Chair of Mining Engineering and Mineral Economics

Master's Thesis

Water Withdrawals, CO2 Emissions and Land Use of Bauxite, Copper, Gold and Iron Ore Production: A general Review and Appraisal for the Year 2016

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Preface, Dedication, Acknowledgement

I dedicate this work to my parents who made it possible for me to study and to my entire family which I can always rely on. I also thank my supervisor Michael Tost who guided me with his experience. The cooperation was very helpful and instructive.

Abstract

While the environmental impact of metal mining is increasing, the quality of environmental analysis is stagnating. Reporting and thus sustainability analysis have not improved in the same way as the demand for resources is increasing. Overall, the environmental impact compared to other industries is low. Technological development counteracts the environmental impact due to increasing resource demand. Because the sites with the most favourable conditions are becoming less and less, the shift to the exploitation of less favourable deposits and the associated higher technical complexity leads to an alarming situation. With the higher effort, the environmental impact also increases. It is becoming increasingly important to be able to obtain more accurate results of global environmental impacts. The current and past methodology is no longer sufficient. Current reporting standards cannot meet the need to make environmental analyses comparable. The unsatisfactory data situation leads to problems faced by authors trying to assess the environmental impact of metal mining. Only transparent corporate-level reporting can lead to comparable quantitative environmental values in order to estimate an global impact that can be tracked over time with reasonable effort. This would require location-specific effort in the measurement and the calculation. The results should be reported summarized in a meaningful and transparent way in annual reports. Environmental impacts should be clearly attributable to a product. This kind of transparency would be an important step towards a more sustainable metal industry. The summary of publications in this area leads to the conclusion that the current methodology has reached its limit and the results of publications vary by a factor of 3 for water withdrawals and CO_2 emissions and by a factor of 2 for land use. In this thesis, values from literature are analysed for comparability and the mean values are used for further calculations if more than one data point is available. Water withdrawals for bauxite, copper, gold and iron ore are within a range of 3705 to 5726 Mm³. CO_2 emissions are within a range of 149.6 to 233 Mt. Land use for mining activities is within a range of 279 to 357 km².

Zusammenfassung

Während die Umweltauswirkungen des Metallbergbaus insgesamt steigen, stagniert die Qualität der Umweltanalyse. Die Berichterstattung und somit die Nachhaltigkeitsanalyse haben sich nicht in der gleichen Weise verbessert, wie die Nachfrage nach Ressourcen zunimmt. Die technologische Entwicklung wirkt den steigenden Umweltauswirkungen aufgrund des steigenden Ressourcen Bedarfs entgegen. Weil die Lagerstätten mit den günstigsten Bedingungen immer weniger werden, führen die Verlagerung zur Ausbeutung weniger günstiger Lagerstätten und der damit verbundene höhere technische Aufwand zu einer alarmierenden Situation. Mit dem höheren Aufwand steigen auch die Umweltauswirkungen. Die Umweltauswirkungen im Vergleich zu anderen Industriezweigen sind insgesamt jedoch (noch) gering. Es wird jedoch immer wichtiger, genauere Ergebnisse globaler Umweltauswirkungen zu erhalten. Die derzeit und in der Vergangenheit angewandte Methodik reicht nicht mehr aus. Aktuelle Berichtsstandards können die Notwendigkeit Umweltanalysen vergleichbar zu machen nicht erfüllen. Die unbefriedigende Datenlage führt zu Problemen, mit denen Autoren konfrontiert sind, die versuchen, die Umweltauswirkungen des Metallbergbaus zu bewerten. Nur eine transparente Berichterstattung auf Unternehmensebene kann zu vergleichbaren quantitativen Umweltwerten führen, um globale Auswirkungen abschätzen zu können, die mit vertretbarem Aufwand über die Zeit verfolgt werden können. Dafür müsste auch standortbezogener Aufwand bei der Messung und der Berechnung betrieben werden. Die Ergebnisse sollten detailliert und übersichtlich auf Unternehmensebene zusammengefasst werden. Z.B. sollten Daten in Jahresberichten umfassend sein und eindeutig einem Produkt zugeordnet werden können. Diese Art von Transparenz wäre ein wichtiger Schritt in Richtung einer nachhaltigeren Metallindustrie. Die Zusammenfassung der Veröffentlichungen in diesem Gebiet führt zu der Schlussfolgerung, dass die derzeitige Methodik an ihrer Grenze angelangt ist und die Ergebnisse von Publikationen für Wasserverbrauch und CO_2 Emissionen um den Faktor 3 variieren und für die Flächennutzung um den Faktor 2. Die Wasserentnahmen für Bauxit, Kupfer, Gold und Eisenerz liegen im Bereich von 3705 bis 5726 Mm³. Die CO2-Emissionen liegen im Bereich von 149,6 bis 233. Die Landnutzung für Bergbauaktivitäten liegt im Bereich von 279 bis 357 km².

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1 Introduction

Mainly local problems are prevalent when we think of environmental impacts of the mining industry. For example high water abstractions in water scarce regions, soil degradation, various emissions affecting the surroundings and mining induced chemical reactions leading to acid mine drainage, poisoning the water long after the mine closed. (Murguia, 2015, p. 15) (Gunson, 2015, p. 1) It is true that the global environmental impact in terms of plain numbers of CO_2 emissions, water withdrawals and land use is low compared to other industry sectors and downstream processes of metal production (Norgate and Haque, 2010 p. 266) (Murguia, 2015, p. iv) (Gunson, 2013, p. 140) but it is also true that in contrast to other industries the effort and therefore the specific environmental impact of producing a certain amount of metal is dependent on the natural properties of the rock and the rock mass of the deposit. In a context of highly increasing resource demand we may soon face a turning point when the increasing effort necessary to supply the world with resources is accompanied with environmental impacts that can no longer be neglected. (Norgate et al., 2007, p. 844) Major environmental problems resulting from this development are greenhouse gas emissions and water consumption. (Norgate and Haque, 2010, p. 270) The lack of environmental data making this investigation necessary is confirmed by the mostly failed attempt of asking companies for more detailed and comparable values. The United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris agreement in 2015 with a goal of "holding the increase in the global average temperature to below 2 °C above pre-industrial levels…or to 1.5 °C above pre-industrial levels” (UN FCCC, 2015, p. 3). To stay within these absolute limits we need to gain more knowledge about environmental impacts of the mining industry and we should focus on investigating trends that could counteract the plan to sustain our planet.

Therefore a closer look on developments is necessary in the present and future to be able to react before a point of no return is reached. To summarize the state of the art, a literature review is conducted and complemented by information from institutions and companies. As the primary goal, the thesis tries to answer the following questions:

- How much water was used globally in 2016 to mine the commodities bauxite, copper, gold and iron ore?
- For what part of the global CO_2 emissions in 2016 can mining of the mentioned commodities be held accountable?
- What was the amount of land used by mining of the mentioned commodities in 2016?
- The development of these figures over time.
- What are the shortcomings of environmental data?
- How can present environmental data be analysed properly?
- What is the current state of environmental reporting and what can be improved?

In the debate of sustainability the two approaches of “weak sustainability” and “strong sustainability can be distinguished. Weak sustainability is based on the assumption that human capital (infrastructure, education, living standards, culture etc.) can substitute natural capital (water, air, mineral resources, pollination of plants etc.) whereas strong sustainability focuses on environmental limits and in essence says that the build-up of human capital is not completely interchangeable with, but limited by natural capital. (Tost et al., 2017, p. 3)

The wider objective of this thesis is to contribute to a strong sustainability approach by providing a summary of the actual state of global CO_2 emissions, water use and land use by mining and other activities that take place at a mine site to produce bauxite, copper, gold and iron ore. Boundary problems, site specific issues, differences in reporting and other problems that hinder comparability of data are discussed in the following chapters in detail.

The most critical input parameters are energy because it is connected to CO_2 emissions and therefore effects climate change; water because it is a scarce resource in many parts of the world (Norgate and Haque, 2010, p. 270) and the used land because it is connected to decreasing biodiversity. (Murguia, 2015)

Numbers of different publications are analysed and compared. The mean of values from different but comparable publications is taken to accomplish a global estimate for CO_2 emission, water and land use in the mining industry. The result is then compared to values from corporate sustainability reports for the year 2016.

2 State of the art

2.1 Literature

To portray the knowledge about quantities of water withdrawals, CO_2 emissions and land use in the mining industry, the first step is to conduct a literature research. Even the most ambitious works trying to come up with numbers are restricted by what is reported. The data is not only limited to mines/companies that are actually reporting but also in terms of boundaries as often datasets comprise mines that employ different processing and metal extraction methods as well as are at different positions of the value chain as they may or may not refine at the mine site. In the case of copper and gold, many mines produce more than one commodity. Iron and bauxite mining take place mainly as single commodity production. For gold and especially copper, the reported numbers often represent the production of a mine producing several commodities. To account for that shortcoming of the data, the most frequently seen method is to use artificial numbers like the market price to separate what has due to technical reasons unavoidably been mixed up. This approach is a compromise that allows distributing water consumption among the produced commodities with the sum of water consumed by a mine being constant (double counting is avoided) but with the problem that specific water consumption of a commodity is highly influenced by these factors.

The method is to calculate a factor f based on the price P and the Quantity Q produced of the commodity i. The total water withdrawn, emissions produced or land used by the mine is represented by the environmental impact E. A total of k commodities are produced at the mine. Most publications referred to in this thesis that are not life cycle analysis use this or a similar method based on the price or on the mass of the metal content in the concentrate. The mathematical function is not always presented.

$$\boldsymbol{f_i = \frac{P_i * Q_i}{\sum_{i=1}^{k} P_i * Q_i}} \quad \boldsymbol{Equ.1: Allocation\ Factor}$$

$$\boldsymbol{E_i = f_i * E} \qquad \boldsymbol{Equ.2: Environmental\ Impact\ Commodity\ i}$$

Northey et al. (2013) is an example for a publication that presents a lot of information about single data points but includes mines with different value chain positions. While some mines in the sample produce concentrate, other produce metal. If I look at the water consumption of 31 copper mines located around the world with very different stages of processing and beneficiation and I take the average it is unclear if that number represents the average amount of water needed to produce a ton of copper. In the case of copper and gold the published data often contains the discussed factors like the market price to account for by products and assign them part of the water consumption. Therefore results for the specific water consumption of a commodity produced at a mine are sometimes incredibly high or incredible low.

The boundary is an issue that has to be mentioned when looking at publications or gathering data. As this thesis looks at what is happening on a mine site, the boundaries in terms of production steps (mining, concentration, purification, refining) are different for the commodities looked at.

Publications that separate process steps are rare because companies report for a production site and not for a production step. Methods applied at a site involved in copper production for example differ greatly. (Northey et al., 2012, p. 120) For iron ore and bauxite, the boundary or the product looked at is the iron ore and bauxite shipped from the mine. For copper and gold, the boundary sometimes includes purification and refining as it is sometimes done at the mine site and therefore reported as a single number. Norgate and Haque (2010) investigated only the mining and concentration stage of copper production.

My conclusion is that numbers from literature make only sense if parameters that influence the result are listed. The list below is a compilation of some obvious factors that highly influence results. That list surely can be extended.

- Boundary description
  A sample should include only production sites at the same position in the value chain.
- Input parameter description
  It is misleading if it is not described what the input parameter comprises. A definition of wordings like water withdrawals and consumption should be included in a publication. For comparability that should be standardized in reporting and research. The OECD defines withdrawals as ‘freshwater

taken from ground or surface water sources, either permanently or temporarily, and conveyed to a place of use. The data include abstractions for public water supply, irrigation, industrial processes and cooling of electric power plants. Mine water and drainage water are included…‘ (OECD, 2018a)

The World resource institute defines water use as ‘the total amount of water withdrawn from its source to be used.’ (WRI, 2018)

And water consumption as ‘the portion of water use that is not returned to the original water source after being withdrawn.’ (WRI, 2018)

The OECD states that there is no general definition of terms. Definitions of water figures vary considerably among member countries and even change over time. (OECD, 2018b)

This means for evaluations of the mining industry that a suitable standard should be defined and applied.

- Data quantity

  A high quantity of data points and a statistical description would be desirable

- Allocation method should be described

  Reporting companies as well as authors of publications should describe their allocation method mathematically.

- Intent of the publication

  The intent of the publication influences the result because of sample bias, boundary issues, allocation method, input parameters and more. The result may be good for a specific purpose but may not be comparable.

- Type of input data LCA vs. company reports

  While LCA has assumptions in the inventory data included, company reports also have assumptions included in the reporting method.

- Sample bias

  This is connected to the intent of the publication. A sample bias leads to the questions of representativeness and comparability.

The variation of results of different publications is within a factor of about 3 for the specific environmental impact of a commodity if values that are very different in terms of input parameters or boundaries are excluded. For land use a factor of about 2 can be observed. The reasons can be assumptions in LCAs like the grade that highly influences the outcome or other factors mentioned above. Within a publication, the variation of data for mine sites can be within a factor of 100 like in Northey et al. (2013) with a range of 9.8 to 1046.9 m³/t Cu of water consumption due to the problems mentioned beforehand. For calculations and comparison of numbers, this thesis refers to averages of company reports taken from literature or LCA results.

To sum up, many statistical and methodological problems occur but still publications come up with numbers intended to represent the specific environmental impact of a commodity that don't show deviations that are impossible to imagine if considering the numerous factors and assumptions influencing the result.

This thesis can be seen as a reflection upon literature results on the one hand and on the other hand takes these numbers and combines it with production data to calculate the global impacts for the year 2016 of bauxite, copper, gold an iron ore production.

The assumption is that the average grade is the same in 2016 as assumed at the time of values referred to in this thesis were published. This is important for LCA because the results only hold for the assumed grade, especially if they are commodity based (opposed to ore based). Values are either published as impact per tonne of ore (ore based) or per tonne of metal (commodity based). It is also assumed that the specific environmental impact of production stayed the same over time. For that reason only the most resent publications are included in this thesis and referring to historical data is avoided. A positive development of environmental impacts can be observed on a regional scale as in the case of water consumption of copper production in Chile, (Cochilco, 2008, p. 28) but in general the assumption of stable environmental impacts of mining in the western world holds. (Nuss & Eckelmann, 2014, p. 2)

Table 1 is a list of publications containing specific environmental data of bauxite, copper, gold and iron ore production. Values refer either to ore processed or metal produced. I chose the publications because they are up to date and provide comprehensible, commodity specific data. The data provided by the publications is summarized in chapter 5.3, 6.2 and 7.2 dealing with the literature of water use, CO_2 emissions and land use of bauxite, copper, gold and iron ore production. In chapter 5.4, 6.4 and 7.3, the average of literature results is taken to calculate the respective global impact. The result is the published average if the data was derived from companies or is the result of a life cycle analysis. The minimum and maximum of the underlying data points is also shown. These min/max data points are sometimes values of a single mine for a specific year and sometimes already an average of data points of multiple companies for a specific year. In the latter case they are not really data points but no data for single mines was published. That is very important for the data regarding water use because it explains the huge range. Some companies seem to declare that they almost consume or withdraw no water while some have very high specific water consumption. The reasons for that are plenty as already discussed above. This topic is discussed more detailed in the chapter regarding water use. Calculations are always done with the results of a publication but never with data from a single mine!

Table 1 contains a basic description of the publications to give an impression of the underlying data, the boundary investigated, allocation method and the intent that influences the way data is presented and biased. Used wordings like withdrawal and consumption are shown as well.

An example for the influence of these factors on the way data is presented is the publication from Mudd (2008) where no method was applied to allocate the impacts to multiple products of the same mine but mines were grouped instead. Mines in a group were considered comparable and therefore the effect of grade, scale and sector can be assessed. The publication is discussed later in more detail but the values are excluded from the calculations because recycled water is included in the data. On the other hand Gunson (2013) stated that grouping would not allow calculation of global water withdrawals, one of the goals of his thesis. The intent of a publication may imply a sample bias as is the case for Cochilco (2008), including only Chilean copper mines. Information about basic assumptions and/or the sample is presented in the column “sample/inventory data”. It shows how data was obtained and can explain for example the huge range of the min/max values in Gunson (2013) regarding water withdrawals in table 5, chapter 5.3. The huge company dataset necessary for the estimation of global withdrawals also included mines with a remarkable low or high water consumption.

The description of the boundary in table 1 should clarify to which production steps the publications refer to. For iron ore and bauxite the boundary is the iron ore and bauxite product. Some values for the publications of table 1 are not used for further investigations in this thesis but shown as an indicator and to provide as much data about the subject as possible. This concerns the CO_2 value for copper concentrate of Norgate and Haque (2010), the CO_2 value for the concentration of base metal ores of Labriola (2009), the publication of Norgate and Lovel (2004), Mudd (2008), partly Mudd (2007a) and Mudd 2007b). The Value for CO_2 emissions of copper concentrate production from Norgate and Haque (2010) was excluded because the boundary in this thesis is copper produced and not concentrate produced. Labriola (2009) was excluded for the same reason. Norgate and Lovel (2004) is excluded from calculations because the definition of the water related value is unknown. Mudd (2008) was excluded because recycled water is included in the results. Mudd (2007a) and Mudd (2007b) are excluded from the CO_2 calculations (but included in chapter 5.4 dealing with calculations of global water withdrawals) because it is unclear if Scope 1 and Scope 2 emissions – the focus of this thesis, are both included in the paper. Consumption and withdrawal are rarely defined and therefore treated as equal in this thesis

Table 1: Literature Overview

Source	Allocation method	Intent of the publication	Sample/LCA inventory data	Boundary	Definitions Water	Definitions CO_2/Land
Mudd, 2007a	None. By-products unconsidered.	Assess the development of production and environmental data of gold mining in Australia	Company reports from 1991 to 2005 with 3 to 19 mines reporting per year	**Gold:** Mining to metal	Consumption	Unknown
Mudd, 2007b	No information provided	Assess the sustainability of global gold production	Companies: 1991 to 2005 with 2 to 59 mines reporting per year.	**Gold:** Mining to metal	Consumption	Unknown
Mudd, 2008	No information provided.	The data have been grouped into principal ore type to better assess the effect on grade, scale and sector	Company data	**Bauxite:** Bauxite product, **Copper:** unclear, **Gold:** Mining to metal	Consumption including recycled water	
Norgate and Lovel 2004, cited in Gunson, 2013	Unknown	Estimate water consumption for several commodities	LCA **Gold:** 3.6 g Au/t **copper:** 3% hydrometallurgy, 2% pyrometallurgy **Iron Ore:** 64% Fe	**Bauxite:** Bauxite product, **Copper:** Mining to metal, **Gold:** Mining to metal	Unknown	
Gunson, 2013	Economic	Estimate global water withdrawals of the metals mining sector	Company data from 2006-2009	**Bauxite:** Bauxite product, **Copper:** Mining to metal, **Gold:** Mining to metal, **Iron Ore:** Iron ore concentrate	Withdrawals	
Norgate and Haque, 2010	None.	To assist the Australian minerals industry in identifying potential areas of improvement of their environmental performance	LCA **copper:** Underground mine, 16.2 t ore/t concentrate.	**Bauxite:** Bauxite product, **Copper:** Mining to concentrate **Iron Ore:** Mining to concentrate		Scope 1 and 2
Norgate and Haque, 2012	Mass and economic for comparison	Compare refractory to non-refractory ore. Identify impacts of various production steps. Sensitivity analysis.	LCA Gold 3,5 g gold/t ore, a stripping ratio of 3, gold is the main product, open-pit mining	**Gold:** Mining to metal	Consumption	Scope 1 and 2
Northey, Haque, Mudd, 2013	Economic	Show opportunities and limits of reported data for creating environmental footprints	Company Reports	**Copper:** Reporting companies are situated at different positions of the value chain of copper production.	Consumption	Scope 1 and 2 and 3 where available
Norgate et al., 2007	One product mine as LCA assumption	Show various environmental impacts	LCA **copper:** Sulphide ore with 3% (Pyrometallurgy) and 2 % (hydrometallurgy)	**Copper:** Mining to metal		Scope 1 and 2

Cochilco, 2008	No information provided	Show the freshwater consumption of Chilean copper mines. Compare concentrators with hydro-metallurgy. Show the development over time.	Company data	**Copper:** Mining to metal	Consumption
Labriola 2009, cited in Norgate and Haque, 2010	Unknown	Unknown	Value for **base metal ores** Underlying data is unknown	According to Norgate and Haque (2010) comparable to their result for a **copper concentrate** but actually unknown.	Unknown
Murguia, 2015	Economic	Estimate the specific directly land use for Au, Cu, Ag, Bauxite, and Fe mining	USGS satellite images and a random sample of mines distributed around the world	**Bauxite:** Bauxite product, **Copper:** Mining to concentrate **Gold:** Mining to concentrate, **Iron Ore:** Mining to concentrate	Directly disturbed land
Sliwka, 2001	None	Quantify the environmental impacts of bauxite mining. The average Global value of bauxite mining is declared as 12 ha/Mt	2 bauxite mines	Mining activities (excluding infrastructure)	Land use for mining activities
International Aluminium Institute, 2009	None	Report sustainability data of bauxite mining	Unknown	Mining and infrastructure	Land use
Ruhrberg 2002	None	Develop a resource management system for metal mining operations	Calculations based on assumptions	Mining activities, infrastructure and subsidence. Value is an average valid for copper mining (open pit and underground)	Land use

2.1.1 Approaches in Literature (LCA and Evaluation of Company Reports)

Two approaches can be seen in publications this thesis refers to. Either inventory data that fits the LCA assumptions is obtained from previous publications or company reports are analysed directly. These methods are discussed in more detail because they are basic and highly influence what is presented in a publication. A dataset from companies can be interpreted and statistical numbers can be obtained. The advantage is that I have a sample that can be interpreted in terms of sample bias and other factors mentioned earlier. A disadvantage is that the data is usually limited and these limitations have to be described.

LCA creates a scenario with invariant frame conditions like the grade and mineralogy of a deposit and takes the environmental data (inventory) for the necessary processes to produce a defined product from external sources or creates an inventory on its own. That inventory is the result of previous analysis. On the other hand, analysis of company data has an underlying variance that can be seen and described. The advantage of LCA is that many data sources can be combined to get the best inventory possible. The disadvantage is the fixed frame condition for which the result holds, prescribed in the inventory data and the LCA assumptions.

> ‘LCA seeks to examine all stages of a product’s life cycle such as material production, manufacturing, distribution, usage, and finally ultimate disposal or recycling. This is achieved by creating an inventory of all the energy and material flows used in the product’s life cycle.’ (Northey et al., 2012, p. 118)

If it is not a full life cycle analysis, different stages from raw material to disposal are analysed and can be classified as follows:

- cradle to entry gate (raw material extraction and refining);
- entry gate to exit gate (product manufacture); and
- exit gate-to-grave (product use, recycling and disposal).

(Norgate et al., 2007, p. 842)

Norgate (2007) conducted a cradle-to-gate LCA for several metals with process data averaged over a few sources that refer to company reports. (Norgate et al., 2007, p. 843)

From that it can be seen that the data underlying an LCA is comparable to a straight analysis of company reports. A difference is that an LCA creates an inventory and therefore needs more detailed data which is often not publicly available. (Norgate and Haque, 2010, p. 266) Fig 1 shows that in the context of the whole metal production process from cradle to grave, the environmental impact of mining is low for aluminium and steel but considerable for copper. In the context of global metal production the share of mining and mineral processing is low and therefore, 'most life cycle assessments of metal production processes do not consider the mining and mineral processing stages in any detail'. (Norgate and Haque, 2010, p. 266) The shortage of detailed company data that would enable better LCAs is discussed in terms of reporting deficiencies and is a concern throughout the whole thesis. (Norgate and Haque, 2010, p. 271) It is mentioned by Norgate and Haque (2010) that the study is preliminary because the available data for creating LCA inventories is not sufficient to date. Industry stakeholders are urged to release data to be able to refine the data base. (Norgate and Haque, 2010, p. 271)

However, numbers from different mine sites for land use and water withdrawal, cannot be directly compared because they do not reflect the full environmental impact they cause. Many impacts connected to water and land use of mining are not understood and can only be evaluated if connected to the environment of the mine. Depending on the value for human existence of the occupied land and the properties of the aquifers, flora and fauna, the environmental impact of the land used, water withdrawn can differ greatly depending on the place of the mine. In contrast to thinking in terms of environment vs. economy, nature can be a contributor to the economy depending on the value of ecosystem services. Storm protection of coastal wetlands is an example for an ecosystem service. (Constanza et al., 2014, p. 153-154)

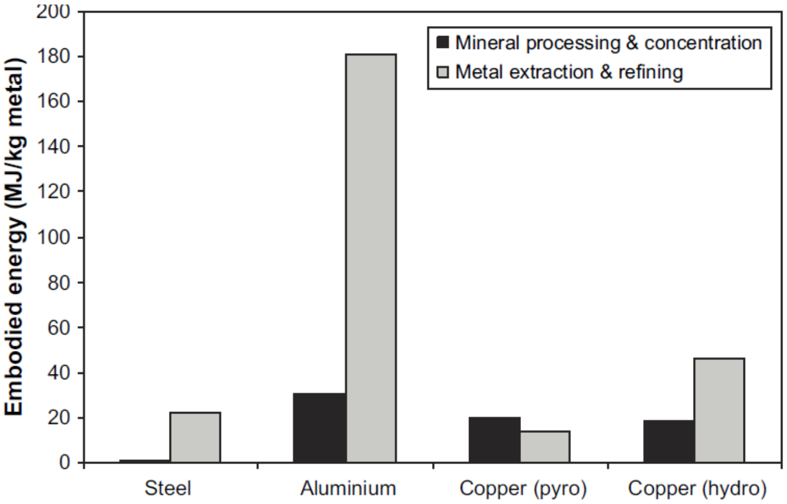

Figure 1: Processing stage contributions to embodied energy of steel, aluminium and copper production. (Norgate and Haque, 2010, p. 267)

2.2 Data Request from Companies and Reporting

The widely used reporting protocol from the Global Reporting Initiative (GRI) renewed its standards in 2016 but companies are still reporting to the old standard for the 2016 reporting period. The standard does not include any split of data to attribute values to products but is a rough guide to what should be reported in general. That makes it really hard to use for comparing companies and obtain information about the sustainability of products. The question leading this discussion is: What is the value of data that cannot be compared to other data? The history of reporting and especially of reporting in a standardized way is very young and the latter can be dated back to the late 90s. (Mudd, 2007b, p. 44) Companies started to report environmental data and the Global Reporting Initiative released its first reporting standard in 2000. (Mudd, 2007b, p. 44) The release of environmental data can be at least dated back to 1971, when Island Copper on Vancouver Island started to release environmental reports. (Gunson, 2013 p. 21)

The shortcomings of the GRI reporting standards and of reporting in general are discussed in literature. Mudd criticises that key aspects like the extent of recycled water used, mine site water inventories and the quality of various waters and impacts on water resources are missing. (Mudd, 2008, p. 136) Reporting on EU level is implemented by “Directive 2014/95/EU of the European Parliament and of the Council…” (eur-lex.europa.eu) It requires larger companies to report social and environmental factors but does not include a reporting standard. “Companies may choose to use widely accepted, high quality reporting frameworks” (ec.europa.eu, 2017)

The information obtained from sustainability reports is fragmentary. I looked for the data shown in table 2 representing the activities of the whole company as well as for the production of the commodities iron ore, gold, bauxite and copper individually. Out of 16 companies, only 2 reported each of the 6 basic numbers shown in table 2 for the mining activities of the whole company in their sustainability reports. All companies reported water withdrawals and CO_2 emissions. Data for the environmental impact that can be attributed to the production of a specific commodity is much more sparsely. Most companies report the total land disturbed by the company but do not include the land disturbed in the reporting period. That makes it difficult to calculate how much land is disturbed by mining or even a commodity. To fill the gaps I wrote to the responsible department or person of the company if more data is available but I do not get many responses. In fact, only Rio Tinto supplies more data than available in the sustainability report. The message I wrote is shown in the annex of this thesis. An example of the table that was attached to the message and the company was asked to complete is also in the annex. This table is created individually for each company according to their products to make it easy to fill in the missing values.

In addition to environmental data I also requested production data that is often not included in annual reports like ore tonnages. The idea was to calculate as many specific environmental numbers for bauxite, copper, gold, and iron ore production as possible from that data and compare it to literature results. For each commodity at least three of the major producers are chosen. The difference to approaches in literature was mainly that environmental data is obtained from sustainability reports for the whole company and not for single mines. These numbers are what is presented to the world and can be easily understood by people not familiar with the mining industry. Therefore these are the numbers that matter most and should be published and described in the most transparent way.

Table 2: Data Request from Companies

Withdrawals		Mio. m^3
Water recycled and reused		Mio. m^3
Total CO_2 Scope 1+2		Mio. t
Land disturbed 2016		km^2
Total land disturbed		km^2
Land rehabilitated		km^2

2.3 Requested Data vs. Literature Values

Companies can be divided into 3 groups. Multi commodity companies, single commodity companies with by and co-products, and companies producing a single commodity without other major sales.

Companies producing a single commodity employ metallurgical steps in the case of bauxite mining and aluminium production that are often reported as a single number. Water and CO_2 data of these companies is therefore unusable for the purpose of this thesis but land use of bauxite mining is reported.

Some multi commodity companies report environmental numbers that can be attributed to a single commodity or a product group. Data representing a product group is of no use because the products in a group are very different to the extent that they obviously come from very different deposits and different mining and processing methods are used. In these cases it is impossible to assign a value to a commodity. That avoids a comparison between companies but also makes it very difficult to calculate the impact of mining a specific commodity.

Single commodity companies with co-products and by-products only report the data of the whole company but never assign values to commodities. That is partly understandable because if more than one commodity is produced in a mine, they may not know what can be attributed to a product and how that should happen. In this case I suggest a much more detailed reporting method. Data for each mining and processing step has to be reported to be able to interpret data better. In the end, that would not solve the allocation problem but would enable more detailed, accurate and comparable environmental analysis. Simple splitting up numbers that cannot be split up meaningfully to serve the purpose of environmental evaluation is a method that does not lead to very useful results.

Very few companies report environmental numbers that can be attributed to a single commodity and if so, they report only one or two numbers but never the full dataset analysed. Many critics of reporting standards and their execution by companies can be found but I would like to go a step further and say that the best reporting standards are useless if reported data is incomparable. Therefore much more dedication must be involved in reporting and especially in reporting process data that can be taken to create LCA inventories.

The results from the requested data on company level are summarized in table 3 and comprise some valuable numbers that can be attributed to a commodity, especially for iron ore as it is produced without by-products and co-products. But for a proper analysis of the other environmental impacts, too few companies report their specific environmental data and therefore not many conclusions can be drawn.

Reported CO_2 emissions of iron ore production are very close to what the only literature source (Norgate & Haque, 2010) suggests (11.9 kg CO_2/t Iron Ore). The same is valid for gold and copper. Also the values from three different companies for the CO_2 emissions of iron ore production are very similar with 10.39, 9.3 and 13 kg CO_2/t Iron Ore. The literature value of water withdrawals of bauxite production is 0.404 m^3/t bauxite and therefore pretty close to the company value of 0.604 m^3/t bauxite. All other values differ to a greater extent from what literature suggests. In the case of CO_2 emissions of copper production it can be seen that values from companies do not only differ from average literature values but also a huge difference can be observed between the companies.

Table 3: Specific Environmental Data from Sustainability Reports on Company Level

CO$_2$

	Metal	Production	Units	Total CO$_2$ Emissions	Units	Specific CO$_2$ Emissions	Units	Average of Literature Values
Commodity	Copper	1.4258	Mt	3.51	Mt	2.46	t CO$_2$/t Cu	3.7
	Copper	0.7845	Mt	6.9	Mt	8.8	t CO$_2$/t Cu	
	Gold					23300	tCO$_2$/t Au	23436
	Iron Ore	169.4	Mt	1.76	Mt	10.39	kg CO$_2$/t Iron Ore	11.9
	Iron Ore	226.958	Mt	2.1	Mt	9.3	kg CO$_2$/t Iron Ore	
	Iron Ore	281.321	Mt	3.7	Mt	13	kg CO$_2$/t Iron Ore	
	Bauxite	47.70	Mt	0.5	Mt	0.01	kg CO$_2$/t Bauxite	4.9

Water

	Metal	Production	Units	Total Withdrawals	Units	Specific Withdrawals	Units	Average of Literature Values
Ore	Gold					0.3793	m^3/t Ore	1.015
Commodity	Copper	1.4258	Mt	350	Mm^3	245	m^3/t Cu	69.21
	Iron Ore	169.4	Mt	177.34544	Mm^3	1.047	m^3/t ore	0.598
	Iron Ore	281.3	Mt	396.5	Mm^3	1.410	m^3/t Iron Ore	
	Bauxite	47.70	Mt	28.8	Mm^3	0.604	m^3/t Bauxite	0.404

Land

	Metal	Production	Units	Total Land Use	Units	Specific Land Use	Units	Average of Literature Values
Commodity	Bauxite	45	Mt	1028	ha	23	ha/Mt	12
	Bauxite	11.1	Mt	368	ha	33.2	ha/Mt	
	Bauxite	47.70	Mt	5131	ha	107.6	ha/Mt	
	Iron Ore	281.3	Mt	3337	ha	11.86	ha/Mt	4.25

3 Methodology, Goals and Calculation Method

With a literature review the thesis gives an overview of the research been done on the topics of CO_2 emissions, water use and land use in the mining industry. In addition, numbers from annual company reports on company level are analysed to contribute to the understanding of the topic and to support the literature research.

The environmental numbers from literature are provided and used together with production data to show the CO_2 emissions, water and land use of bauxite, copper, gold and iron ore production in 2016. Overlapping conclusions of publications about how findings can be interpreted are portrayed.

Difficulties that lie in the nature of the topic and problems that can be overcome are discussed. The development of sustainability of the mining industry in the future in the context of the present and past are discussed and represented with data from literature. At last, the information is summarized and conclusions about the current state, future outlook and shortcomings of today's approach towards a more sustainable and transparent mining industry are drawn. The resulting numbers are put in the context of global water withdrawals, greenhouse gas emissions and land use.

3.1 Calculation Method

The average of the literature results from chapter 5.3, 6.2 and 7.2, as well as the minimum and maximum value are multiplied with production data. Not all presented values are used for calculations because definitions and research boundaries of the publications vary. Publications presenting values with very different definitions are neglected. For example values including only or mainly Scope 1 emissions and publications including recycled water in the assessment are neglected. If a publication provides more than one value as results, the average of these values is taken to consider the publication in the overall average of all relevant publications. That is the case if different ore types or different processing methods for a commodity are investigated in a publication. The reason is that one publication should not be weighted more than another. The calculations are based on three sources of production data: Commodity production in 2016 and 2015 and ore processed in 2015. The average of ore based values from literature is multiplied with the value for the global ore processed in 2016. That is the result from Equation 3. Because information about the ore processed in 2016 is not available Equation 3 is the extrapolation from 2015 to 2016. That is possible with the assumption that the average grade is the same in 2015 and 2016. The result from equation 3 is then multiplied with the average, the minimum and the maximum of ore based literature results. To calculate the minimum scenario or the maximum scenario, the “Average of Ore Based Literature Results” in equation 4 has just to be replaced with the minimum or the maximum of the literature results to calculate the minimum and maximum scenarios. Results are shown in chapter 5.4, 6.4 and 7.3. It should be noted that the calculations are rough estimations but reflect the magnitude of environmental impacts of bauxite, copper, gold and iron ore production.

Equation 5 is similar to Equation 4 but there is no need to extrapolate from 2015 to 2016 because the commodity production in contrast to the ore production of 2016 is known. The average, minimum and maximum commodity based values are multiplied with production data for 2016 from Reichl (2018). In chapter 5.4, 6.4 and 7.3 the calculated values are described more detailed.

$$\frac{Comm. Prod. 2016\ (Reichl\ 2018)}{Comm. Prod. 2015\ (Reichl\ 2017)} \times Ore\ Proc. 2015\ (Lutter\ 2015) = Ore\ Proc. 2016$$

$\boldsymbol{Equ.}\ 3\text{:}\ \boldsymbol{Ore\ Proc. 2016}$

$$Aver. of Ore\ Based\ Literature\ Results\ \times Ore\ Proc. 2016 = Impact\ 2016\ (Land, Water\ CO2\text{:})$$

$\boldsymbol{Equ.}\ 4\text{:}\ \boldsymbol{Impact\ 2016\ Ore\ Based}$

$$Aver. of\ Comm.\ Based\ Literature\ Results \times Commodity\ Production\ 2016 = Impact\ 2016\ (Land, Water, CO2)$$

$\boldsymbol{Equ.}\ 5\text{:}\ \boldsymbol{Impact\ 2016\ Commodity\ based}$

4 Gold, Iron Ore, Bauxite and Copper production

This chapter looks at standard mining and processing procedures for the most common ore types and implications on CO_2 emissions, water, and land use. Correlations of the specific environmental impact of a commodity produced and site specific data like ore type and size of operation may be valid for a commodity but cannot be seen as general rules for mining operations. An example is the water consumption that follows the rules of economy of scale in the case of precious metals but not in the case of base metals, leading to greater efficiency with higher throughput for precious metals. (Mudd, 2008, p. 136)

Critical production steps in terms of environmental impact of commodities also differ. Iron ore and bauxite form high grade deposits naturally (e.g. typically 60% for iron ore and 22% for bauxite in Australia) and therefore loading and hauling make larger contributions to the total greenhouse gas emissions than the comparably simple processing. (Norgate and Haque, 2010 p. 266-26) For copper, with its lower grade deposits crushing and grinding are the critical steps for reducing greenhouse gas emissions. (Norgate and Haque, 2010 p. 266)

"…the majority of recent production occurred from ore grades in the range 0.5-1.5% Cu." (Northey et al., 2012, p. 120)

Gold deposits having even lower grades show high resource intensity for mining and processing.

'…the current world mean ore grade is in the order of 3-4 g/t Au.' (Norgate and Haque, 2012, p. 54) That makes 0.0003 - 0,0004 % Gold in the ore which is a factor of 10^{-3} lower than copper and other base metals.

Another obvious factor that influences energy consumption is the mining method. 'Underground mining requires more energy than surface mining due to greater requirements for hauling, ventilation, water pumping and other operations.' (Norgate and Haque, 2010, p. 267)

4.1 Bauxite production

This thesis only deals with the production of saleable bauxite and excludes further metallurgical processes of aluminium production.

Fig. 2 illustrates the rather simple process applied for beneficiation of the soft material. '…bauxite does not require complex processing.' (International Aluminium Institute 2018)

Compared to most other metal commodities processing is simple and includes washing, wet screening and mechanical sorting. (ibid.)

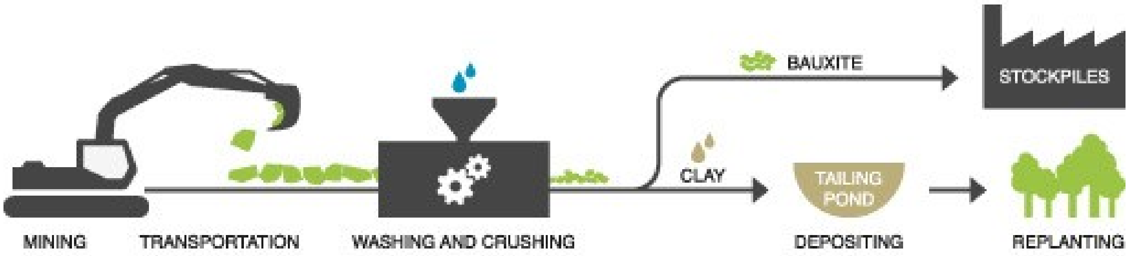

Figure 2: Bauxite Production (Hydro, 2018)

The high grade is illustrated by assumptions of the United States Geological Survey. 'As a general rule, 4 tons of dried bauxite is required to produce 2 tons of alumina, which, in turn, produces 1 ton of aluminium.' (USGS, 2018, p. 31) Therefore impacts on water and air are comparably low and not much data is available.

Because of the nature of lateritic bauxite deposits, being a horizontal layer of weathered rock and soil underneath the top soil, the land use per ton of mined bauxite is high as can be seen in chapter 7.2 and chapter 2.3. (David Tilley, 2018)

4.2 Copper production

Before metallurgical processes are applied to extract the copper from the minerals, either a concentrate of about 30% copper is produced or the ore is leached directly. The concentrate is produced by flotation. Also, oxide and sulfide ores undergo different processing steps according to their chemistry. (Norgate and

Haque, 2010, p. 267) Fig. 3 shows possible ways of how copper can be produced from mining to copper cathode.

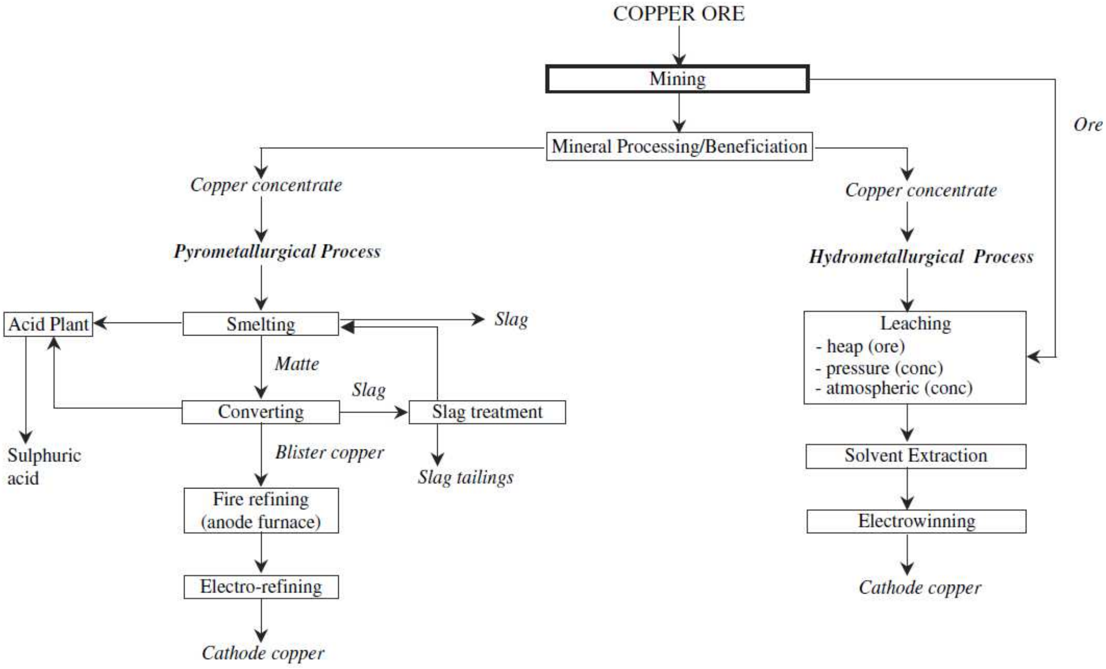

Figure 3: Main processing routes for copper production (Norgate, 2007, p. 840)

Water plays a crucial role in the copper production process. Examples for the applications of water are: Dust suppression, control of moisture content in slopes, cool drilling and hauling equipment, grinding of ore, to transfer the concentrate in the form of slurry, flotation, and to cool furnaces. (Northey et al., 2012, p. 125-126)

The two routes of copper production displayed in Fig. 3 show the difference between hydrometallurgical processing and pyrometallurgical processing. While for the latter, concentration using flotation is necessary, with hydrometallurgical processing the ore can be leached directly to produce a copper solution. Processes involved with pyrometallurgical copper production are mining, concentrating, smelting and refining, while hydrometallurgical processing involves mining, leaching, solvent extraction and electro winning. Different leaching methods are applied from in-situ leaching to leaching of ore that undergoes beneficiation beforehand. Leaching involves the treatment of ore with acid to form a copper solution. (Northey et al., 2012, p. 119)

Because electrowinning is a large energy consumer, the environmental impact in terms of CO_2 emissions is higher for pyrometallurgical processing. (Norgate et al., 2007, p. 844)

It can be seen in Chapter 5.3 that the water withdrawals for concentration preceding the pyrometallurgical process are likely to be much higher than for hydrometallurgical processes.

In the environmental discussion it is also worth looking at the development of grades and the implications on impacts of production steps.

Cut-off grades are around 0.5% and the average ore grades is estimated to be less than 1% (Schlesinger et al., 2011, cited in Northey et al. 2012, p. 120).

> ‘Large variability in the data exists independent of ore grade for sites which include a smelter. Factors which contribute to these are differences in smelting technologies, the minerals present in the feed concentrate, and the proportion of this feed concentrate which is imported into the site from other copper operations’ (Northey et al., 2012, p. 122)

In the context of falling ore grades it is interesting that below grades of 0.5% Cu, fuel consumption exceeds electricity consumption and above this grade it is the other way round. Ore grade is also the major factor influencing energy consumption of mining and beneficiation. (Northey et al., 2012, p. 124) Together with the previous statement that we are currently mining around 0.5% and grades are falling, the finding indicates a turn in energy consumption for copper production.

The variability of energy consumption for a particular ore grade is also high due to difference in rock hardness and mineralogy. Comminution and flotation has to be adapted accordingly. (ibid.)

4.3 Gold production

The current world mean ore grade of about 3 to 4 g/t Au could fall to 1g/t Au in 2050. (Müller and Frimmel, 2010, cited in Norgate and Haque, 2012 p. 54)

Broadly gold ores can be subdivided into non-refractory and refractory. Processing of refractory ore is more complex and involves more steps to separate the metal from the gangue as can be seen in Fig. 4. (Norgate and Haque, 2012, p. 54)

These additional steps influence the energy consumption in a way that emissions are two times higher for refractory ore. (Norgate and Haque, 2012, p. 57)

‘The mining and comminution stages made the greatest contribution to the greenhouse gas footprint of gold production’…’ falling gold ore grades will have a major impact on the environmental profile,’ (Norgate and Haque, 2012, p. 53)

In addition to vein deposits, gold can also be found in placer deposits deriving from eroded vein deposits that have been deposited by water. (Norgate and Haque, 2012, p. 54)

Fig. 4 describes the main three different ways of how gold can be produced with increasing complexity of the ore from left to right.

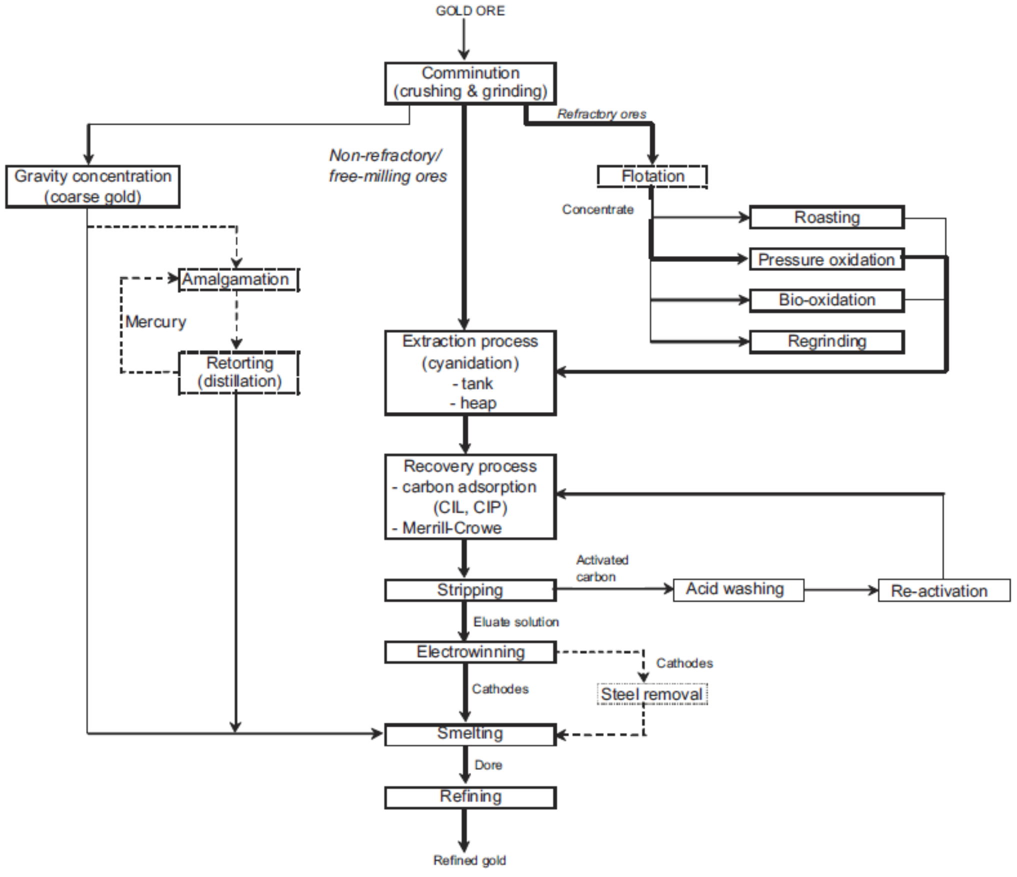

Figure 4: General processing flowsheet for gold ores. (Norgate & Haque, 2012, p. 55)

4.4 Iron Ore production

Fig. 5 shows the boundary used for the LCA of iron ore mining of Haque and Norgate (2015) which uses the same inventory data and shows the same result as

Norgate and Haque (2010) cited in chapter 5.3, with the result of 11.9 kg CO_2/t ore. It is assumed that iron ore is mostly produced by screening and magnetic separation. (Norgate and Haque, 2010, p. 269)

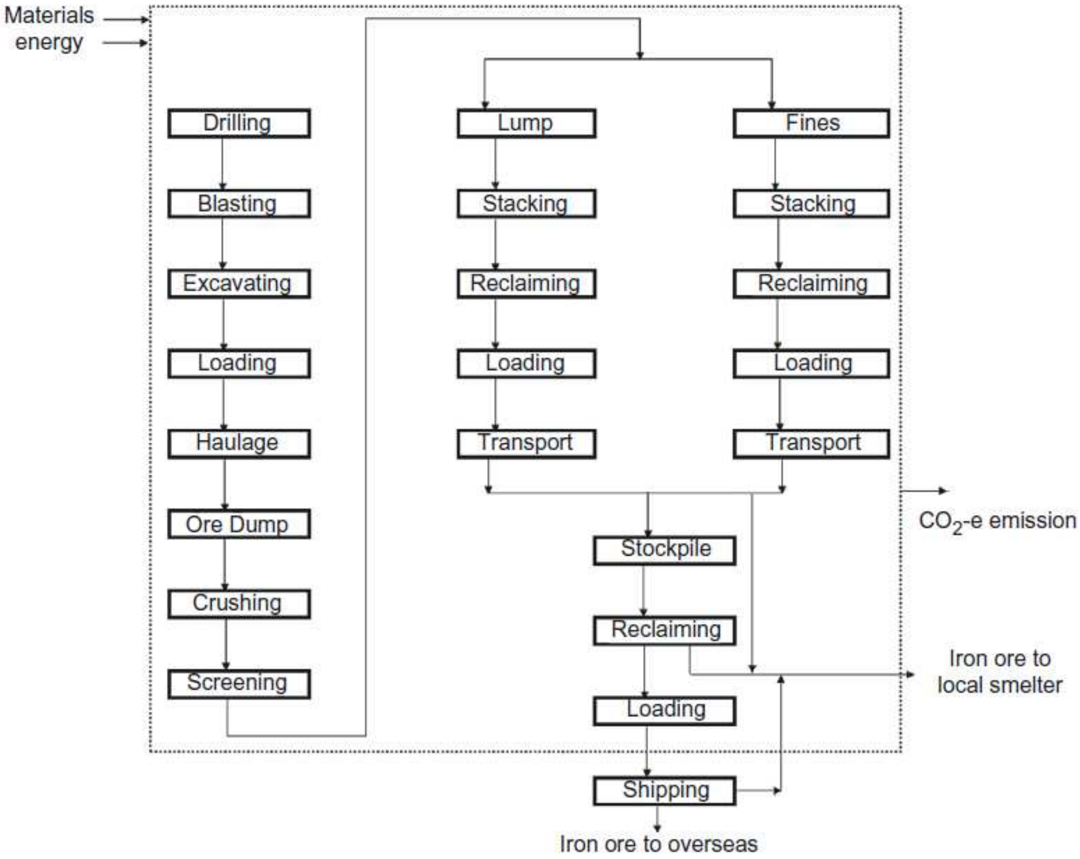

Figure 5: Flowsheet of iron ore production. (Haque & Norgate, 2015, p. 620)

5 Water use

5.1 Introduction

Gunson (2013) mentioned that mine water systems are not really part of the discourse in mineral processing literature. A Gap exists between literature from the eighties and the commodities boom in the mid-2000s. The topic is neglected and should be more prevalent in mining journals. (Gunson, 2013, p. 35) Recycling of water has become common practice in the mining industry and major parts of the water consumption are recycled water since the seventies. (Turcotte, 1986 cited in Gunson, 2013 p. 56)

Therefore, different measures can be applied to quantify water use depending on what is included in the calculations. For example publications including recycled water show much higher values but do not reflect the environmental impact best. Possibilities of how water consumption can be evaluated are limited by the quality of company reports because finally all evaluations like LCA are based on company data. When analysing water use you can look at the amount of water consumed by the processing plant and other mining activities like dust suppression. This limited approach would raise the question of the amount of recycled water and if it is included in the calculations or not. Also discharged water, seepage of tailings ponds, evaporation and other water sinks have to be taken into consideration. The evaluation and reporting of these numbers is discussed more detailed in the following chapters.

A more holistic approach than describing consumption of various processes would be to look at the amount of water withdrawn from the surrounding environment and the amount discharged to the environment. In this case, the question would be the definition of discharge and withdrawal. For example if evaporation and seepage is counted as discharge or only the excess water of the mine. A lot of water can be stored in tailings ponds and by seepage and evaporation discharged over a longer period of time. It would be necessary to measure and report the amount of water entrained in the tailings, calculate the evaporation and account for rain and seepage to obtain valuable numbers for the calculation of an environmental impact. (Gunson, 2013, p. 7-49) Even if a company reports a complete water balance, accounting for all water stores, sources and sinks it does not tell much about the environmental impact without reporting where the water comes from, what quality it has and where and how it is discharged. Data that is published in none of the 16 sustainability reports of major mining companies looked at for obtaining data for this thesis are the change of water stores and the discharge mechanism (water sinks).

It is also a problem that terms like consumption are often not defined in publications. For example Mudd (2007a) examined the water consumption of gold mining in Australia and it is not clear if he writes about withdrawals or the water that goes into the processes and mining activities.

‚Although this is not a full lifecycle water balance, it can be reasonably expected that the substantial majority of water is used during operations.‘ (Mudd, 2007a p. 639)

However, other publications deal with a more representative sample of mines and clearly define what the parameters comprise and if all this data is analysed and compared to companies reporting their overall withdrawals it is possible to a make a proposition about water withdrawals of bauxite, copper, gold and iron ore production for the year 2016.

5.2 Water Balance

Fig 6 illustrates how water flows at a mine site can be accounted for. ‘A mine site water balance is an account of all water sources, sinks, and stores on a mine site.’ (Gunson, 2013, p. 7) The result of a water balance indicates in theory whether water is discharged or withdrawn at a mine site.

- Positive water balance ≡ Discharge of excess water
- Negative water balance ≡ Withdrawal
- Neutral water balance ≡ Sources and sinks are in balance

The real situation is more complex and sites withdraw and discharge water at the same time. A mine having a neutral water balance for the reporting period may has to discharge water in one season and withdraw water the other season. Therefore the result of a water balance does not help much with evaluating an environmental impact. (Gunson, 2013, p. 7)

If looked at the water use of a mine site over a period of time that is the reporting period, the water balance can be calculated as shown in Fig. 6. That figure is in compliance with the definitions chosen by Gunson (2013) with additional information that would be useful to calculate the true environmental impact of water consumption at a mine site and is also partly reported by companies.

Gunson (2013) wrote that the reason for choosing these definitions was mainly because they are common practice, the environmental impact is well reflected and also the GRI guidelines are in line with this way of accounting water. (Gunson, 2013, p. 17)

The more detailed explanation of the water balance in the original thesis is reduced to the relevant factors for the purpose of this thesis.

Diverted water: Water that is not used by any consumer on the mine site but is diverted due to operational reasons without treatment. (Gunson, 2013, p. 13)

Water Sinks: Evaporation, discharge, entrained water in concentrate and tailings and other losses. (Gunson, 2013, p. 13)

Discharge: Excess water that must often be treated and discharged from the mine site. For example water from mine dewatering if there is no use for it. Seepage is also considered a discharge. (Gunson, 2013, p. 13)

Water Source: Examples for water sources that have to be accounted for in a mine site water balance are captured precipitation, water from mine dewatering, moisture in the ore and external makeup water. (Gunson, 2013, p. 13)

Water Store: A reservoir where water can be accumulated or discharged. (Gunson, 2013, p. 13)

Recycled Water: Water that is treated and reused by water consumers. (Gunson, 2013, p. 11)

Water withdrawals: Water taken from the surroundings of the mine site and intended for use or storage. Mine dewatering, captured precipitation, municipal water, surface or groundwater abstraction. (Gunson, 2013, p. 14)

Several reasons justify including mine dewatering and captured precipitation in the water withdrawals. Aquifers that supply water to consumers like local communities are affected by mine dewatering. Captured precipitation would refill aquifers and other reservoirs like lakes and rivers. It is also common reporting practice to do so. (Gunson, 2013, p. 14)

In fact water that is withdrawn will go back to the environment somewhere along the product chain of a mineral commodity. The question is just how far away from the original water source it is discharged or lost and what the discharge and loss mechanisms (water sinks) are.

Even if such detailed data would be available, it must be interpreted in a reasonable way and combined with measures for the scarcity of water and the impact on biodiversity at the mining location to tell the environmental impact.

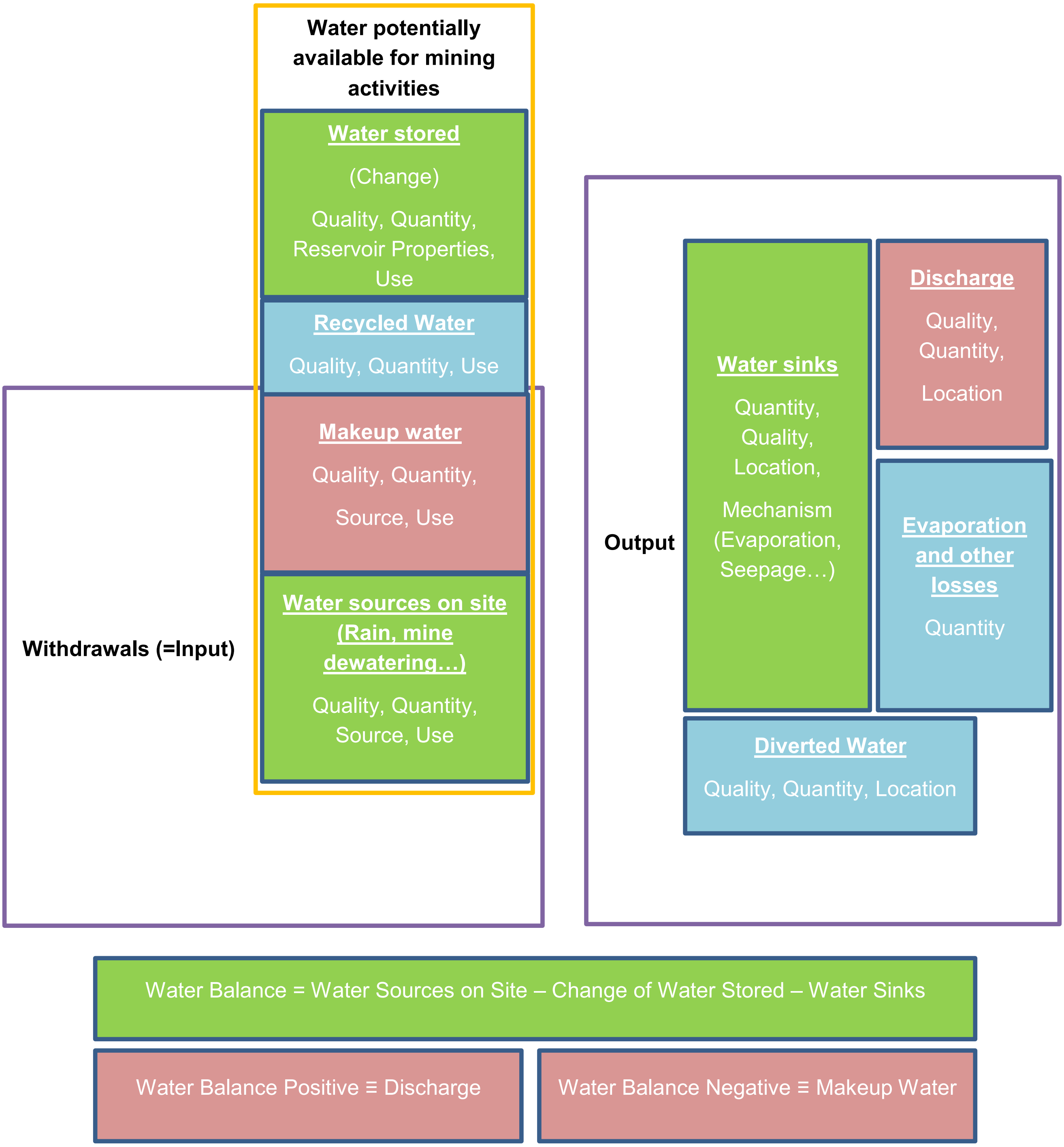

Figure 6: Water Balance

A simpler approach is to say that every withdrawal from the environment causes an alteration to the ecosystem. No matter if the water later evaporates somewhere in the process, is stored in a tailings pond, or discharged a kilometre farther. The problem with this approach is that it goes round in circles as the diversion of a river that would pass the mine has an environmental impact but may not be reported. As every use of water finally is just a diversion of water in the hydrosphere, the question is what the impact of that diversion is.

Because of all this problems, the number that is most widely available and reflects the environmental impact best, is the water withdrawn from the surrounding environment.

For a better description of the impact of water withdrawals, the quality of withdrawn and discharged water, the water sources, the scarcity of water and the impact on biodiversity depending on the location of the mine are useful indicators.

5.3 Literature review of water use

Literature does not show as much coherence about mine water use as would be desirable. Global estimates with systematic effort also cannot be found. (Gunson, 2013, p. 28) Gunson (2013) came up with a range of 6.2 to 7.8 billion m³ of global annual water withdrawals in the metal mining industry, investigating the period of 2006-2009. Table 4 shows the results of Gunson (2013) of annual water withdrawals and compares it to values calculated for 2016 in this thesis.

Table 4: Global water withdrawals in the period of 2006-2009 calculated by Gunson (2013) compared to values calculated in this thesis for 2016 from table 6

Commodity	Min. global water withdrawn per annum in the period of 2006-2009 [Mm³]	Max. global water withdrawn per annum in the period of 2006-2009 [Mm³]	Min. global withdrawals in 2016 calculated in this thesis. [Mm³]	Max. global withdrawals in 2016 calculated in this thesis. [Mm³]
Bauxite	*65*	*79*	*115*	*115*
Copper	*1060*	*1380*	*840*	*1440*
Gold	*733*	*1111*	*800*	*2221*
Iron Ore	*453*	*766*	*1950*	*1950*

The topic is of high importance because a vast amount of water is withdrawn for mining in the driest locations in the world like Australia, Northern Chile, Southern Peru, Central Asia, and the Southwest United States. (Gunson, 2013, p. 1)

To identify water consumers, water sinks, dependencies of the quantity of water used and to describe accounting and reporting problems are challenges faced by whoever tries to make evaluations regarding this topic. '…typically the mineral processing plant is where most water is required on a site and the TSF[1] is where most water is lost.' (Gunson, 2013, p. 28)

If a mine is producing 2 or more commodities in the same processing plant, there is no reasonable way to obtain numbers that perfectly reflect the water consumption of one of the produced concentrates. A way that could shed more light on the topic is to look at the processing steps needed to produce the concentrates and accordingly allocate the water consumption to the product if possible. That would lead to better LCA inventory data. But problems would still remain, for example how should processing steps like milling and screening that precede a possible split of processing routes of different products be allocated? How does the mineralogy influence the processing parameters? Still, comparability would be difficult but it would be a step forward.

That problem was also faced by Gunson (2013), the most comprehensive publication dealing with water withdrawals of the mining industry, when he investigated on global water withdrawals of metals mining. He had to allocate water withdrawals to main products, by-products and co-products what makes it even more compelling to group mines with different products but similar processing methods. He argues that it would be more reasonable to group mines with similar processes to compare them. However, that would not allow calculating global water withdrawals. (Gunson, 2013, p. 68-69)

Furthermore he argued that two methods can be used to extrapolate from a sample of mines to global water withdrawals; based on commodity production or ore production. He applied both methods and in his thesis both of his results were taken into account, one in m^3/t ore and the other in m^3/t metal. (Gunson, 2013, p. 69) Also this thesis follows the same approach as it takes literature data that either refers to resource intensity and emission intensity of processed ore, or metal produced to compare and analyse it.

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[1] Tailings Storage Facility

Furthermore a sample bias can influence the result and therefore it is necessary to include mines in different climates on different continents, producing a significant share of world production to have representative data for global production. The scatter of the data in Fig. 7 reflects the mentioned problems. Deposit and ore type complexity, differences in reporting of recycled water, climate, type and degree of processing are some of the factors that can highly influence the reported water consumption. (Mudd, 2007b, p. 51)

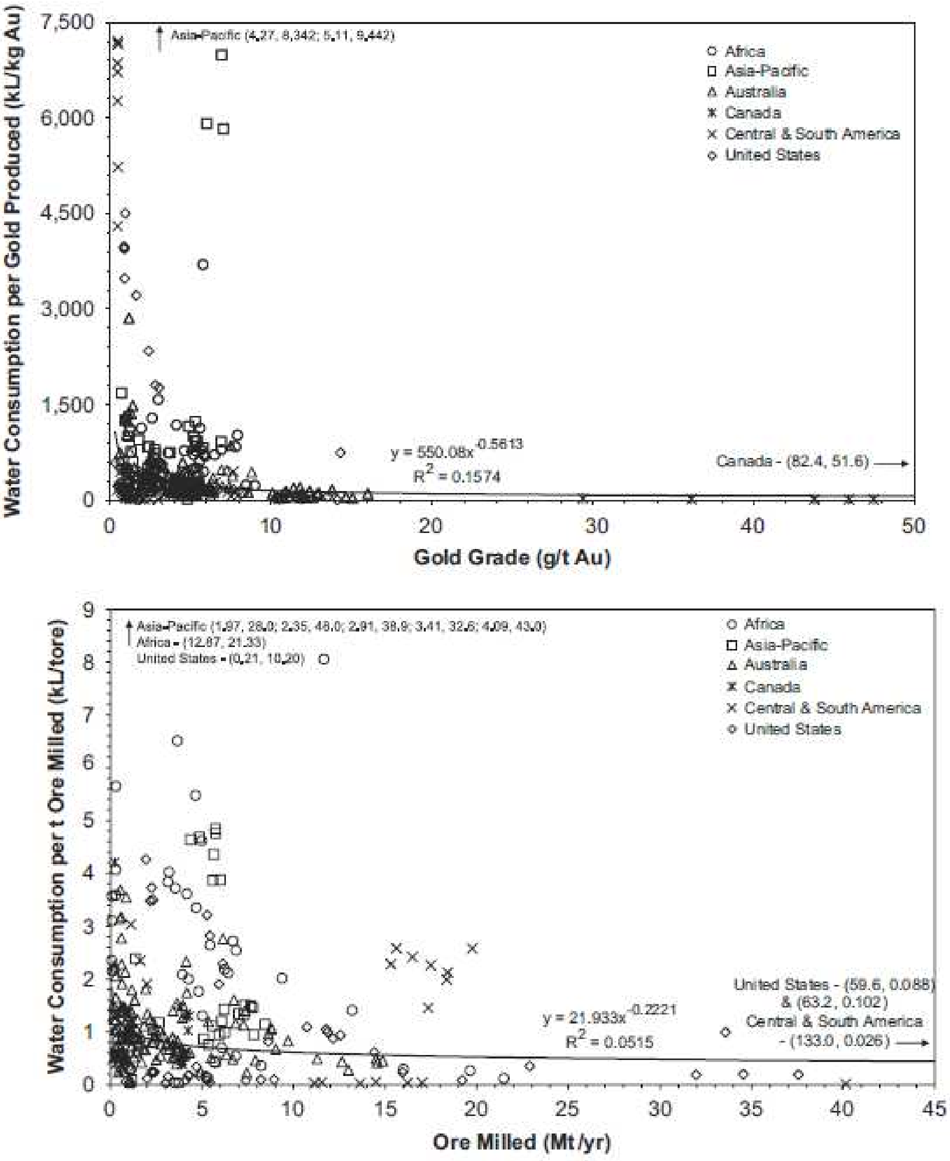


Figure 7: Water consumption in gold mining (Mudd, 2007b, p. 52)

The scatter in Fig. 7 can be described by a list of factors influencing embodied water:

- Climate conditions (e.g. temperate, arid, tropical)
- Primary water source: surface water, ground water, or saline water (marine or otherwise)
- Ore mineralogy and geochemistry (especially as this affects processing)
- Tailings and waste rock/overburden management (especially as this affects water management)
- Type of commodity (e.g. uranium requires extensive dust suppression)
- The extent of re-use and recycling
- Minesite water management regime (e.g. allowable discharges or not; treatment)
- Surrounding communities, land uses, and/or industries (e.g. towns, national parks, farms)
- Project design and configuration (e.g. open cut and/or underground mining, concentrator and/or smelter, hydrometallurgical plant, heap leaching, solvent extraction, electrowinning)
- The initial moisture content of the ore and waste rock
- If the mine is above or below the water table
- Surrounding hydrogeological conditions (e.g. high permeability aquifers; artesian ground water depressurisation issues).

(Mudd, 2008, p. 137-138)

‘Variation in water intensity is generally due to inconsistencies in reporting method, the geographical location of the mining operations, limited economies of scale of production site, and the climate type (i.e. arid regions in Australia and Chile or temperature to subarctic climates in Canada or Finland)’ (Northey et al., 2012, p. 118) Increased evaporation losses in hot arid regions lead to less water being available for recycling. Dust suppression consumes more water as well and therefore withdrawals increase. (Northey et al., 2012, p. 126)

Data shows that the variability of water intensity of copper production can be better explained by the differences of processing technologies than by the grade of the ore. (Northey et al., 2012, p. 126) Also the principle of economy of scale is not a good indicator for water intensity of copper mining. The regional variability, thus climate and abundance of water seem to have a higher influence on water intensity than throughput. (Northey et al., 2012, p. 126) For precious metals economy of scale is valid and higher throughput leads to lower water intensity. (Mudd, 2008, p. 136) It is important to note that there seems to be no connection between water consumption and time in the gold mining industry. This applies to CO_2 emissions and cyanide consumption as well. (Mudd, 2007b, p. 54)

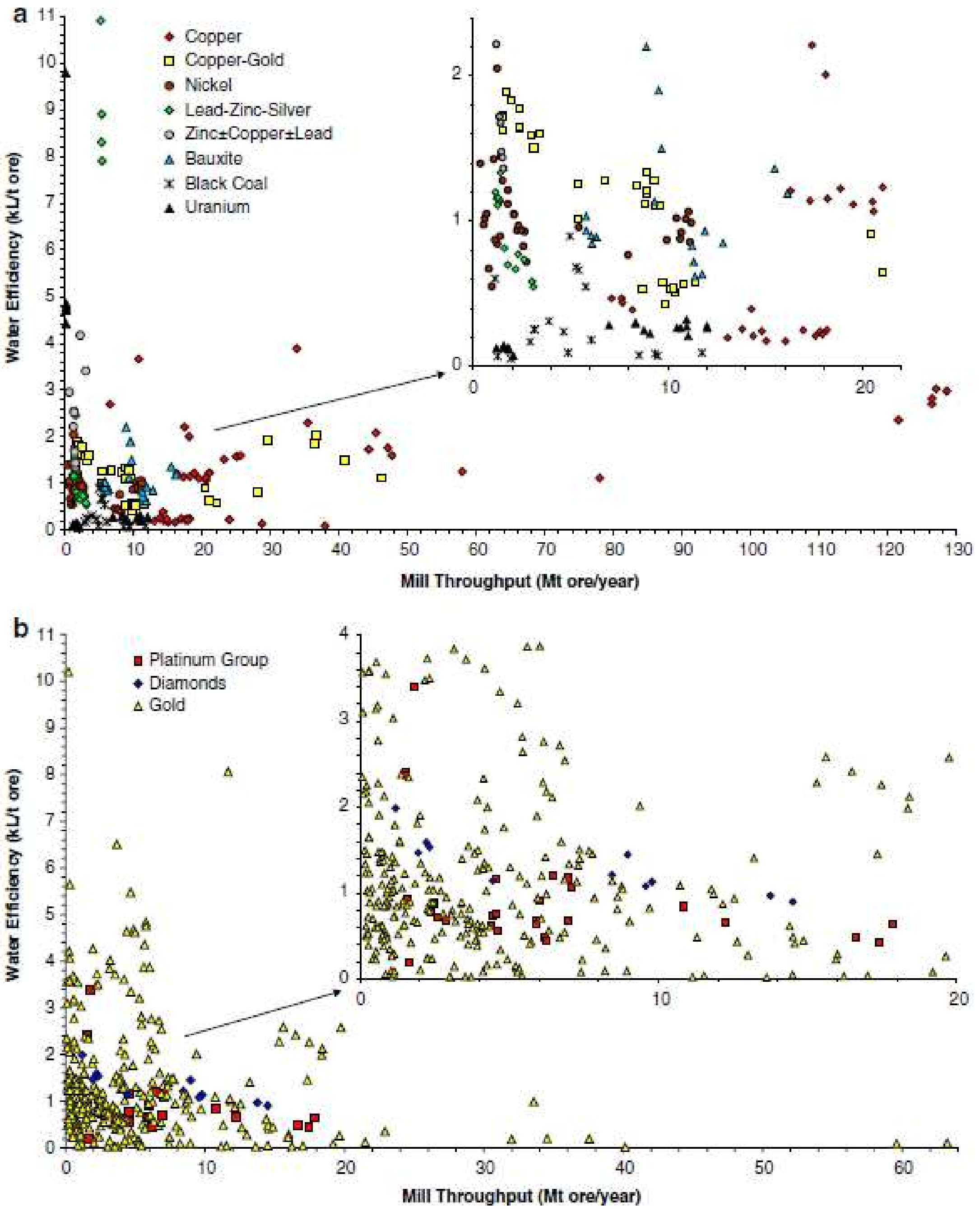
For bauxite and iron ore such relationships are not investigated.

Increasing efficiency seems to outweigh falling grades. That observation is important for the future outlook because there might be a point when grades are falling further, while efficiency cannot be increased anymore and water intensity begins to rise. When that point will be reached and what the implications are, would be part of a separate investigation. Fig. 9 shows that small scale operations of precious metals are likely to have a high amount of embodied water. (Mudd, 2008)

‘In general, particularly for precious metals (e.g. gold), data in Fig. 9 suggests that as ore throughput declines, there is an increased likelihood of higher water consumption. Second, with respect to throughput scale, there is surprisingly no clear evidence that larger scale leads to greater efficiency in base metals and bulk minerals.’ (Mudd, 2008, p. 141)

For gold, platinum and diamonds economy of scale can be observed and it is likely that large scale operations are less water intensive. (Mudd, 2008, p. 141)

Copper production plotted against water intensity is shown in Fig. 8. ‘Limited economies of scale are shown to be present in the industry when operations are considered on a regional basis.’ (Northey et al., 2013, p. 126)



erations

Figure 9: Embodied water versus mill throughput top base metals, uranium, bauxite and black coal; bottom precious metals and diamonds (Mudd, 2008, p. 140)

Regarding the relationship between water consumption and ore grade there is clear evidence that the current development to lower grade deposits comes with increasing water intensity. (Mudd, 2008, p. 141) Fig. 10 shows that relationship.

'…while there is significant scatter, it is also clear that lower grades have an increasing chance of very high embodied water per unit metal/mineral. (Mudd, 2008, p.141)

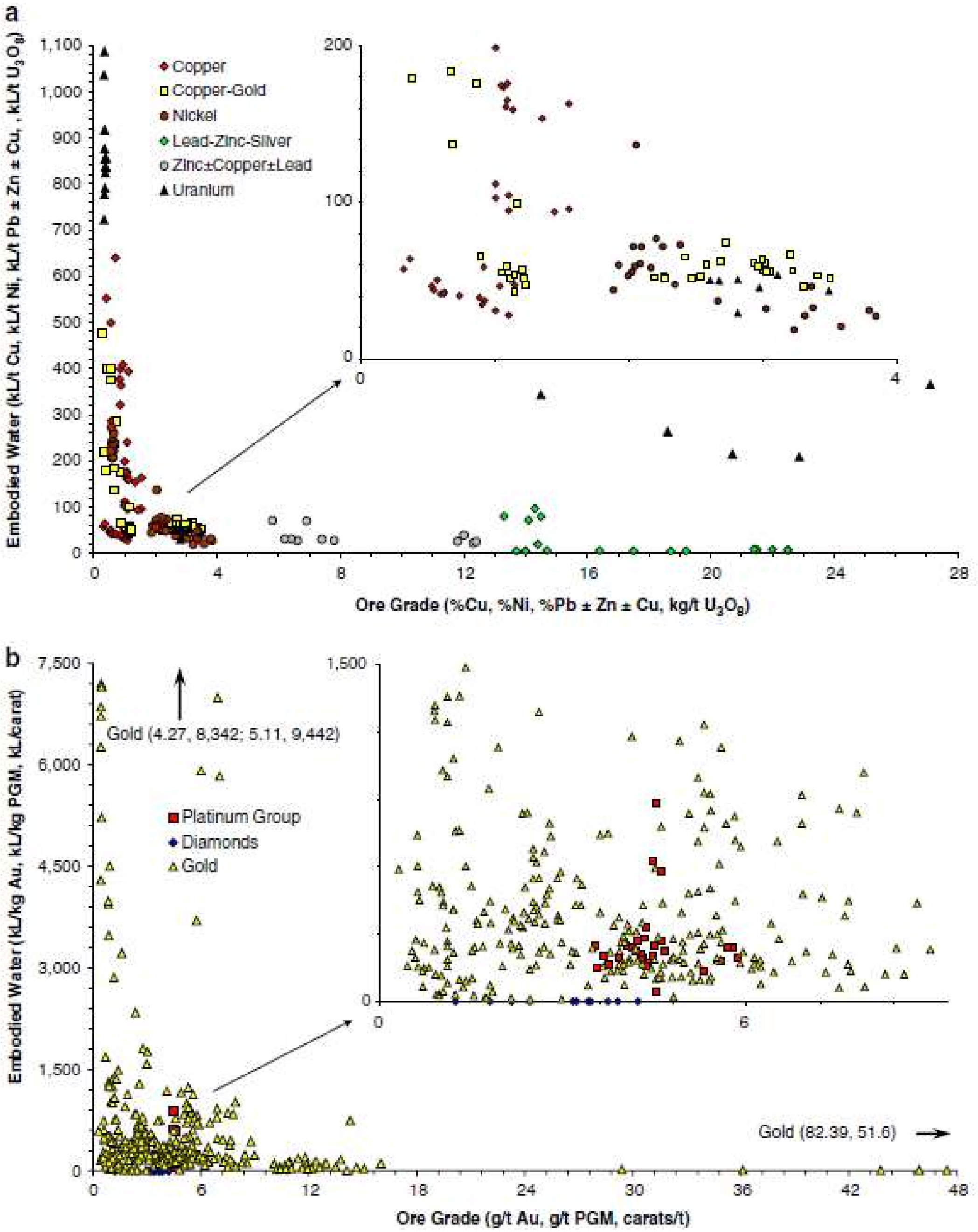


Figure 10: Embodied Water Versus Ore Grade: Top Base Metals, Uranium, Bauxite and Black Coal; Bottom Precious Metals and Diamonds (Mudd, 2008, p. 141)

5.3.1 Values from Literature

Table 5 shows the gathered data of all commodities investigated in this thesis. Values from publications with a red contour are used in chapter 5.4 to calculate global withdrawals while the other publications serve as additional information although they are not considered comparable. Only publications presenting values that reflect withdrawals/consumption without recycled water being included are considered for calculations. For bauxite and iron ore little data is available. For copper production some publications distinguish pyrometallurgical production from concentrate and hydrometallurgical production without or little previous concentration. All publications but one show that hydrometallurgical production consumes significantly less water. Norgate and Lovel (2004) surprisingly seem to not include the water intensive flotation stage needed to concentrate the copper and therefore show a significantly lower value for pyrometallurgical production. The higher values for bauxite, copper and gold production from Mudd (2008) could be due to recycled water being included as he stated, while all other publications either refer to withdrawals or consumption only. Consumption and withdrawal are undefined in most publications.

For gold production, results (average/LCA result) are within a factor of about 3. Results for copper show a similar variation, when the higher values of 172 m^3/t Cu (1.27 m^3/t ore) for copper-only deposits and 116 m^3/t Cu (1.22 m^3/t ore) for Cu-gold deposits of Mudd (2008) can be explained by recycling water being included. The values from Norgate and Lovel (2004) for the pyrometallurgical processing is taken as cited by Gunson (2013) because the original publication was not available. It includes mine and mill, smelting and refining but does not investigate the water intensive concentration stage and therefore the sum of the individual processing stages shows a significantly lower value of 20.73 m^3/t Cu compared to 88.03 m^3/t from Gunson and 70.4 m^3/t from Northey et al. (2013). This is not an error because it is nowhere stated that the sum of the values should reflect the water use of copper production but seems to be merely a compilation of investigated water consumptions for some mining and processing stages. Because of that Norgate and Lovel (2004) is not included in calculations in this thesis for the global water consumption but shown as an informative value for various production steps.

I have to add that the above reflects my interpretation and understanding of these studies. Therefore the data is presented as seen and the reader of this thesis may come to a different conclusion.

Table 5: Summary of Literature Values for Water Use of Bauxite, Copper, Gold and Iron Ore Production. Only Publications with a Red Contour are Used for Calculations in Chapter 5.4.

Bauxite

	Max	Min	Average /LCA	Units	Source	Description	Boundary	Allocation method
Ore			1.09	m^3/t bauxite	Mudd, 2008	Consumption including recycled water from company reports	From mining to bauxite product	None
	1.154	0.022	0.404	m^3/t bauxite	Gunson, 2013	Withdrawals from company reports	From mining to bauxite product	None

Copper

	Max	Min	Average /LCA	Average	Units	Source	Description	Boundary	Allocation method
Ore			1.27		m^3/t ore	Mudd, 2008	Consumption of copper production including recycled water from company reports copper only production	From mining to metal	No information provided.
			1.22		m^3/t ore	Mudd, 2008	Consumption of copper production including recycled water from company reports copper-gold production	From mining to metal	No information provided.
	3.065	0	0.521	0.371	m^3/t ore	Gunson, 2013	Withdrawals from company reports	From mining to metal (processing with concentrators)	Economic
	0.432	0.1	0.22		m^3/t ore	Gunson, 2013	Withdrawals from company reports	From mining to metal (hydro-metallurgical processing)	Economic
	1.1	0.79	0.945	0.58	m^3/t ore	Cochilco, 2008	Conumption from company reports	From mining to metal (processing with concentrators)	No information provided

	0.3	0.13	0.215		m^3/t ore	Cochilco, 2008	Consumption from company reports	From mining to metal (processing with concentrators)	
Commodity	1046.9	9.8	70.4		m^3/t Cu	Northey, Haque, Mudd, 2013	Water consumption from company reports	Reporting oerations apply different methods: underground and/or open pit mining, concentration, smelting, refining, leaching, solvent extraction and electrowinning	Economic
			20.73		m^3/t Cu	Norgate and Lovel, 2004, Cited in Gunson, 2013	LCA but consumption is not clearly defined	Pyrometallurgy: Sum of the process steps below (mine and mill, smelting, refining)	Unknown
			29.4		m^3/t Cu	Norgate and Lovel, 2004, Cited in Gunson, 2013	LCA but consumption is not clearly defined	Hydrometallurgy: Sum of the process steps below (mine and heap, SX/EW)	Unknown
			6.4		m^3/t Cu	Norgate and Lovel, 2004, Cited in Gunson, 2013	LCA but consumption is not clearly defined	SX/EW	Unknown
			7.8		m^3/t Cu	Norgate and Lovel, 2004, Cited in Gunson, 2013	LCA but consumption is not clearly defined	Copper smelting	Unknown
			0.6		m^3/t Cu	Norgate and Lovel, 2004, Cited in Gunson, 2013	LCA but consumption is not clearly defined	Refining of smelted copper	Unknown
			23		m^3/t Cu	Norgate and Lovel, 2004, Cited in Gunson, 2013	LCA but consumption is not clearly defined	Mine and heap	Unknown
			12.33		m^3/t Cu	Norgate and Lovel, 2004, Cited in Gunson, 2013	LCA but consumption is not clearly defined	Mine and mill	Unknown
			172		m^3/ t Cu	Mudd, 2008	Consumption including recycled water copper only production	From mining to metal	No information provided.
			116		m^3/t Cu	Mudd, 2008	Consumption including recycled water copper-gold production	From mining to metal	No information provided.
	402.61	0.013	88.03	68.02	m^3/t Cu	Gunson, 2013	Withdrawals from company reports	From mining to metal (processing with concentrators)	Economic
	96.18	27.77	48.01		m^3/t Cu	Gunson, 2013	Withdrawals from company reports	From mining to metal (hydro-metallurgical processing)	Economic

Gold

	Max	Min	Average/ LCA	Average	Units	Source	Description	Boundary	Allocation method
Ore	1.72	0.67	0.88		m^3/t ore	Mudd, 2007a	Consumption from company reports	From mining to metal	None
	2.87	0.72	1.42		m^3/t ore	Mudd, 2007b	Consumption from company reports	From mining to metal	No information provided
			1.96		m^3/t ore	Mudd, 2008	Consumption including recycled water from company reports	From mining to metal	No information provided.
			0.74		m^3/t ore	Norgate and Lovel, 2004, Cited in Gunson, 2013	LCA but consumption is not clearly defined	From mining to metal	Unknown
	10.9	0.003	0.745		m^3/t ore	Gunson, 2013	Withdrawals from company reports	From mining to metal	Economic
Comm.	666,000	224,000	325,000		m^3/t Au	Mudd, 2007a	Consumption from company reports	From mining to metal	None
	178,300,0	224,000	691,000		m^3/t Au	Mudd, 2007b	Consumption from company reports	From mining to metal	No information provided
			716,000		m^3/t Au	Mudd, 2008	Consumption from Company reports including recycled water	From mining to metal	No information provided.
			259,290	273,715	m^3/t Au	Norgate and Haque, 2012	Consumption from LCA (non-refractory ore)	From mining to metal	Mass
			288,140		m^3/t Au	Norgate and Haque, 2012	Consumption from LCA (non-refractory ore)	From mining to metal	Economic
			259,290		m^3/t Au	Norgate and Haque, 2012	Consumption from LCA (refractory ore)	From mining to metal	Mass
			288,140		m^3/t Au	Norgate and Haque, 2012	Consumption from LCA (refractory ore)	From mining to metal	Economic
	474,200,0	610	400,000		m^3/t Au	Gunson, 2013	Withdrawals from company reports	From mining to metal	Economic

Iron Ore

	Max	Min	Average/ LCA	Units	Source	Description	Boundary	Allocation method
Commodity	3	0.094	0.598	m^3/t ore	Gunson, 2013	Withdrawals from company reports	Mining and processing	None
			0.21	m^3/t ore	Norgate and Lovel, 2004, Cited in Gunson, 2013	LCA but consumption is not clearly defined	Mine and Mill	Unknown

5.4 Global water withdrawals in 2016

The goal of this chapter is to provide a range (scenarios) of the yearly global water withdrawals of bauxite, copper, gold and iron ore. To calculate the minimum, maximum and average scenarios I add up the respective values from table 6. If it is only possible to calculate a single value from literature as in the case of iron ore, this value is considered in all 3 scenarios. This is done for commodity based results and ore based results separately. The results are 6 values: The sum of the ore based averages, the sum of the commodity based averages, the sum of the minimum values and the sum of the maximum values of both, ore based and commodity based. Table 7 shows the result.

Bauxite							
	Result of the Literature Review			**Production Data**	**Production 2016**		**Withdrawals 2016 [Mm^3]**
Commodity	Average	0.404	m^3/t Bauxite	Reichl 2018	284.9	Mt Bauxite	115

Copper							
	Result of the Literature Review			**Production Data**	**Production 2016**		**Withdrawals 2016 [Mm^3]**
Ore	Average	0.475	m^3/t Ore	IRP 2018, Reichl 2017, Reichl 2018	2267	Mt ore	1080
	Max.	0.58	m^3/t Ore				1300
	Min.	0.371	m^3/t Ore				840
Commodity	Average	69.21	m^3/t Cu	Reichl 2018	20.42	Mt Cu	1413
	Max.	70.4	m^3/t Cu				1440
	Min.	68.02	m^3/t Cu				1389

Gold							
	Result of the Literature Review			**Production Data**	**Production 2016**		**Withdrawals 2016 [Mm^3]**
Ore	Average	1.015	m^3/t Ore	IRP 2018, Reichl, 2017, Reichl, 2018	1074	Mt Ore	1090
	Max.	1.42	m^3/t Ore				1530
	Min.	0.745	m^3/t Ore				800
Commodity	Average	422428.75	m^3/t Au	Reichl, 2018	0.003214	Mt Au	1358
	Max.	691000	m^3/t Au				2221
	Min.	273715	m^3/t Au				880

Iron Ore							
	Result of the Literature Review			**Production Data**	**Production 2016**		**Withdrawals 2016 [Mm^3]**
Commodity	Average	0.598	m^3/t Iron Ore	Reichl 2018	3259	Mt Iron Ore	1950

Table 6: Global water withdrawals of Bauxite, Copper, Gold and Iron Ore production in 2016

Table 7: The Sum of Global Water Withdrawals of Bauxite, Copper, Gold and Iron Ore Production

Ore	Average, Maximum and Minimum Scenarios of CO_2 Emissions from Bauxite, Copper, Gold and Iron Ore Production for 20016	Sum of averages	4235	Mm^3
		Sum of Max.	4895	Mm^3
		Sum of Min.	3705	Mm^3

Commodity	Average, Maximum and Minimum Scenarios of CO_2 Emissions from Bauxite, Copper, Gold and Iron Ore Production for 20016	Sum of averages	4836	Mm^3
		Sum of Max.	5726	Mm^3
		Sum of Min.	4334	Mm^3

Equ 6 serves as an example of how the average value in table 6 for commodity based literature results from table 5 is calculated. In this case Mudd (2008) is excluded from the calculations because recycled water is included, and Norgate and Lovel (2004) is excluded because it is very unclear what it comprises and also the boundary is not clear. Also publications providing more than one value are considered only once in the average in a way that the average from these values is taken before calculating the overall average. In the example this is the case for the thesis of Gunson (2013), providing a value for hydrometallurgical processing (48.01 m^3/t Cu) and for pyrometallurgical processing (88.03 m^3/t Cu). The ore production of 2016 is calculated from the sources as stated in chapter 3.1. The withdrawals in 2016 derive from a simple multiplication of the literature result and the production in 2016. Only the red framed values from table 5 are taken into account. Other values in table 5 serve as additional information.

$$\frac{\mathbf{70.4+68.02}}{\mathbf{2}}=\mathbf{69.21}$$

$\boldsymbol{Equ.}\,6\text{:}\ \boldsymbol{Average\ Water\ Consumption\ of\ Copper\ Production}$

When we talk about water withdrawals of the mining industry and put them in the context of world water withdrawals we have to be aware that they only account for a small portion. (Gunson 2013 p. 18)

In 2010 about 4000 Gm^3 have been withdrawn globally. (Fao, 2018) The sum of the global water withdrawals calculated from the minimum and maximum values from literature in 2016 of bauxite, copper, gold and iron ore production is between roughly 5726 and 3705 Mm³, resulting in a range of 0.14 and 0.093 percent of global withdrawals assuming that withdrawals stayed roughly the same until 2016. The result of this thesis, calculated with the averages of ore based literature values is 4235 Mm³ and calculated with commodity based values 4836 Mm². Because publications often use different, undefined terms like consumption and withdrawals, this must be seen as a limitation of the calculations but publications used for calculations are carefully selected for the best estimate of water withdrawals possible.

5.5 Conclusions of the Chapter Water Withdrawals

Publications dealing with water use in the mining industry are limited in terms of presenting an average value for specific water withdrawals of a commodity. Furthermore the observation that specific water use seems to be stable over time is also assumed in the calculations for the total water withdrawals in 2016 in this thesis. Ore grade is an important factor for the prediction of water withdrawals and therefore we may reach a point in the future when technological advance and decreasing grades are not in balance anymore and water intensity begins to rise quickly. Climate conditions highly influences water withdrawals as well. Economy of scale has more influence on withdrawals for precious metals than on withdrawals for base metals, leading to fewer withdrawals per tonne with increasing throughput for precious metals. Problems with sample bias, allocation factors and so forth make results blurry. The attempt to validate data by comparing literature values with company data partly failed because reporting on company level is too intransparent. All of the major companies looked at in this thesis report water use in some form, but data that cannot be allocated to a product is useless for environmental analysis on company level. Reporting has to be much more detailed to achieve comparability. For an accurate estimation of global water withdrawals, evaluation of detailed reporting on company level is the most obvious way to achieve good results fast. To overcome the allocation problem I would suggest to group mines with the same products and report water withdrawals for example of mines producing copper and gold as a single number because there simply is no solution that enhances data quality. If production of these mine sites is reported too, allocation factors can be applied if desired by the reader. Anyway, good global estimations would only be possible if withdrawals are reported for a high percentage of global production.

6 CO_2 Emissions

6.1 Introduction

Unlike downstream processes, the extraction and concentration of minerals often takes place in remote places and only a minority is directly affected by most of the emissions. The perceivable emissions of mining like dust, noise and so forth are often considered and listed in literature because they are important for the operation of a mine. Safety reasons, relationships with stakeholders surrounding the mine, efficiency and the health of the employees, make for example the control of dust dispersion critical for operations.

On the other hand greenhouse gas emissions have been widely ignored by literature. One purpose of this thesis is to find out if greenhouse gas emissions were rightly ignored by mining literature in the past and if in the future should be included in mine planning due to falling ore grades and rising energy demand for production subsequently.

6.2 Literature review of CO_2 emissions

We can classify the sources of greenhouse gas emissions of mining operations in different ways. Possible approaches would be to distinguish between mining and processing, classify by power source (electricity or fuel) and to distinguish emissions caused on site and emissions caused by power that is generated somewhere else. This topic is closely linked to reporting and therefore discussed in the next chapter in more detail.

Because allocation problems of CO_2 emissions are similar to those of water and have already been discussed in the respective chapter, they will only be mentioned briefly here.

Energy source and environmental impact are naturally interlinked. (Norgate et al., 2007, p. 845) ‘GHG emissions during the production of copper are largely a result of the use of fossil fuel energy’. (Northey et al., 2013, p. 125) The relationship between energy source and emissions is expressed as an emission factor in kg CO_2/kWh. Australian emission factors for example are higher than Chilean ones because there, large part of the energy is generated from the burning of coal. (Northey et al., 2013, p. 125) For this thesis emissions from the generation of electricity and from the burning of fuels on site are relevant. That includes electricity from the grid, on site power generation and fuel used for powering equipment like LHD equipment.

The discussion about factors influencing CO_2 emissions includes grade, complexity of the deposit, technological development, reporting methods and emission factors. Fig 11 shows that low grades are connected to high energy intensity and therefore likely higher CO_2 emissions. Emission factors are highly influencing the resulting CO_2 emissions as well. The burning of fossil fuels increases emission factors. Lower grades indicate higher energy intensity and therefore increasing GHG emissions. ‘However, GHG emissions display much more variability with respect to ore grade as shown by the low R2 value.’ This is shown in Fig. 12 (Northey et al., 2013, p. 125) It must be noted that Scope 3 greenhouse gas emissions, emissions that are not directly related to production, are included in Fig. 12. Scope 1 emissions refer to emissions generated on site and mainly include emissions from the burning of fuels (direct emissions). Scope 2 emissions refer to emissions from purchased electricity heat or steam. (ghgprotocol.org, 2018a)

> ‘Scope 3 is all the remaining energy associated with the emission generated by third party material suppliers, travel of the employees, etc. that are generally outside the boundary of the production site.’ (Northey et al., 2013, p. 119)

Generally companies only report Scope 1 and 2 GHG emissions data, and so direct comparison with previous LCA work, which includes Scope 3, is difficult.’ (Northey et al., 2013, p. 119) To highlight the influence, it is important to note that copper cathode GHG intensity is three times higher when Scope 3 emissions are considered. (Northey et al., 2013, p. 125)

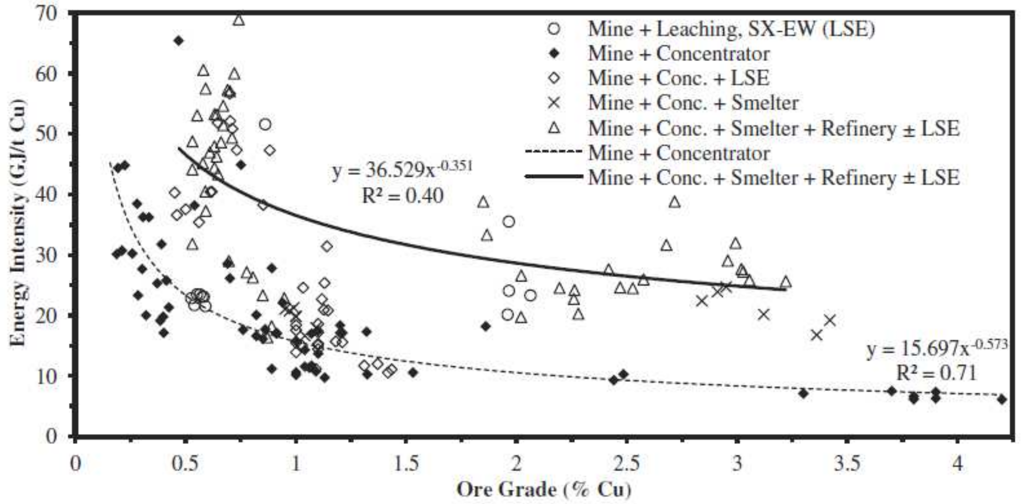


Figure 11: Energy intensity as a function of ore grade for 31 copper operations, with each data point representing a year of production. (Northey et al., 2013, p.123)

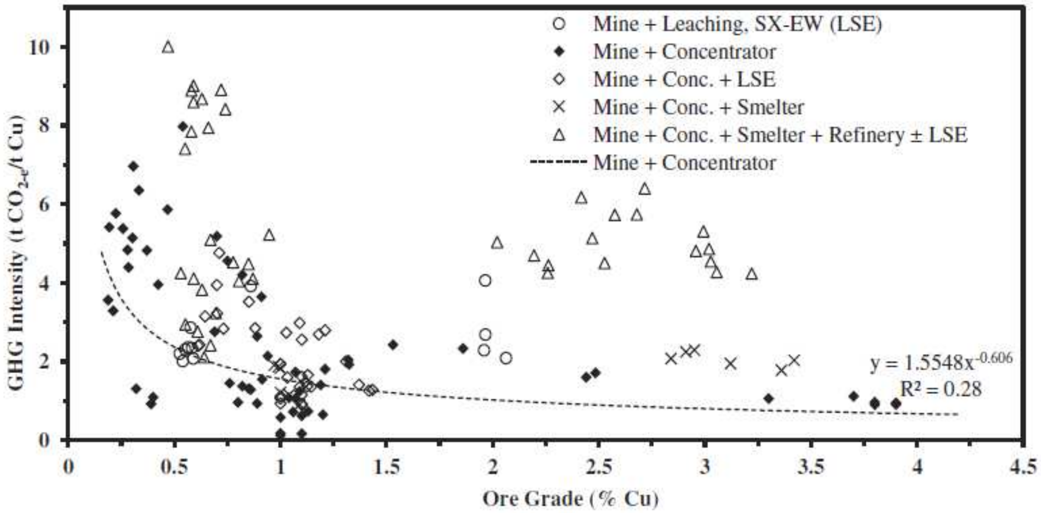


Figure 12: GHG intensity as a function of ore grade for 28 copper operations, with each data point representing a year of production. (Northey et al. 2013, p.124)

For further discussion I want to refer to some key points made in publications dealing with energy consumption and CO_2 emissions in the mining industry. An overlap of conclusions can be observed.

- **Declining ore grades and increasing complexity of deposits**

  With globally declining ore grades, the amount of ore mined and processed to obtain the same quantity of metal is increasing. Subsequently the specific energy of metal production is increasing, assumed that process efficiency stays the same. (Norgate & Haque, 2010, p. 266) It is indicated by a number of studies that the shift from lower grades and more complex deposits leads to increasing energy intensity. (Nuss & Eckelmann, 2014, p. 2)

- **Development of new technology and resulting increase in energy efficiency**

  The trend of the logic conclusion of increasing energy intensity due to declining grades and more complex deposits might be compensated by development of more efficient technology. (Nuss & Eckelmann, 2014, p. 2)

  Mudd (2007a) came to the conclusion that there are no significant trends in gold mining in Australia regardless if looked at the energy per ore processed or per kg gold produced. The time span looked at in this study is 1991 to 2005 with a varying amount of data points per year. ‘In general, there appear to be no significant trends over time for all key resource intensity aspects analysed (energy, water and cyanide consumption and carbon dioxide emissions) and as such these graphs have not been included.‘ (Mudd, 2007a, p. 635)

  However, in countries that faced a lot of technological development in a short time like China, it can be seen that the increased efficiency leads to lower energy intensity. (Wang and Feng, 2017, p. 81)

  In more developed countries we may have already reached a state of equilibrium where higher energy intensity due to declining ore grades is compensated by technological development. However, there might be a point where the efficiency maximum is reached. We inevitable have to go for lower grades in the future with rising resource demand globally, leading to an increase of energy intensity.

- **Lack of data for the CO_2 emissions of the mining and processing steps of metal production**

  Life cycle analysis of metal production often does not include the mining and processing steps in detail due to the lack of publicly available data and the minor significance compared to the downstream processes. (Norgate & Haque, 2010, p. 266)

- **Allocation of environmental impacts of co-products**

‘…it is necessary to divide the environmental impacts from the process and all upstream processes among all metal co-product(s).’ (Nuss & Eckelmann, 2014, p. 4) Common approaches are mass allocation and economic allocation. (ibid.)

‘…modern metals production system is a highly interconnected system with many of the metals being derived from multiple ores and as co-products with other metals along the stages of mining, purification, and refining’ (ibid.) That makes it difficult to allocate environmental impacts of production steps to a single metal. (ibid.)

The same problem occurs with the evaluation of the environmental impact on the hydrosphere and the allocation of land used by mining and processing stages.

- **Discussion about the significance of CO_2 emissions in the mining industry in a global context.**

  The discussion about the role of the mining industry regarding global warming can be supported by various numbers; including the values calculated in Chapter 6.4. In Chapter 6.4 the CO_2 emissions of bauxite, copper, gold and iron ore production in 2016 are put into the context of overall global CO_2 emissions and CO_2 emissions of the global metal production sector.

6.2.2 Values from literature

The calculations in chapter 6.4 are based on values from literature, shown in table 8. Only the red framed publications are considered. Norgate and Haque (2010) and Labriola (2009) are excluded from the calculations of copper related emissions because the values refer to copper concentrate and not to metal produced. Mudd 2007a and Mudd 2007b are excluded as well because they do not make clear statements about Scope 1, Scope 2 and Scope 3 emissions. Thus the different boundary makes these values noteworthy but not comparable to other publications. Estimations for CO_2 emissions of copper and gold show a similar variation as water does. It is noticeable that all values from life cycle analysis are higher than results based on company reports for the same metal.

Table 8: Summary of Literature Values for CO_2 Emissions of Bauxite, Copper, Gold and Iron Ore Production. Only Publications with a Red Contour are Used for Calculations in Chapter 6.4.

Bauxite CO_2

	Max	**Min**	**Average/LCA**	**Units**	**Source**	**Description**	**Boundary**	**Allocation method**
Ore			4.9	kg CO_2/t bauxite	Norgate and Haque, 2010	LCA	From mining to bauxite product	None

Copper CO_2

	Max	**Min**	**Average/ LCA**	**Average**	**Units**	**Source**	**Description**	**Boundary**	**Allocation method**
Ore			38.8		kg CO_2/t ore	Norgate and Haque, 2010	LCA	From mining to concentrate	None
			32		kg CO_2/t ore	Labriola, 2009, cited in Norgate and Haque 2010	According to Norgate and Haque (2010) comparable to the result of 38.8 kg CO_2/t ore above	Value for base metal ores	Unknown
Commo dity	8.5	0.9	2.6		t CO_2/t Cu	Northey, Haque, Mudd, 2013	Company reports	Reporting operations apply different methods: underground and/or open pit mining, concentration, smelting, refining, leaching, solvent extraction and electrowinning	Economic
			3.3	4.8	t CO_2/t Cu	Norgate et al., 2007	LCA "cradle to gate" Smelting/Converting and electro-refining	From mining to metal	None
			6.2		t CO_2/t Cu	Norgate et al., 2007	LCA "cradle to gate" Heap leaching and SX/EW	From mining to metal	None

Gold CO_2

	Max	Min	Average/ LCA	Average	Units	Source	Description	Boundary	Allocation method
Ore	50	23.2	36		kg CO_2/t ore	Mudd, 2007a	Company reports	From mining to metal	None
	40.9	5.8	21.7		kg CO_2/t ore	Mudd, 2007b	Company reports	From mining to metal	No information provided
			61.7	69.5	kg CO_2/t ore	Norgate and Haque, 2012	LCA non refractory ore	From mining to metal	Mass
			77.2		kg CO_2/t ore	Norgate and Haque, 2012	LCA refractory ore	From mining to metal	Economic
Commodity	16700	10700	14100		t CO_2/t Au	Mudd, 2007a	Company reports	From mining to metal	None
	16400	3700	11500		t CO_2/t Au	Mudd, 2007b	Company reports	From mining to metal	No information provided
			26840	23436	t CO_2/t Au	Norgate and Haque, 2012	LCA refractory ore	From mining to metal	Mass
			17562.3		t CO_2/t Au	Norgate and Haque, 2012	LCA non refractory ore	From mining to metal	Mass
			19520		tCO_2/t Au	Norgate and Haque, 2012	LCA non refractory ore	From mining to metal	Economic
			29820		t CO_2/t Au	Norgate and Haque, 2012	LCA refractory ore	From mining to metal	Economic

Iron CO_2

	Max	Min	Average/LCA	Units	Source	Description	Boundary	Allocation method
Commodity			11.9	kg CO_2/t ore	Norgate and Haque, 2010	LCA	Mining to port (Iron Ore)	None

6.3 Reporting of CO_2 emissions

The widely reported approach is to distinguish between emissions generated at the mine (direct emissions) and emissions that derive from energy generated somewhere else (indirect emissions). Thirdly, emissions that are connected to company activities but are outside of the boundary of the production site are considered as “Scope 3” emissions. This approach is the standard set by the GHG protocol (ghgprotocol.org, 2018a) and is adopted by the GRI standard. (Global Reporting Initiative, 2018a)

The GHG protocol is an initiative from the late 1990s when the need for an international standard for greenhouse gas accounting and reporting was recognized. (Global Reporting Initiative, 2018b)

For all disclosures, emission factors and a more detailed description of the data than the summary below suggests has to be reported to be in compliance with the GRI standard. For the goals of this thesis the description of Scope 1, Scope 2 and Scope 3 emissions is sufficient.

Disclosure 305-1

- Scope 1: GHG emissions from sources that are owned or controlled by an organization (GRI 305 Emissions 2016)

Electricity produced on site should be classified as direct energy by the reporting company. (Northey et al., 2012, p. 122) That did not change in the new standard.

It is unclear how much of the electric energy is generated on site. ‘It is not uncommon for mining operations to produce a proportion of their electricity from fuel burnt on-site.’ (Northey et al., 2012, p. 122) ‘Crushing and grinding plants are usually powered by electric motors, with the electricity often generated onsite using a diesel fuel-based engine and generator.’ (Norgate & Haque, 2010, p. 269)

Disclosure 305-2

- Scope 2: Indirect GHG emissions from consumption of purchased energy (electricity, heating, cooling, and steam) (GRI 305 Emissions, 2016)

Disclosure 305-3

- Scope 3: Indirect GHG emissions not included in energy indirect (Scope 2) GHG emissions that occur outside of the organization, including both upstream and downstream emissions (GRI 305 Emissions, 2016)

Scope 3 emissions can be higher than emissions from production. The greenhouse gas intensity for copper cathode calculated by Xstrata was 3 times higher when Scope 3 emissions were considered in addition to Scope 1 and 2. (Northey et al., 2012, p. 125) The calculated value of 12.7 t CO_2/t Cu including Scope 3 emissions is indeed about 3 times higher than the average of literature values in table 8 considering only Scope 1 and Scope 2 emissions.

The reporting standard used seems to have a high influence on the reported quantity of CO_2 emissions. When BHP reports to its internal standard, the emissions were 26% higher compared to an external standard. Using the same external standard as BHP, 2010 Mt. Isa Mines and Xstrata North Queensland sustainability reports showed a 10% increase using this standard. (Northey et al., 2012, p. 125)

Companies are being criticized that the reported data is not very useful for LCA. Main points are the lack of detail regarding type of energy input (thermal, heat, electrical, diesel), energy consumers and whether electricity is generated on or off-site. The opportunities for environmental analysis as the basis for identifying the main sources of emissions and therefore showing chances for improvements are limited due to lack of detailed reporting. (Northey et al., 2012, p. 122)

6.4 Global CO_2 emissions in 2016

The global metal production was held accountable for 3.4 Gt of direct and indirect CO_2 emissions in 2008. (Nuss & Eckelman, 2014, p. 1). The final energy use in the mining and quarrying sector was 1.81 EJ in 2004, (IEA, 2007, p. 40) and in 2005 the sum of emissions deriving from direct energy generation and process emissions was 98 Mt CO_2. (IEA, 2008, p. 481)

To compare this data with company data is associated with problems because electricity used at production sites is not included.

Table 9: Global CO_2 emissions of Bauxite, Copper, Gold and Iron Ore Production in 2016

Bauxite							
	Result of the Literature Review			**Production Data**	**Production 2016**		**CO_2 Emissions 2016 [Mt]**
Commodity	Average	4.9	kg CO_2/t Bauxite	Reichl 2018	284.9	Mt Bauxite	1.4

Copper							
	Result of the Literature Review			**Production Data Sources**	**Production 2016**		**CO_2 Emissions 2016 [Mt]**
Commodity	Average	3.7	t CO_2/t Cu	Reichl WMD 2018	20.42	Mt Cu	75
	Max.	4.8	t CO_2/t Cu				97
	Min.	2.6	t CO_2/t Cu				53

Gold							
	Result of the Literature Review			**Production Data Sources**	**Production 2016**		**CO_2 Emissions 2016 [Mt]**
Ore	Average	69.5	kg CO_2/t Ore	IRP 2018, Reichl, 2017; Reichl 2018	1074	Mt Ore	74.6
	Max.	77.2	kg CO_2/t Ore				82.9
	Min.	61.7	kg CO_2/t Ore				66.3
Commodity	Average	23436	t CO_2/t Au	Reichl, 2018	0.003214	Mt Au	75.32
	Max.	29820.5	t CO_2/t Au				95.84
	Min.	17560	t CO_2/t Au				56.44

Iron Ore							
	Result of the Literature Review			**Production Data**	**Production 2016**		**CO_2 Emissions 2016 [Mt]**
Commodity	Average	11.9	kg CO_2/t Iron Ore	Reichl 2018	3259	Mt Iron Ore	38.8

Table 10 is calculated in the same way as table 7

Table 10: The Sum of Global CO_2 Emissions of Global Bauxite, Copper, Gold and Iron Ore Production

Ore	Average, Maximum and Minimum Scenarios of CO_2 Emissions from Bauxite, Copper, Gold and Iron Ore Production for 20016	Sum of averages	189.9	Mt
		Sum of Max.	220.1	Mt
		Sum of Min.	159.5	Mt

Commodity	Average, Maximum and Minimum Scenarios of CO_2 Emissions from Bauxite, Copper, Gold and Iron Ore Production for 20016	Sum of averages	190.5	Mt
		Sum of Max.	233	Mt
		Sum of Min.	149.6	Mt

> ‘It should be noted that energy use and CO_2 emissions related to power generation are allocated to the electricity sector in IEA statistics….As a consequence, sub-sector energy use and emission data based on company emission data may differ from the figures in the IEA statistics.’ (IEA, 2007, p. 43)

I conclude that final energy use and direct energy generation is the same and equals Scope 1 (direct energy use). Process emissions of mining are low and therefore the IEA numbers for the sub sector mining and quarrying include mainly fuel use on site for haulage and other activities.

While the total global CO_2 emissions from the burning of fossil fuels and industry were 36.4 Gt in 2016 (Globalcarbonproject.org, 2016), 190.5Mt CO_2 emissions can be attributed to the production of bauxite, copper, gold and iron ore when the average of the literature values based on commodity produced, is multiplied with the global commodity production. For ore based values combined with the global ore processed, the result is almost the same with 189.9 Mt emitted. That is about 0.52 percent of the total global CO_2 emissions. The minimum and maximum values from literature lead to a range of 149.6 to 233 Mt CO_2 emitted in 2016 from the production of bauxite, copper, gold and iron ore.

6.5 Conclusions CO_2 emissions

Similar to water use, local conditions like emission factors and reporting methods influence reported numbers and therefore literature results. In a situation of falling grades and increasing complexity of deposits CO_2 emissions are expected to rise. Technological advance and increasing difficulty of extraction are in balance at the moment, leading to stable specific emissions over time but it is not clear how long that situation will last. The problem of allocation factors appears again in the case of CO_2 emissions and is summarized in the conclusions about water use. Furthermore, reporting standards cannot meet the needs of thorough environmental investigations.

7 Land use

7.1 Introduction

This is a very broad topic that is looked at in this thesis in a rather simplified way to actually be able to come up with numbers about the land use of gold, iron ore, bauxite and copper mining. I am saying broad because the impact of a mining operation on the land extends the production site and alters the surrounding environment. Therefore it is not clear beforehand what the term land use means. Not much information can be found about how much land is used by mining of metals in general but estimations can be found in literature about the metals investigated in this thesis. Also the magnitude of land use of mining in general is estimated in literature.

The main work by Murguia (2015) referred to in this thesis, refers to the term “direct used land”. This includes the mine site and surrounding infrastructure up to a certain limit of distance. Subsidence is not included for example. “…access roads were measured only up to 500 m from the mine industrial area (MIA).” (Murguia, 2015, p. 89)

A lot of definitions of land use can be imagined and are mostly determined by the measuring method and its limitations. Examples for shortcomings of methods to measure the direct used land are: Resolution of satellite images, limits of automated image interpretation, invisible disturbances like subsidence on 2D images, timespan from recultivation to visibility of recultivated area as undisturbed. (Murguia, 2015)

Apart from the visible disturbed surface, the true impact highly depends on the place and the type of land the mine is built on. Investigations of land use make more sense if potential alternative uses of that land are considered. The distribution of mines is also not random with respect to zones of biodiversity but a statistical analysis showed that mining more likely happens in zones of high biodiversity. (Murguia, 2015)

The question about the opportunity of alternative land uses for human purposes of the mine site has to be investigated before mining happens. Emissions and invisible disturbances influence a much bigger area than the mine site and decrease the number of possible opportunities to use the land. The question is whether the land is more valuable to humanity because of its natural traits like biodiversity or flood prevention and the extent to which mining impacts these gains. To better understand the impact of land use it is necessary to assign a value to the area that reflects the impact on biodiversity, climate and possible alternative usages. For measuring the true impact it is also important to take into account that the area surrounding the mine is made unusable for many other cultural and economic purposes due to emissions and safety risks. The risk of subsidence, even if not yet visible affects the possible usage of the land surrounding a mine. To raise awareness of how nature contributes to our wellbeing and also protects us from catastrophes like floods a valuation of diverse biomes in terms of monetary values can show the value of ecosystem services. (Constanze et al., 2014, p. 153)

The question if it is sustainable to mine at a certain location has to be solved for each mine individually by measuring the true impacts. Only the effort of a multidisciplinary approach can answer that question and not engineering or economics alone. In this scenario environmental impact has to be translated into cultural and economic impact. The question leading this discussion would be: What are the costs of mining and where is the borderline of acceptance to sustain our culture for future generations. The environmental impact of one country as one part of the body impacts the other part. This is not only true for gaseous emissions or the pollution of the ocean but also for alteration of land. Indigenous cultures are destroyed by occupying their land. We decrease diversity of cultures and the opportunity to learn from one another.

7.2 Literature review of land use

According to the SNL Metals & Mining database there are 2700 metal producing mines in the world. In addition, 25000 mines produce industrial minerals and 100000 quarries exist. (Ericsson, 2012, cited in Murguia, 2015 p.18-19)

‘Mining might be occupying considerably less than 1% of the world’s terrestrial land surface’ (Bridge 2004, cited in Murguia, p. 3-4). Estimates for the global area disturbed by mining range from 0.3 to 1 %. Hooke and Duque (2012) estimated the global area disturbed by mining to be 0.4 Mkm^2. That equals 0.3 % of the terrestrial surface. The estimations have in common that they are vague. Either the basis for the estimation is unclear as in the case of Norse et al. (1992), suggesting a global area disturbed by mining of 0.5 to 1.0 Mkm^2 (Norse et al., cited in Hooke and Duque, 2012), or data was only available for some countries and the global estimate is an extrapolation like the estimate by Hooke and Duque (2012). (Hooke and Duque, 2012, p. 7)

The terms land cover and land use can be distinguished. A land cover, like a forest can have multiple uses. For mining, an obvious approach is to say that the area of the mine site equals the disturbed land. Murguia refers in his work to the term cumulative net area disturbed which equals the amount of land occupied to carry out the mining activities. That area is usually a very small part of the concession area. (Murguia, 2015, p. 14-15)

On the other hand, the impact of mining activities can affect a much bigger area. Chemical reactions initiated by mining activities and mine waste dumped into rivers have an impact on the environment. The value of the land is therefore decreased. An example is the dumping of mine waste into rivers, causing fish loss in huge areas as happened in Papua New Guinea. Mine waste dumped into a river caused fish loss in an area of 480 km^2. (Boge, 1998, cited in Murguia, 2015, p. 15)

Calculations in this thesis only refer to data of direct land use. An estimate of the specific land use of gold, bauxite, copper, silver and iron ore based on a random sample of mines around the world was done by Murguia (2015).

The study focused on the mine site visible on satellite images and included access roads up to 500 m from the mine site but excluded exploration and subsidence. (Murguia, 2015, p. 89) The study focused on the life cycle phase of mining and beneficiation. The knowledge of the precise geographic location of the mines in the sample, visible on medium resolution (15 to 100 m/pixel) images with a temporal resolution of 16 to 18 days was a prerequisite for the success of the study. The images used are free of charge and have been released by the USGS in 2008. Open pit and underground large scale mines that produced in 2011 were considered. (Murguia, 2015, p. 21-54) Fig 13 summarizes the research boundary.

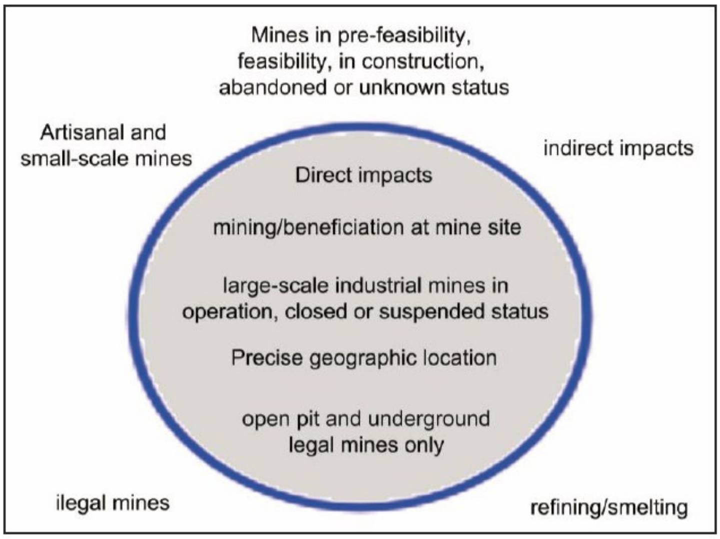


Figure 13: Research boundaries of mine selection for specific land requirements (Murguia, 2015, p. 22)

Table 11 not only shows specific values for land use but also provides the land use calculated by Murguia (2015) for the year 2011 of each commodity investigated in this thesis. That is the cumulative net area disturbed in 2011. The data is complemented with other investigations on direct land use for copper and bauxite.

Table 11: Summary of Literature Values for Land Use of Bauxite, Copper, Gold and Iron Ore Production. Only Values with a Red Contour are Used for Calculations in Chapter 5.4.

Bauxite								
	Max	**Min**	**Average/LCA**	**Units**	**Source**	**Description**	**Boundary**	**Allocation method**
Ore			7.98	ha/Mt ore	Murguia, 2015	Directly disturbed land visible on satellite images	Mine site	None
			95780	ha	Murguia, 2015	Directly disturbed land visible on satellite images in the period of one year (2011)	Mine site	None
			12	ha/Mt ore	Sliwka 2001	Area used for mining activities. (Infrastructure is considered negligible in comparison)	Mine Site	None
			16	ha/Mt ore	International Aluminium Institute, 2009	Area used for mining activities	Unknown	None

Copper								
	Max	**Min**	**Average/LCA**	**Units**	**Source**	**Description**	**Boundary**	**Allocation method**
Ore			4.5	ha/Mt ore	Murguia, 2015	Directly disturbed land visible on satellite images	Mine site	Economic
			415245	ha	Murguia, 2015	Directly disturbed land visible on satellite images in the period of one year (2011)	Mine site	Economic
			2	ha/Mt ore	Ruhrberg 2002	Mine Site: Waste dumps, subsidence, tailings pond…	Unknown	Unknown

Gold

	Max	Min	Average/LCA	Units	Source	Description	Boundary	Allocation method
Ore			6.7	ha/Mt ore	Murguia, 2015	Directly disturbed land visible on satellite images	Mine site	Economic
			371,815	ha	Murguia, 2015	Directly disturbed land visible on satellite images in the period of one year (2011)	Mine site	Economic

Iron

	Max	Min	Average/LCA	Units	Source	Description	Boundary	Allocation method
Ore			4.25	ha/Mt ore	Murguia, 2015	Directly disturbed land visible on satellite images	Mine site	Economic
			267344	ha	Murguia, 2015	Directly disturbed land visible on satellite images in the period of one year (2011)	Mine site	Economic

7.3 Global land use in 2016

For the calculations of Table 12 and 13 the red framed values from table 11 are used and multiplied with production data to calculate minimum maximum and average scenarios where possible. The procedure is the same as with water and CO_2.

Table 12: Global Land Use of Bauxite, Copper, Gold and Iron Ore Production in 2016

Bauxite							
	Result of the Literature Review			**Production Data**	**Production 2016**		**Land Use 2016 [km^2]**
Commodity	Average	12	ha/Mt Bauxite	Reichl, 2018	284.9	Mt Bauxite	34
	Max.	16	ha/Mt Bauxite			Mt Bauxite	46
	Min.	7.98	ha/Mt Bauxite			Mt Bauxite	23

Copper							
	Result of the Literature Review			**Production Data**	**Production 2016**		**Land Use 2016 [km^2]**
Ore	Average	3.3	ha/Mt Ore	IRP 2018, Reichl 2017, Reichl 2018	2267	Mt ore	75
	Max.	4.5	ha/Mt Ore				100
	Min.	2	ha/Mt Ore				45

Gold							
	Result of the Literature Review			**Production Data**	**Production 2016**		**Land Use 2016 [km^2]**
Ore	Average	6.7	ha/Mt Ore	IRP 2018, Reichl, 2017, Reichl, 2018	1074	Mt Ore	72

Iron Ore							
	Result of the Literature Review			**Production Data**	**Production 2016**		**Land Use 2016 [km^2]**
Commodity	Average	4.25	ha/Mt Iron Ore	Reichl, 2018	3259	Mt Iron Ore	139

Table 13 is calculated in the same way as table 7.

Table 13: The Sum of Global Land Use of Bauxite, Copper, Gold and Iron Ore Production

Ore	Average, Maximum and Minimum Scenarios of CO_2 Emissions from Bauxite, Copper, Gold and Iron Ore Production for 20016	Sum of averages	320	km^2
		Sum of Max.	357	km^2
		Sum of Min.	279	km^2

Commodity	Average, Maximum and Minimum Scenarios of CO_2 Emissions from Bauxite, Copper, Gold and Iron Ore Production for 20016	Sum of averages	320	km^2
		Sum of Max	357	km^2
		Sum of Min.	279	km^2

To sum up, 320 km², have been newly disturbed by mining of bauxite, copper, gold and iron ore in 2016 when calculating with the average from literature values, whereas the range resulting from the minimum and maximum values is 279 km² to 357 km². Compared to the value for the currently disturbed surface by mining from Hooke and Duque (2012) of 0.4 Mkm² mentioned in chapter 7.2, and the 0.5 to 1 Mkm² estimated by Norse et al. (cited in Hooke and Duque, 2012), the maximum calculated in this thesis of 357 km² newly disturbed surface in 2016 is fractional.

7.4 Conclusions land use

Satellite technology allows for measuring of direct impacts but is limited. The resolution, the top view and other problems restrict the measurements to the mine site where vegetation is removed. This approach does neither fully reflect the disturbed land, nor does it show the environmental impact. Activities and the subsequent disturbances a mining operation causes can be invisible in a top view. Additionally invisible impacts and future impacts like subsidence and acid mine drainage cannot be accounted for with that approach. Overall the information of the specific impact obtained from publications is sparse. A factor of about 2 between the results of publications can be observed.

8 Conclusion and personal statement

I think that research in the field of environmental impacts of commodity production can only come up with better numbers, than published at the moment when either a very big database is created, or better, companies provide more detailed and transparent data in their annual reports in a way that the site specific data is summarized in a comprehensible, standardized and therefore comparable manner. I assume that the difficulty of obtaining a huge dataset with environmental values that represents global production is too high at the moment. Therefore, conclusions of publications show a lot of limitations that are often described. Subsequently results for specific environmental data for the production of a commodity vary with a factor of about 3 for CO_2 emissions and water withdrawals and with a factor of about 2 for land use.

Personally, I would only start again investigating on a global level when proper data is available and statistical analysis can be done.

More interestingly, qualitative analyses of comparable data can show trends like the technological development, and the increased effort connected to exploiting lower grade deposits being in balance, leading to stable specific emissions.

I am also not sure if it makes sense to make further quantitative investigations on global level because the values are low compared to total global values and the real impact is site specific. What has been published until now seems fine for an estimation of the magnitude of water withdrawals, CO_2 emissions and land use but it seems like further investigations will not lead to better values if the methodology will not be changed.

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Annex Table of Contents

1. Data request from companies

I wrote the following email with the exemplary table below attached to the responsible department of 15 major companies, asking to complete the missing information. The requested environmental information was either not published at all or published in a way that does not allow attributing it to a single product.

1.1 Message sent to companies

Dear Sir or Madam,

as part of my studies at my university, Montanuniversität Leoben I am presently writing a master thesis. I am looking into the environmental - more specifically CO2, water and land - impacts of Fe, Cu, Al and Au mining and what the impact of an internalisation through pricing of these impacts might be.

As part of this, I am currently looking at the environmental impacts of the largest mining companies and I was wondering if you could help me with [Company] production, environmental and economic data beyond what you already report on your webpage, i.e. commodity based production and environmental data. The data will not be published in a form that could be linked to a single companies, but only in accumulated form as a comparison to accumulated commodity specific data from the literature.

Please find attached an Excel sheet that I would ask you to fill in and return to me by 20 April.

Please let me know if you have any questions.

Thanks in advance for your help and best regards,

Benjamin Bayer

1.2 Attached table

Company:			
Data year:			
Explanations: Please see comments (marked with red corners) in relevant cells.			
For the environmental data points, we consider the relevant GRI definitions, so please use GRI data, if available			
Please fill in the data in the red framed cells and check the others (from annual reports)			
Production data required			
Product	**Metal produced**	**Units**	**Ore processed**
Copper produced		10^3 t	
Copper ore processed		10^3 t	
Iron ore produced		10^3 t	
Environmental data required			
Product	**Environmental issue**	**Unit**	**Number**
Company Total	Water withdrawals	Mm^3	
	Water recycled and reused	M m^3	
	Total CO2 Scope 1+2	Mt CO2e	
	Land disturbed 2016	Km^2	
	Total land disturbed	Km^2	
	Land rehabilitated	Km^2	
Cu	Water withdrawals	million m^3	
	Water recycled and reused	million m^3	
	Total CO2 Scope 1+2	million t CO_2e	
	Land disturbed 2016	Km^3	
	Total land disturbed	Km^3	
	Total land rehabilitated	Km^3	
Iron Ore	Water withdrawals	million m^3	
	Water recycled and reused	million m3	
	Total CO2 Scope 1+2	million t CO2e	
	Land disturbed 2016	km2	
	Total land disturbed	km2	
	Total land rehabilitated	km2	