Rio Tinto	$ 33,781,000,000	32,000,000	Rio Tinto, 2016
Vale	$ 27,488,000,000	14,000,000	Vale, 2016
FMG (Fortescue Metal Group)	$ 7,100,000,000	1,760,000	FMG, 2016

Table 13. Summary of self-reported revenues and emissions in the year 2016 from large-scale mining companies that extract aluminium (bauxite ore), copper, gold and iron ore.

3.2 Results

All reviewed companies reported their emissions and revenues in annual reports. This master thesis considers scope 1 and 2[15] from the companies' sustainability reports, since not all the firms report their emissions exclusively for the ore extraction but for the whole mining cycle. In terms of total outputs, the firms that produce aluminium are accountable for the largest CO_2 emissions to the atmosphere with an overall of ca. 103 Mt, followed by iron ore miners/ steel producers with ca. 48 Mt. Copper and gold producers contribute with ca. 31 Mt and 13 Mt respectively. Accordingly, a pricing scheme for carbon emissions would have the highest negative impact on aluminium (bauxite ore) producers' revenues in both 2 ºC and 1.5 ºC scenario (Table 14 and 15). Notably, copper mining companies' revenues were not only the highest in 2016 for this sample, but also their total CO_2 emissions were lower when compared to those from bauxite ore extraction.

Companies	Revenues (MUSD)	Emission (Mt)	Min. emission costs MUSD$_{2016}$	Max. Emission costs MUSD$_{2016}$	Min. Impact to revenues	Max. Impact to revenues
Aluminium						
Alcoa	$ 9,318	22	$ 501	$ 1,461	5.38%	15.68%
Chalco	$ 25,616	69	$ 1,578	$ 4,598	6.16%	17.95%
Hydro	$ 9,756	13	$ 299	$ 871	3.06%	8.93%
Copper						
Codelco	$ 11,537	5	$ 115	$ 335	1.00%	2.90%
Freeport-McMoRan	$ 14,830	10	$ 239	$ 697	1.61%	4.70%
Glencore	$ 42,142	35	$ 81	$ 235	0.19%	0.56%
BHP	$ 30,900	69	$ 159	$ 462	0.51%	1.50%
Southern Copper	$ 5,379	5	$ 124	$ 361	2.30%	6.71%

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[15] Scope 1 are direct emissions from sources that are owned or control by the Company. Scope 2 are indirect emissions from sources that are owned or controlled by the Company (EPA, 2018).

Gold						
Barrick	$ 8,558	4	$ 84	$ 244	0.98%	2.85%
Newmont	$ 6,711	4	$ 99	$ 288	1.47%	4.29%
Anglo Gold Ashanti	$ 4,254	4	$ 93	$ 272	2.20%	6.40%
Goldcorp	$ 3,510	1	$ 26	$ 77	0.75%	2.18%
Kinross	$ 3,472	2	$ 36	$ 105	1.04%	3.03%
Iron ore						
Rio Tinto	$ 33,781	32	$ 736	$ 2,144,0	2.18%	6.35%
Vale	$ 27,488	14	$ 322	$ 938,0	1.17%	3.41%
FMG (Fortescue Metal Group)	$ 7,100	2	$ 40	$ 117,9	0.57%	1.66%

Table 14. Impact of CO_2/ton prices, in a 2º C scenario, to extractive companies' revenues, coasting CO_2 emissions with a min. value of USD_{2016} 23/tCO_2 and max. value USD_{2016} 67/tCO_2.

Companies	Revenues (MUSD)	Emission (Mt)	Min. emission costs MUSD2016	Max. Emission costs MUSD2016	Min. Impact to revenues	Max. Impact to revenues
Aluminium						
Alcoa	$ 9,318	22	$ 763	$ 2,027	8.19%	21.76%
Chalco	$ 25,616	69	$ 2,402	$ 6,382	9.38%	24.91%
Hydro	$ 9,756	13	$ 455	$ 1,209	4.66%	12.39%
Copper						
Codelco	$ 11,537	5	$ 175	$ 465	1.52%	4.03%
Freeport-McMoRan	$ 14,830	10	$ 364	$ 967	2.45%	6.52%
Glencore	$ 42,142	35	$ 123	$ 326	0.29%	0.77%
BHP	$ 30,900	7	$ 242	$ 642	0.78%	2.08%
Southern Copper	$ 5,379	5	$ 189	$ 501	3.51%	9.32%
Gold						
Barrick	$ 8,558	4	$ 128	$ 339	1.49%	3.96%
Newmont	$ 6,711	4	$ 150	$ 400	2.24%	5.96%
Anglo Gold Ashanti	$ 4,254	4	$ 142	$ 378	3.34%	8.88%
Goldcorp	$ 3,510	1	$ 40	$ 106	1.14%	3.03%
Kinross	$ 3,472	2	$ 55	$ 146	1.58%	4.20%

Iron ore									
Rio Tinto	$	33,781	32	$	1,120	$	2,976	3.32%	8.81%
Vale	$	27,488	14	$	490	$	1,302	1.78%	4.74%
FMG (Fortescue Metal Group)	$	7,100	2	$	62	$	164	0.87%	2.31%

Table 15. Impact of CO$_2$/ton prices, in a 1.5 ºC scenario, to extractive companies' revenues, coasting CO$_2$ emissions with a min. value of USD$_{2016}$ 35/tCO$_2$ and max. value USD$_{2016}$ 93/tCO$_2$.

Comparing companies' total production outputs with CO$_2$ emissions may serve as an indicator for mineral specific taxation. Nevertheless, it has to be considered that for this master thesis, it is used the total firm's CO$_2$ emissions and not those specific per commodity. The data shows that the carbon emission levels are strongly dependent on the metal, with copper having the highest emissions per company's total output, then aluminium production, and with much lower emissions per output iron ore (see Table 16 and Figure 4). The output of gold is measured in ounces and is shown separately in Figure 5.

The two figures also illustrate that significant differences exist in the efficiency of production per ton measured in CO$_2$ output. Since the major source for emissions in the mineral industry stems from processing and the associated power consumption, these findings suggest that efficiencies can be improved for low-performing companies. However, the absence of a clear regulation for reporting of CO$_2$ emissions makes such values difficult to compare. While those companies listed on international exchanges are required to disclose their emissions, there is no defined methodology in doing so.

Companies	Emission (Mt)	Production	Emissions per unit of total output
Aluminium (Mt)			
Alcoa	22	45	0.49
Chalco	69	38	1.82
Hydro	13	11	1.18
Copper (Production Mt)			
Codelco	5	19	0.26
Freeport-McMoRan	10	2	5.00
Glencore	35	1	35.00
BHP	7	2	3.50
Southern Copper	5	1	5.00
Gold (Production Moz)			
Barrick	3.646	5.5	0.66
Newmont	4.3	5.3	0.82
Anglo Gold Ashanti	4.062	3.6	1.12
Goldcorp	1.143	2.9	0.40
Kinross	1.568	2.8	0.56
Iron ore (Production Mt)			
Rio Tinto	32	281	0.11
Vale	14	349	0.04
FMG (Fortescue Metal Group)	2	181	0.01

Table 16. CO_2 Emissions per ton and per ounce of production and emissions per unit of companies' total output. Source: Companies' sustainability reports 2016.

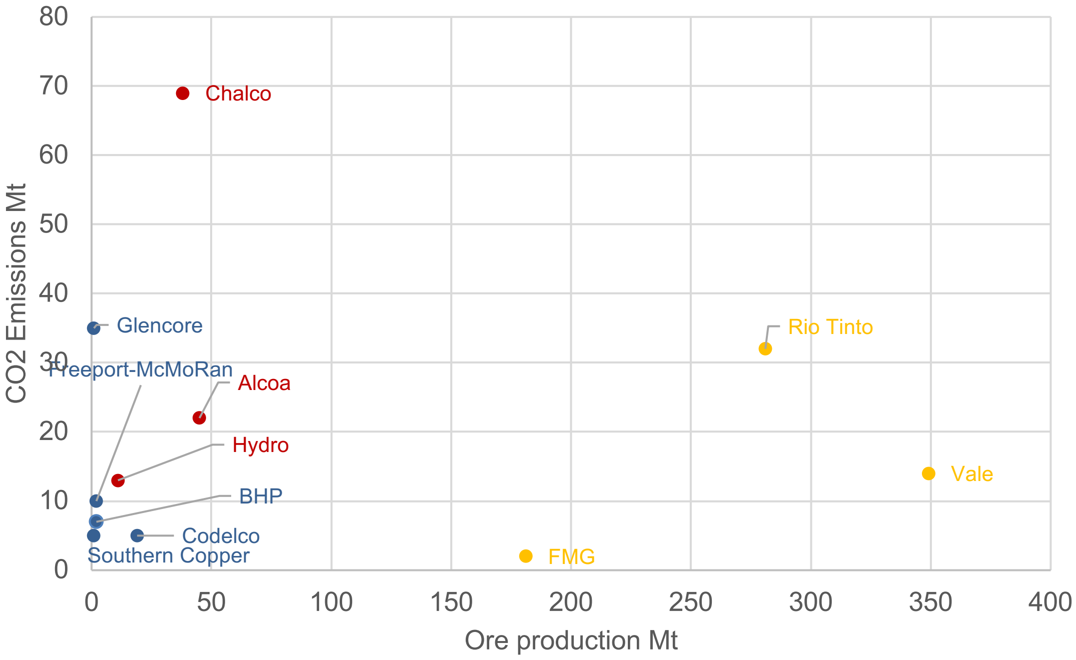

Figure 4. Indicators of the relationship between amount of emissions of CO_2 and company's total output in the year 2016. Source: Companies' annual reports from the year 2016.

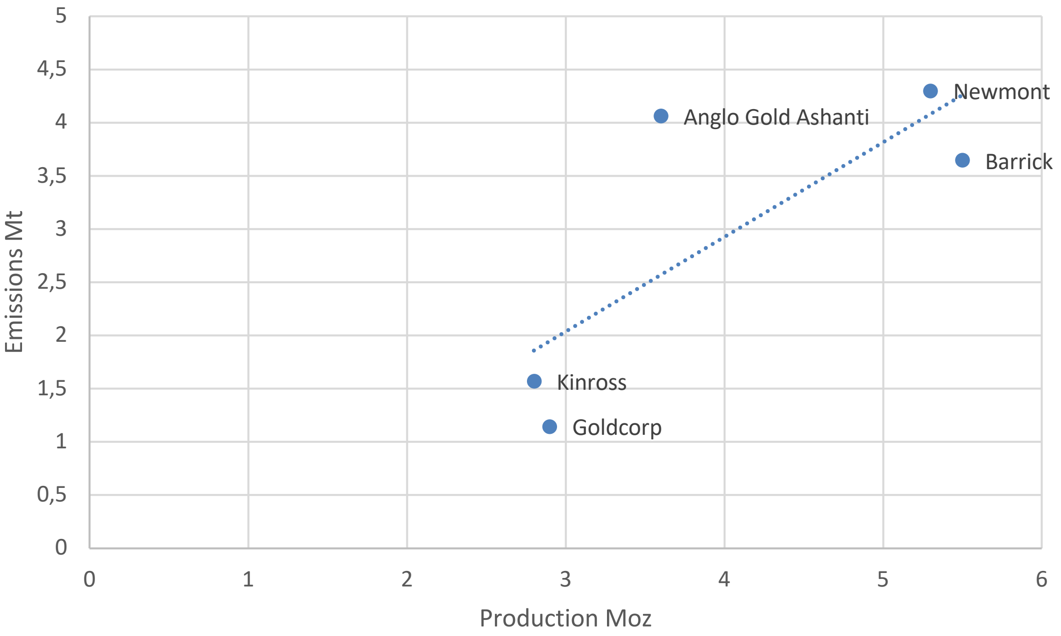

Figure 5. Relationship between amount of emissions of CO_2 per produced ounce of gold. Source: Companies' annual reports from the year 2016.

If the same costs for emissions are applied to all companies, the extent to which the firm's profitability is affected depends on amount of emissions and revenues. Figure 6 shows that significant differences in both revenues and emissions exist across companies, independent of which mineral they produce. Copper producers tend to have the most revenues compared to their CO_2 emissions, with BHP and Glencore performing significantly better than other companies. The next best ratio is by iron ore producers, followed by gold producers. Bauxite ore producers perform the worst, showing the lowest revenues per emitted ton of CO_2.

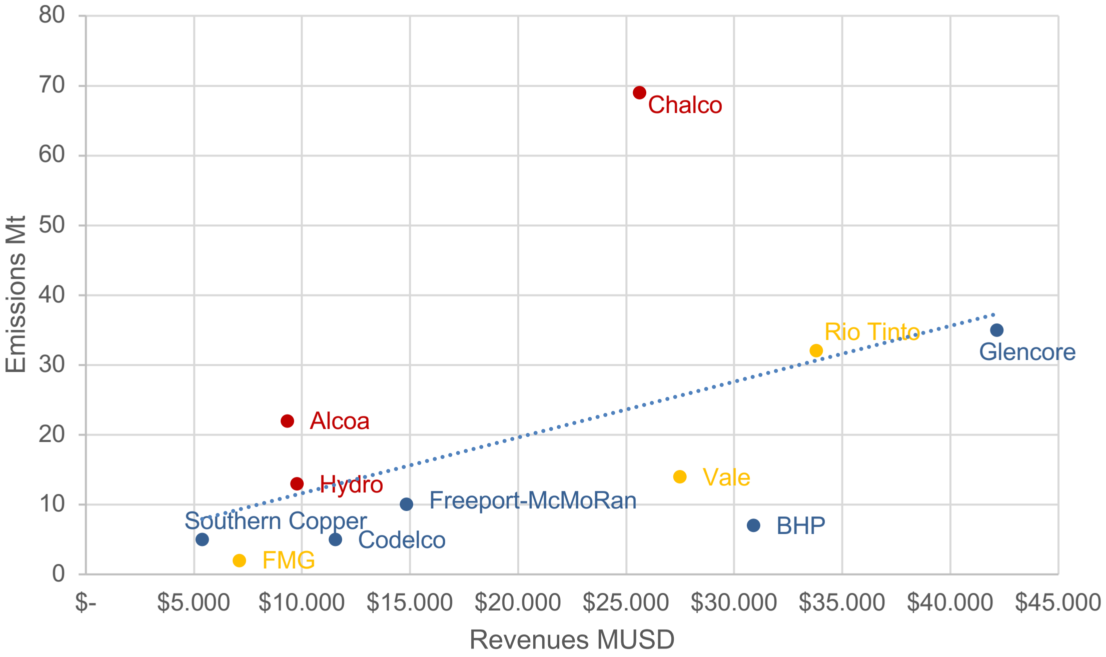

Figure 6. Relationship between amount of emissions of CO_2 and companies' revenues. Source: Companies' annual reports of the year 2016, WMD and Tost et al (2018).

In accordance to the World Gold Council (2018), the assessed companies that produce aluminium emit by far more CO_2 per USD than copper, gold and iron. Iron has less emissions intensity per unit value, while gold and copper show a similar trend (Figure 7). This means that aluminium companies, in order to make one unit of revenue emit about 2.4 times more CO_2 than gold and copper, and ca. 3.7 times above those of iron ore.

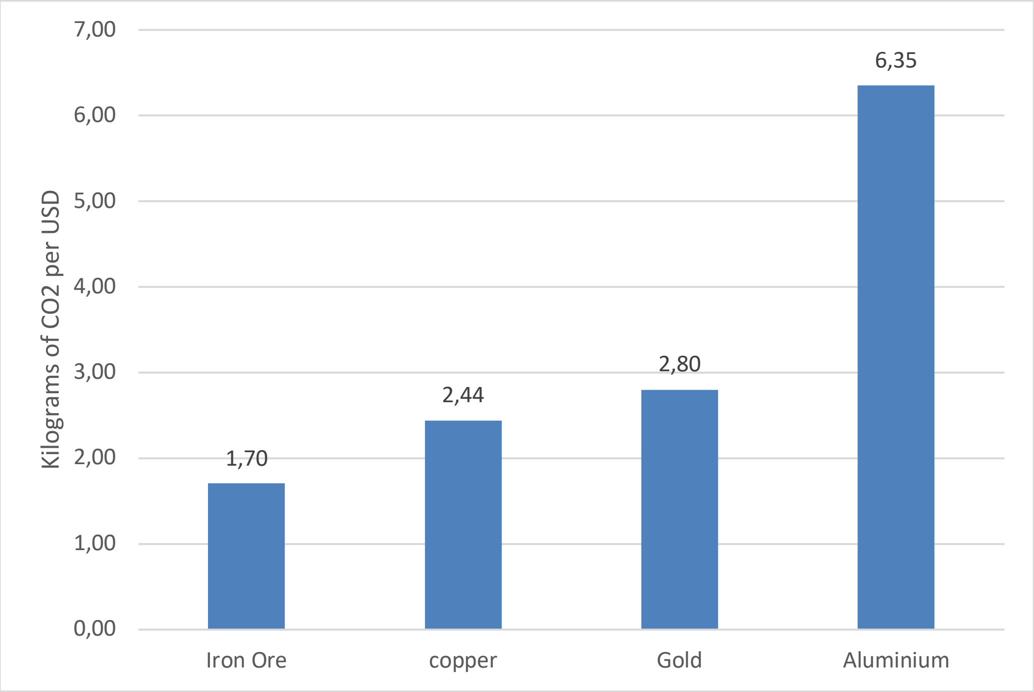

Figure 7. Emissions intensity per unit value. Source: Companies' annual and sustainability reports.

All the profits from the assessed companies (Annex VI) that produce bauxite ore will exhaust as a result of an additional max. cost of USD_{2016} 67 CO_2/t (Table 17). In the case in which a minimum cost of USD_{2016} 23 CO_2/t is introduced, only Hydro would be able to keep making profit. This are the hypothetical outcomes for a 2 ºC scenario. Under this costing scheme, only Glencore and Southern Copper will be able to make profit if both, minimum and maximum USD_{2016} CO_2/t are considered. Codelco, Freeport-McMoRan and BHP Billiton won't have profits in any of the scenarios. This is also due to profit loses that Freeport-McMoRan and BHP report for the year 2016. The firms that produce gold are able to afford the given prices of CO_2/t, excluding Anglo Gold Ashanti and Kinross. Anglo Gold Ashanti won't be able to make profit if any of the costs are added, while Kinross will only be able to support the min. value for CO_2/t.

In a 1.5 ºC scenario, with prices of USD_{2016} 35 CO_2/t minimum and USD_{2016} 93 CO_2/t maximum, more companies will fail on making profit (Table 18). From the reviewed firms that produce bauxite ore, only Hydro will be able to make profit if only a price of USD_{2016} 35 CO_2/t is considered. For all the companies that produce copper and gold their profits will be exhausted with a max. given price for CO_2/t, excepting Southern Copper and Goldcorp. Southern Copper and Goldcorp are able to afford the minimum and maximum prices. Codelco, Glencore, Newmont and Kinross can still make profit with a price for CO_2/t of USD_{2016} 35. Under both, 2 ºC and 1.5 ºC scenario, with the given minimum and maximum prices per ton of CO_2, the companies that produce iron ore are able to make profit.

Companies	Min. Impact to revenues	Max. Impact to revenues	Profit margin
	Aluminium		
Alcoa	5.38%	15.68%	-4.29%
Chalco	6.16%	17.95%	1.31%
Hydro	3.06%	8.93%	8.04%
	Copper		
Codelco	1.00%	2.90%	4.33%
Freeport-McMoRan	1.61%	4.70%	-21.31%
Glencore	0.19%	0.56%	327%
BHP	0.51%	1.50%	-20.18%
Southern Copper	2.30%	6.71%	14.46%
	Gold		
Barrick	0.98%	2.85%	7.65%
Newmont	1.47%	4.29%	3.28%
Anglo Gold Ashanti	2.20%	6.40%	1.48%
Goldcorp	0.75%	2.18%	4.62%
Kinross	1.04%	3.03%	2.68%
	Iron ore		
Rio Tinto	2.18%	6.35%	14.14%
Vale	1.17%	3.41%	14.46%
FMG (Fortescue Metal Group)	0.57%	1.66%	13.87%

Table 17. Percentage of profits out of revenues and comparison with impact of CO_2/t prices in a 2 ºC Source: Company's annual reports from the year 2016.

Companies	Min. Impact to revenues	Max. Impact to revenues	Profit Margin
		Aluminium	
Alcoa	8.19%	21.76%	-4.29%
Chalco	9.38%	24.91%	1.31%
Hydro	4.66%	12.39%	8.04%
		Copper	
Codelco	1.52%	4.03%	4.33%
Freeport-McMoRan	2.45%	6.52%	-21.31%
Glencore	0.29%	0.77%	3.27%
BHP	0.78%	2.08%	-20.18%
Southern Copper	3.51%	9.32%	14.46%
		Gold	
Barrick	1.49%	3.96%	7.65%
Newmont	2.24%	5.96%	3.28%
Anglo Gold Ashanti	3.34%	8.88%	1.48%
Goldcorp	1.14%	3.03%	4.62%
Kinross	1.58%	4.20%	2.68%
		Iron ore	
Rio Tinto	3.32%	8.81%	14.14%
Vale	1.78%	4.74%	14.46%
FMG (Fortescue Metal Group)	0.87%	2.31%	13.87%

Table 18. Percentage of profits out of revenues and comparison with impact of CO_2/t prices in a 1.5 ºC Source: Company's annual reports from the year 2016.

Coherent with these findings, costs under different pricing scenarios for CO_2 emissions turn out differently. In the minimum pricing for 2 ºC scenario (USD_{2016} 23 CO_2/t), the costs for emissions accrue to an average share of each companies' revenue of 1.91%, and 5.57% under the maximum pricing scheme (USD_{2016} 67 CO_2/t). In a 1.5 ºC scenario the averages are 2.91% and 7.73%, considering a minimum price of USD_{2016} 35 CO_2/t and maximum of USD_{2016} 93 CO_2/t. These ranges however mask the very significant effect on the worst-performing companies, which, for example, under the maximum pricing scheme in a 2 ºC, accrue to up to 24.91% of revenues of Chalco or 21.95% of those of Alcoa. Under a 1.5 ºC limit value the percentages are 17.95% and 15.68%. In comparison, the share of revenue from such additional costs of the best performing company Glencore is affected by less than 1% in both pricing scenarios, as can be seen in the previous Table 15 and following Figures 8 and 9.

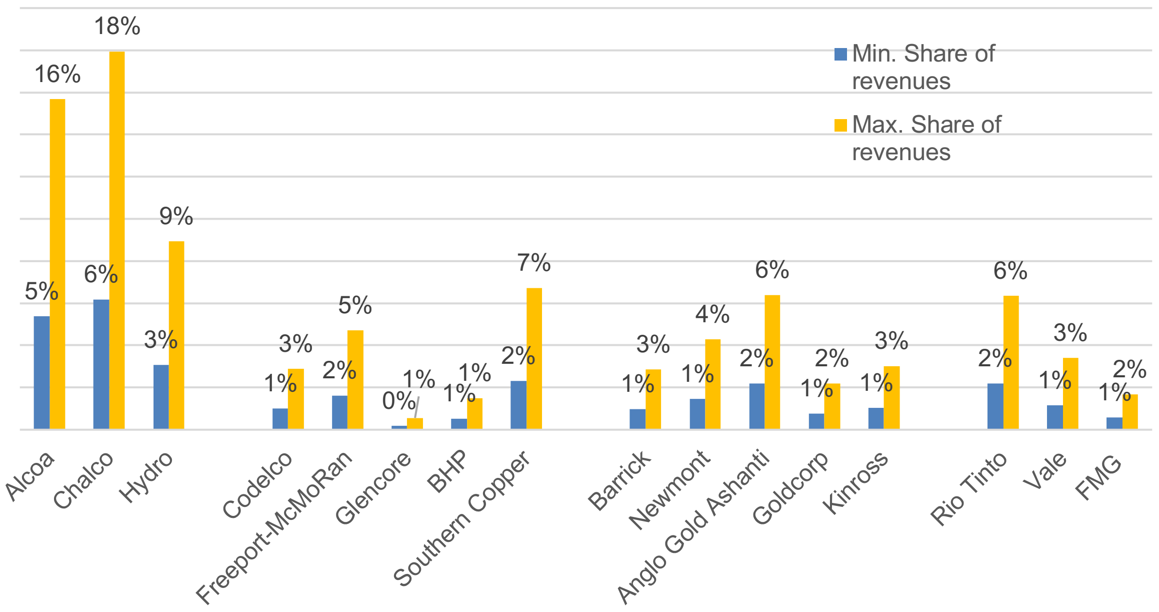

Figure 8. Impact of costs of CO_2/ton to companies' revenues, in a 2 ºC scenario, assuming a minimum cost of USD_{2016} 23 CO_2/t and a maximum cost of USD_{2016} 67 CO_2/t.

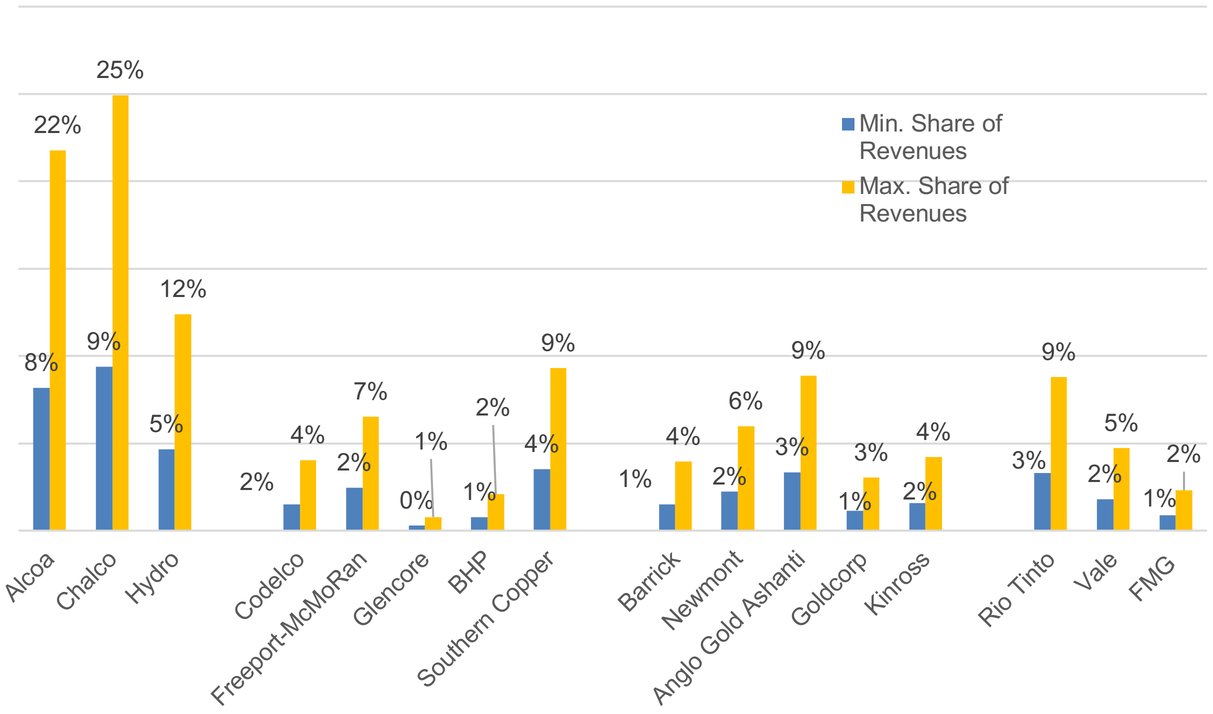

Figure 9. Impact of costs of CO_2/ton to companies' revenues, in a 1.5 ºC scenario, assuming a minimum cost of USD_{2016} 35 CO_2/t and a maximum cost of USD_{2016} 93 CO_2/t.

4 Conclusion

The climate change planetary boundary, when appropriately costed, implies an economic impact to metal's mining. It is still challenging to valuate land-use change and fresh-water use in a global scale, since there is not a consensus regarding their specific impact to the environment. Hence, no limit value for those planetary boundaries has yet been internationally implemented.

In the case of climate change, the Paris Agreement is a tool to enforce global limit values in which society must operate. The accord has been ratified by 185 parties, with the aim to prevent temperature to increase above 2 ºC from pre-industrial levels and make further efforts to stay within 1.5 ºC. To achieve such targets, countries have committed to establish policies within their own boundaries that will have an economic impact to their industries.

The case study of this master thesis shows that if prices of CO_2 are added, companies' revenues can not only be significantly diminished, but profits may be completely exhausted. Only the assessed companies that extract iron ore will be able to afford CO_2 prices in a range of USD_{2016} 23 – 93/tCO_2. It is evidenced the large differences of adverse effects across different mineral sectors, but also among the producers.

The limitations of this study include a relatively small sample of compiled CO2 prices and assessed firms, which only allow to draw limited conclusions regarding other producers. While these companies represent a significant share for each of the mineral produced and mineral production overall, it only includes the largest companies. For a comprehensive analysis, small and medium-sized enterprises should be also considered. Another issue is that no revenue or profit values, as well as CO_2 emissions by commodity were assessed, but only for the firm as a whole. Most of the companies in this sample engage in the production of more than one mineral. Another discussed shortcoming is the lack of a consistently applied methodology to account for CO_2 emissions by companies and the reliability of the self-reported data.

5 References

AAAS. 2007. AAAS Board Statement on Climate Change: Approved by the board of directors American Association for Advancement of Science 9 December 2006. 2 P. Retrieved from: https://www.aaas.org/sites/default/files/s3fs-public/aaas_climate_statement_0.pdf

Alcoa. 2016. Annual Report 2016. Retrieved from: http://www.annualreports.com/HostedData/AnnualReportArchive/a/NYSE_AA_2016.pdf

Allen, M.R., O.P. Dube, W. Solecki, F. Aragón-Durand, W. Cramer, S. Humphreys, M. Kainuma, J. Kala, N. Mahowald, Y. Mulugetta, R. Perez, M.Wairiu, and K. Zickfeld, 2018: Framing and Context. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press. Retrieved from: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter1_Low_Res.pdf

AMS. 2012. Climate Change: An information statement of the American meteorological society. Retrieved from: https://www.ametsoc.org/index.cfm/ams/about-ams/ams-statements/archive-statements-of-the-ams/climate-change1/

Anglo Gold Ashanti. 2016. Annual Financial Statements. Retrieved from: https://www.anglogoldashanti.com/investors/annual-reports/#2016

Arslan, A. 2008. Shadow Vs. Market Prices in Explaining Land Allocation: Subsistence Maize cultivation in Rural Mexico. Kiel Working paper No. 1469. Retrieved from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.601.1708&rep=rep1&type=pdf

Baiocchi, G. 2012. Methods on dimensions of ecological economics. Ecological Economics 75: 1-9.

Barrick. 2016. 2016 Year-end Report and Fourth Quarter Results. Retrieved from: https://barrick.q4cdn.com/788666289/files/doc_financials/quarterly/2016/q4/Barrick-2016-Q4-Year-End-Report.pdf

Barthlott, W., Kreft, H., Mutke, J., Daud Rafiqpoor, M. 2007. Geographic patterns of vascular plant diversity at continental to global scale. Erdkunde, band 61, heft 4:305-316. Retrieved from: https://www.researchgate.net/publication/215672847_Geographic_patterns_of_vascular_plant_diversity_at_continental_to_global_scale/link/0fcfd50472769a1c6c000000/download

Bierkens, M.F.P., Reinhard, S., Brujin, J., Veninga, W & Wada, Y. 2019. The Shadow Price of Irrigation Water in Major Groundwater-Depleting Countries. Retrieved from: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018WR023086

BHP. 2016. BHP Billiton Annual Report 2016. Retrieved from: https://www.bhp.com/media-and-insights/reports-and-presentations/2016/09/2016-annual-reporting-suite

Bimal, K. P & Rashid, H. 2016. Land Use change and Coastal Management. Climatic Hazards in Coastal Bangladesh, Butterworth-Heinemann, chapter 6:183-207. Retrieved from: https://www.sciencedirect.com/science/article/pii/B9780128052761000065

Brander, M & Davis, G. n.d. Greenhouse Gases, CO_2, CO_2e, and Carbon: What Do All These Term Means? Retrieved from: https://ecometrica.com/assets//GHGs-CO2-CO2e-and-Carbon-What-Do-These-Mean-v2.1.pdf

Bundesministerium. 2016. Plan de Acción Climática 2050. Bundesministerium für Umwelt, Naturschutz, Bau un Reaktorsicherheit. Retrieved from: https://unfccc.int/sites/default/files/resource/klimaschutzplan_2050_es_bf_0.pdf

Canfin, P., Grandjean, A & Mestrallet, G. 2016. Mission Report-Proposal for aligning carbon prices with the Paris Agreement. 15 P.

CDP, 2018. Carbon Pricing Corridors: The Market View 2018. Carbon Pricing Leadership Coalition. 39 P.

Chalco, 2016. 2016 Annual Results Announcement. Retrieved from: http://www.chalco.com.cn/chalcoen/rootfiles/2017/03/23/1490229844504018-1490229844506299.pdf

Climate Home News. 2019. Russia to ratify Paris Agreement; Putin says wind power 'shakes worms from de ground'. Retrieved from: https://www.climatechangenews.com/2019/07/09/russia-ratify-paris-agreement-putin-says-wind-power-shakes-worms-ground/

Codelco. 2016. Annual Report 2016. Retrieved from: https://www.codelco.com/memoria2016/en/

Council of the European Union. 2015. Ratification of the Doha Amendment. Retrieved from: http://data.consilium.europa.eu/doc/document/ST-10400-2014-REV-5/en/pdf

DDP, 2017. Carbon prices in national deep decarbonization pathways Insights from the Deep Decarbonization pathways project (DDP). 13 P.

De Groot, R., Brander, L., Van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodrigues, L. C., ten Brink, P & van Beukering, P. 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosystem Services, 1:50-61.

Department of Energy and Climate Change. 2009. Carbon Valuation in UK Policy Appraisal: A Revised Approach. Climate change Economic Department of Energy and Climate Change. 128 P.

EEA. 2019. Water use in Europe – Quantity and quality face big challenges. Retrieved from: https://www.eea.europa.eu/signals/signals-2018-content-list/articles/water-use-in-europe-2014

ELD Initiative. 2015. The value of land: Prosperous lands and positive rewards through sustainable land management. Retrieved from: https://www.eld-initiative.org/fileadmin/pdf/ELD-main-report_en_10_web_72dpi.pdf

ELD Initiative. 2017. The costs of land degradation and benefits of sustainable land management in Africa. Fact Sheet. Retrieved from: https://www.eld-initiative.org/fileadmin/pdf/Africa_Fact_Sheet.pdf

ELD Initiative. n.d. The ELD campus: Background. Retrieved from: https://www.eld-initiative.org/en/knowledge-hub/eld-campus/

EPA. 2016. Social Cost of Carbon. Accessed 25 August 2019, Retrieved from: https://www.epa.gov/sites/production/files/2016-12/documents/social_cost_of_carbon_fact_sheet.pdf

EPA. 2018. Greenhouse Gases at EPA. Accessed 20 September 2019, Retrieved from: https://www.epa.gov/greeningepa/greenhouse-gases-epa

ESS. 2018. European Attitudes to Climate Change and Energy: Topline results from Round 8 of the European Social Survey. Issue 9. 20 P. Retrieved from: https://www.europeansocialsurvey.org/docs/findings/ESS8_toplines_issue_9_climatechange.pdf

European Commission. n.da. Climate change consequences. Accesses 27 August 2019, Retrieved from: https://ec.europa.eu/clima/change/consequences_en

European Commission. n.db. Emissions cap and allowance. Accessed 27 August 2019, Retrieved from: https://ec.europa.eu/clima/policies/ets/cap_en

European Commission. n.dc. Effort sharing 2021-2030: targets and flexibilities. Accessed 26 August 2019, Retrieved from: https://ec.europa.eu/clima/policies/effort/regulation_en

European Commission Decision (ECD). 2017. Climate action, environment, resource efficiency and raw materials. 102 P.

FMG. 2016. Annual Report 2016. Retrieved from: http://www.annualreports.com/HostedData/AnnualReportArchive/F/ASX_FMG_2016.pdf

FAO.2014. Water withdrawal. Retrieved from: http://www.fao.org/nr/water/aquastat/infographics/Withdrawal_eng.pdf

FAO. 2016. AQUASTAT Main Database- Food and Agriculture Organization of the united Nations (FAO). Retrieved from: http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en

Freeport-McMoRan, 2016. 2016 Annual report. Retrieved from: http://www.annualreports.com/HostedData/AnnualReportArchive/f/NYSE_FCX_2016.pdf

Gerten, D., Hoff, H., Rockström, J., Jägermeyr, J., Kummu, M & Pastor, A. V. 2013. Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements. Current Opinion in Environmental sustainability, 5:551-558.

Gillingham, K & Stock, J, H. 2018. The Cost of Reducing Greenhouse Gas Emissions. Retrieved from: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf

Glencore. 2016. Annual report 2016. Retrieved from: https://www.glencore.com/dam/jcr:79d87b60-d53a-4f1a-9dbe-4d523f27de83/GLEN-2016-Annual-Report.pdf

Global Carbon Budget. 2018. Annual emissions of carbon dioxide (CO_2) from flaring, measured in tonnes. Retrieved from: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Goldcorp. 2016. Annual Report 2016. Retrieved from: https://s22.q4cdn.com/653477107/files/doc_financials/2016/2016-Annual-Report.pdf

Guivarch, C & Rogelj, J. 2017. Carbon price variations in 2 ºC scenarios explored. 15 P. Retrieved from: https://pdfs.semanticscholar.org/f8ca/312d9ee0ae250cad251d522569c8662c1290.pdf?_ga=2.220114201.1086278196.1566896990-1154557875.1566152357

Hare, B & Meinshausen, M. 2006. How Much Warming are We Committed to and How Much can be Avoided? Climatic Change 75 (1): 111-149. Retrieved from: https://www.researchgate.net/publication/225876492_How_Much_Warming_are_We_Committed_to_and_How_Much_can_be_Avoided

Heistermann, M. 2017. HESS Opinions: A planetary boundary on freshwater use is misleading. Hydrol. Earth Syst. Sci., 21, 3455-3461. Retrieved from: https://www.hydrol-earthh-syst-sci.net/21/3455/2017/hess-21-3455-2017.pdf

HM Government. 2017. The Clean Growth Strategy: leading the way to a low carbon future. Retrieved from: https://unfccc.int/sites/default/files/resource/clean-growth-strategy-amended-april-2018.pdf

Houghton, R. A., Hackler, J. L & Lawrence, K. T. 1999. The U.S. Carbon Budget: Contributions from Land-Use change. Science, Vol 285: 574-578.

Huang, S & Pollack, H. 1997. Late quaternary temperature changes seen in world-wide continental heat flow measurements. Geophysical Research Letters, Vol. 24, No. 15: 1947-1950.

Huang, Z., Hejazi, M., Li, X., Tang, Q., Vernon, C., Leng, G., Liu, Y., Döll, P., Eisner, S., Gerten, D., Hanasaki, N & Wada, Y. 2018. Reconstruction of global gridded monthly sectoral water withdrawals for 1971-2010 and analysis of their spatiotemporal patterns. Hydrol. Earth. Sci. 22, 2117-2133. Retrieved from: https://www.hydrol-earthh-syst-sci.net/22/2117/2018/hess-22-2117-2018.pdf

Hydro. 2016. Annual Report 2016. Retrieved from: https://www.miningdataonline.com/reports/annual/NorskHydro-2016-annual-report.pdf

International Energy Agency (IEA). 2015. Energy Technology Perspective: Mobilising Innovation to Accelerate Climate Action. 418 P.

Investopedia. 2019. Shadow pricing. Accessed 12 September 2019, Retrieved from: https://www.investopedia.com/terms/s/shadowpricing.asp

IPCC. 2014. Climate change: Summary for Policy Makers. Retrieved from: https://www.ipcc.ch/report/ar5/syr/

Johnson, S. 2017. Difference Between Global Warming & the Greenhouse Effect. Retrieved from: https://sciencing.com/difference-global-warming-greenhouse-effect-8092474.html

Kaplan, J.O., Krumhardt, K.M., Ellis, E.C., Ruddiman, W.F., Lemmen, C., & Klein Goldewijk, K. (2011). Holocene carbon emissions as a result of anthropogenic land cover change. The Holocene, 21(5), 775–791.

Kinross. 2016. Annual Report 2016. Retrieved from: http://www.annualreports.com/HostedData/AnnualReportArchive/k/TSX_K_2016.pdf

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., Pickers, P. A., Korsbakken, J. I., Peters, G. P., Canadell, J. G., Arneth, A., Arora, V. K., Barbero, L., Bastos, A., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Doney, S. C., Gkritzalis, T., Goll, D. S., Harris, I., Haverd, V., Hoffman, F. M., Hoppema, M., Houghton, R. A., Hurtt, G., Ilyina, T., Jain, A. K., Johannessen, T., Jones, C. D., Kato, E., Keeling, R. F., Goldewijk, K. K., Landschützer, P., Lefèvre, N., Lienert, S., Liu, Z., Lombardozzi, D., Metzl, N., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S., Neill, C., Olsen, A., Ono, T., Patra, P., Peregon, A., Peters, W., Peylin, P., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Rocher, M., Rödenbeck, C., Schuster, U., Schwinger, J., Séférian, R., Skjelvan, I., Steinhoff, T., Sutton, A., Tans, P. P., Tian, H., Tilbrook, B., Tubiello, F.

N., van der Laan-Luijkx, I. T., van der Werf, G. R., Viovy, N., Walker, A. P., Wiltshire, A. J., Wright, R., Zaehle, S., and Zheng, B.: Global Carbon Budget 2018, Earth Syst. Sci. Data, 10, 2141–2194, https://doi.org/10.5194/essd-10-2141-2018, 2018.

Lighart, T. N & Van Harmelen. 2019. Estimation of shadow prices of soil organic carbon depletion and fresh water depletion for use in LCA. The international Journal of Life Cycle Assessment. 18 P.

Lionboui, H., Fadlaoui, Z., Elame, F & Benabdelouahab, T. 2014. Water pricing impact on the economic valuation of water resources. International Journal of Education and Research, Vol 2, No 6: 147-166.

Mac, D. 2017. What is the relationship between global warming and the greenhouse effect? Retrieved from: https://socratic.org/questions/what-is-the-relationship-between-global-warming-and-the-greenhouse-effect

McKinsey. 2009. Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve. Retrieved from: https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/Sustainability/Our%20Insights/Pathways%20to%20a%20low%20carbon%20economy/Pathways%20to%20a%20low%20carbon%20economy.ashx

Mitchell, J.F.B. 1989. The ‘’Greenhouse’’ effect and climate change. Reviews of Geophysics, 27 (1), 115.

Newmont. 2016. 2016 Annual Report and Form 10-k. Retrieved from: https://s1.q4cdn.com/259923520/files/doc_financials/annual/2016/Newmont-2016-Annual-Report-Bookmarked-PDF-for-website.pdf

NOAA-ESRL. 2018. Annual mean carbon dioxide (CO_2) concentration data from the Mauna Loa monitoring station. Retrieved from: https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html

Nordhaus, T., Shellenberger, M & Blomqvist, L. 2012. The Planetary boundaries Hypothesis: a review of the Evidence. Break Through Institute. 39 P.

Nordhaus, W. 2007. The Challenge of Global Warming: Economic Models and Environmental Policy. Yale University. 153 P.

Nordhaus, W. 2013. DICE 2013R: Introduction and User’s Manual. Second Edition. 102 P.

Nordhaus, W. 2014. Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. Journal of the Association of Environmental and Resource Economists, Vol1, No.1/2, pp 273-312. Retrieved from: https://www.jstor.org/stable/pdf/10.1086/676035.pdf

OECD-IEA. 2017. Climate action, environment, resource efficiency and raw materials. 102 P.

OECD-FAO. 2018. OECD-FAO Agricultural Outlook 2018-2027. Retrieved from: http://www.agri-outlook.org/Outlook_flyer_EN.pdf

Oki, T & Kanae, S. 2006. Global Hydrological Cycles and World Water Resources. Science, Vol. 313: 1068-1072.

Postel, S. 1992. The last oasis: facing water scarcity. Worldwatch environmental alert series. 193 P.

Republique Française. 2017. Summary for decision-makers. Retrieved from: https://unfccc.int/sites/default/files/resource/National_Low_Carbon_Strategy_v2_EN.pdf

Revkin, A. 2019. Most Americans now worry about climate change- and want to fix it. National Geographic. Retrieved from: https://www.nationalgeographic.com/environment/2019/01/climate-change-awareness-polls-show-rising-concern-for-global-warming/

Rio Tinto. 2016. 2016 Annual report. Retrieved from: https://www.riotinto.com/documents/RT_2016_Annual_report.pdf

Ritchie, H & Roser, M. 2017. CO_2 and other Greenhouse Gas Emissions. Retrieved from: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin, III, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. Schellnhuber, B. Nykvist, C. A. De Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, & J. Foley. 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecology and Society 14(2): 32.

Rogelj, D., Popp, A., Calvin, K., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., Van Vuure, D. P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., Havlík, P., Humpenöder, F., Stehfest, E & Tavoni, M. 2018a. Scenarios towards limiting global mean temperature increase below 1.5°C. Nature Climate Change, Vol 8, 325:332.

Rogelj, D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, M. V. Vilariño. 2018b. Mitigation pathways compatible with 1.5°C in the context of sustainable development. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. In Press.

Royal Society of Chemistry. N. d. Periodic Table. Retrieved from: http://www.rsc.org/periodic-table

Sala, O., Chapin III, F. S & Huber-Sannwald, E. 2000. Potential Biodiversity Change: Global Patterns and Biome Comparisons. Retrieved from: https://www.agro.uba.ar/users/sala/pdfs/100-sala.pdf

Sandbang, 2019. Carbon Price Viewer. Retrieved form: https://sandbag.org.uk/carbon-price-viewer/

Schurer, A., Mann, M. E., Hawkins, E., Tett, S.F.B., Hegerl, G.C. 2017. Importance of pre-industrial baseline for likelihood of exceeding Paris goals. Nature Climate Change, 7 (8), 563-567.

Southern Copper Corp. 2016. Annual Report 2016. Retrieved from: http://www.annualreports.com/HostedData/AnnualReportArchive/s/NASDAQ_SCCO_2016.pdf

The European Union. 2016. The EU Emissions Trading System (EU ETS). Accessed 15 September 2019, Retrieved from: https://ec.europa.eu/clima/sites/clima/files/factsheet_ets_en.pdf

The Government of Japan. 2019. The long-term strategy under the Paris Agreement. 119 P. Retrieved from: https://unfccc.int/sites/default/files/resource/The%20Long-term%20Strategy%20under%20the%20Paris%20Agreement.pdf

The White House. 2016. United States Mid-Century Strategy for Deep Decarbonization. Accessed 23 August 2019, Retrieved from: https://unfccc.int/files/focus/long-term_strategies/application/pdf/mid_century_strategy_report-final_red.pdf

The White House. 2017. Statement by President Trump on the Paris Climate Accord. Accessed 25 September 2019, Retrieved from: whitehouse.gov/briefings-statements/statement-president-trump-paris-climate-accord/

The World Bank, 2019a. Carbon Pricing Dashboard. Accessed 24 August 2019, Retrieved from: https://carbonpricingdashboard.worldbank.org/map_data

The World Bank. 2019b. Official exchange rate (LCU per US$, period average). Accessed 18 September 2019, Retrieved from: https://data.worldbank.org/indicator/pa.nus.fcrf

Tost, M., Bayer, B., Hitch M., Lutter, S., Moser, P & Feiel, S. 2018. Metal Mining's Environmental Pressures: A Review and Updated Estimates on CO2 Emissions, Water Use, and Land Requirements. Sustainability 10:2-14.

UNDESA. 2014. Transboundary waters. Accessed 5 August 2019, Retrieved from: https://www.un.org/waterforlifedecade/transboundary_waters.shtml

UNESCO. 2019. The United Nations World Water Development Report 2019: leaving no one behind. Accessed 17 August 2019, Retrieved from: https://unesdoc.unesco.org/ark:/48223/pf0000367306

UNFCCC. n. d. International agreements on climate action. Accessed 25 August 2019, Retrieved from: https://www.consilium.europa.eu/en/policies/climate-change/international-agreements-climate-action/

United Nations. 2015. Paris Agreement. Accessed 25 July 2019, Retrieved from: https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

United Nations. 2019. Climate Action Summit 2019. Accessed 25 September 2019, Retrieved from: https://www.un.org/en/climatechange/un-climate-summit-2019.shtml

United Nations. n. d. Sustainable Development Goals. Accessed 17 August 2019, Retrieved from: https://www.un.org/sustainabledevelopment/water-and-sanitation/

University of Cambridge. 2019. Linking planetary boundaries to business: Part of Kering's series on planetary boundaries for business. Cambridge Institute for Sustainability Leadership. Accessed 2 October 2019, Retrieved from: https://www.cisl.cam.ac.uk/resources/natural-resource-security-publications/linking-planetary-boundaries-to-business-part-of-kerings-series-on-planetary-boundaries-for-business

USGS. 2015. Mining water use. Accessed 6 August 2019, Retrieved from: https://www.usgs.gov/mission-areas/water-resources/science/mining-water-use?qt-science_center_objects=0#qt-science_center_objects

USGS. 2019. Where is Earth's Water? Accessed 1 October 2019, Retrieved from: https://www.usgs.gov/special-topic/water-science-school/science/where-earths-water?qt-science_center_objects=0#qt-science_center_objects

USGS. N.d. How much Water is There on Earth. Accessed 18 August 2019, Retrieved from: https://www.usgs.gov/special-topic/water-science-school/science/how-much-water-there-earth?qt-science_center_objects=0#qt-science_center_objects

Vale. 2016. Annual Report: Form 20-F. Retrieved from: http://www.vale.com/EN/investors/information-market/annual-reports/Pages/default.aspx

Williams, R. B., Al-Hmoud, R., Segarra, E & Mitchell, D. 2017. An estimate of the Shadow Price of Water in the Southern Ogallala Aquifer. Journal of Water Resources and Protection, 9: 289-304. Retrieved from: https://pdfs.semanticscholar.org/fcd9/a62dc1c50ba187b943ec5b62d797d32d4ab8.pdf

World Bank Group. 2018. State and Trends of Carbon Pricing 2018. 62 P. Accessed 26 September 2019, Retrieved from: https://openknowledge.worldbank.org/bitstream/handle/10986/29687/9781464812927.pdf?sequence=5&isAllowed=y

World Gold Council. 2018. Gold and climate change: An introduction. Accessed 26 September 2019, Retrieved from: https://www.gold.org/goldhub/research/gold-and-climate-change-introduction

World Mining Data. 2018. Iron and ferro alloys metals, non-ferrous metals, precious metals, industrial minerals, mineral fuels. Federal Ministry of Sustainability and Tourism, Vienna. 263 P. Retrieved from: http://www.world-mining-data.info/wmd/downloads/PDF/WMD2018.pdf

Yang, Y., Zhang, S., Lui, Y., Xing, X & De Sherbinin, A. 2017. Analyzing historical land use changes using a Historical Land Use Reconstruction Model: a case study in Zhenlai County, northeastern China. Scientific Reports 7:1-16.

Young, R & Loomis, J. B. 2017. Determining the Economic Value of Water: Concepts and Methods. RFF Press, second edition. 359 P.

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8 List of Abbreviations

AC	Abatement Costs
CV	Contingent Valuation
DDPP	Deep Decarbonization Pathways Project
DICE	Dynamic Integrated Model of Climate and Economy
ELD	Economics on Land Degradation
EPA	Environmental Protection Agency
EU ETS	European Union Emission Trading Scheme
FAO	Food and Agricultural Organization of the United Nations
GDP	Gross Domestic Product
IAM	Integrated Assessment Model
IEA	International Energy Agency
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
MAC	Marginal Abatement Costs
MAD	Moroccan Dirham
OECD	Organisation for Economic Co-operation and Development
SDGs	Sustainable Development Goals
SCC	Social Cost of Carbon
SOC	Soil Organic Carbon

SPAs	Shared Policy Assumptions
SSPs	Shared Socioeconomic Pathways
UNDESA	United Nations Department of Economic and Social Affairs
USGS	United states Geological survey

9 Annex

Annex I. Summary of compiled prices of tCO_2 from literature research. The table only includes the prices that consider a 2 °C scenario.

Price CO2/ton		Unit	Time Horizon	Valuation Methodology	Source
Min	Max				
5	40	USD/t CO2	2020	IAM & Social Cost of Carbon	DDPP, 2017
5	15	USD2010/t CO2	2020	IAMs	Guivarch et al., 2017
5	20	USD/t CO_2	2020	Marginal abatement costs	OECD-IEA, 2017
14	31	GBP/t CO_2	2020	Marginal Abatement Costs	Department of Energy and climate change, 2009
18	250	USD$_{2010}$/t CO_2	2020	Integrated Models	Edenhofer et al., 2014
24	50	USD/t CO_2	2020	Marginal abatement costs (chemical and power sector)	CDP, 2018
20	30	EUR/tCO_2	2020	Expert interviews	Canfin et al, 2016
30	90	GBP/t CO_2	2020	Marginal Abatement Costs	Department of Energy and climate change, 2009
30	50	USD/t CO_2	2020	Marginal abatement costs	IEA, 2015
30	120	USD/t CO2	2050	Marginal Abatement Costs	OECD-IEA, 2017
35	105	GBP/t CO2	2030	Marginal Abatement Costs	Department of Energy and climate change, 2009
40	80	USD/t CO_2	2020	Social Cost of Carbon	The World Bank, 2019a
45	75	USD/t CO_2	2030	Marginal abatement costs	IEA, 2015
60	170	USD/t CO2	2040	Marginal Abatement Costs	OECD-IEA, 2017
80	190	USD/t CO2	2050	Marginal Abatement Costs	OECD-IEA, 2017
100	300	GBP/t CO2	2050	Marginal Abatement Costs	Department of Energy and climate change, 2009
-	30	USD/t CO2	2020	Expert interviews (tCO2 price for energy sector)	Canfin et al, 2016
-	20	USD$_{2005}$/t CO_2	2015	IAM (DICE)	Nordhaus, 2007
-	50	EUR/tCO2	2020	Expert interviews	Canfin et al, 2016
-	190	USD/t CO2	2050	Marginal Abatement Costs	OECD-IEA, 2017

Annex II. Summary of compiled prices of tCO_2 from literature research. The table only includes the prices that consider a 1.5 °C scenario.

Price CO2/ton			Time Horizon	Valuation Methodology	Source
Min	**Max**	**Unit**			
15	45	USD_{2010}/tCO_2	2020	IAM	Guivarch., 2017
50	165	USD_{2010}/tCO_2	2020	IAM (average discounted prices)	Rogelj et al., 2018a
135	6060	USD_{2010}/tCO_2	2030	IAM (undiscounted values)	Rogelj et al., 2018b
	50	$USD_{2005}/t\ CO_2$	2020	IAM (DICE)	Nordhaus, 2007

Annex III. Compiled Prices of CO_2/t in USD for a 2 ºC. The value of money is related to the time horizon of the study, unless the authors have specified different.

Price CO_2/ton		Value of money base year	Time Horizon	Valuation Methodology	Source
Min	Max				
5	40	2020	2020	IAM & Social Cost of Carbon	DDPP, 2017
5	15	2010	2020	IAMs	Guivarch et al., 2017
5	20	2020	2020	Marginal abatement costs	OECD-IEA, 2017
19	41	2020	2020	Marginal Abatement Costs	Department of Energy and climate change, 2009
18	250	2010	2020	Integrated Models	Edenhofer et al., 2014
24	50	2020	2020	Marginal abatement costs (chemical and power sector)	CDP, 2018
18	27	2020	2020	Expert interviews	Canfin et al, 2016
40	120	2020	2020	Marginal Abatement Costs	Department of Energy and climate change, 2009
30	50	2020	2020	Marginal abatement costs	IEA, 2015
40	80	2020	2020	Social Cost of Carbon	The World Bank, 2019a
-	30	2020	2020	Expert interviews (tCO2 price for energy sector)	Canfin et al, 2016
-	20	2005	2015	IAM (DICE)	Nordhaus, 2007
-	45	2020	2020	Expert interviews	Canfin et al, 2016

Annex IV. Calculation of exchange rate factor per unit

Year	US inflation rate	(US inflation rate)/100	Inflation Rate Factor	2005	2010	2016	2020
2005	3.4	0.034	1.034	1			
2006	3.2	0.032	1.032	1.032			
2007	2.9	0.029	1.029	1.06192			
2008	3.8	0.038	1.038	1.10228			
2009	-0.3	-0.003	0.997	1.09897			
2010	1.6	0.016	1.016	1.11655	1		
2011	3.1	0.031	1.031	1.15117	1.031		
2012	2.1	0.021	1.021	1.17534	1.05265		
2013	1.5	0.015	1.015	1.19297	1.06844		
2014	1.6	0.016	1.016	1.21206	1.08553		
2015	0.1	0.001	1.001	1.21327	1.08662		
2016	**1.3**	**0.013**	**1.013**	**1.22904**	**1.10074**	**1**	**0.92568**
2017	2.1	0.021	1.021				0.93772
2018	2.4	0.024	1.024				0.95741
2019	2	0.02	1.02				0.98039
2020	2.7	0.027	1.027				1
2021	2.3	0.023	1.023				

Annex V. Exchange rates use to convert CO_2/t prices to 2016 base year.

Year	Inflation Rate Factor	Exchange rate
2005	**1.229048362**	**19%**
2006	1.190938335	16%
2007	1.157374475	12%
2008	1.115004311	12%
2009	1.11835939	10%
2010	**1.100747431**	**7%**
2011	1.067650272	5%
2012	1.045690766	3%
2013	1.030237208	1%
2014	1.014013	1%
2015	1.013	0%
2016	1	1%
2017	0.987166831	3%
2018	0.966862714	6%
2019	0.944201869	7%
2020	**0.925688107**	**11%**
2021	0.892540747	

Annex 6. Percentage of company's profits out of their revenues. Source: Company's annual reports of the year 2016.

Companies	Revenues (MUSD)	Profits	Profit/Revenues
		Aluminium	
Alcoa	$ 9,318,000,000	-$ 400,000,000	-4.29%
Chalco	$ 25,616,038,410	$ 336,265,860	1.31%
Hydro	$ 9,756,309,524	$ 784,047,619	8.04%
		Copper	
Codelco	$ 11,537,000,000	$ 500,000,000	4.33%
Freeport-McMoRan	$ 14,830,000,000	-$ 3,160,000,000	-21.31%
Glencore	$ 42,142,000,000	$ 1,379,000,000	3.27%
BHP	$ 30,900,000,000	-$ 6,235,000,000	-20.18%
Southern Copper	$ 5,379,000,000	$ 778,000,000	14.46%
		Gold	
Barrick	$ 8,558,000,000	$ 655,000,000	7.65%
Newmont	$ 6,711,000,000	$ 220,000,000	3.28%
Anglo Gold Ashanti	$ 4,254,000,000	$ 63,000,000	1.48%
Goldcorp	$ 3,510,000,000	$ 162,000,000	4.62%
Kinross	$ 3,472,000,000	$ 93,000,000	2.68%
Iron ore			
Rio Tinto	$ 33,781,000,000	$ 4,776,000,000	14.14%
Vale	$ 27,488,000,000	$ 3,976,000,000	14.46%
FMG (Fortescue Metal Group)	$ 7,100,000,000	$ 985,000,000	13.87%