NTNU – Trondheim
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The Environmental Impact of the Future Anthropogenic Copper Cycle

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MASTER THESIS

for

Student Anne-Jori Løhre

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The Environmental Impact of the Future Anthropogenic Copper Cycle

Det globale kobberkretsløpets miljøpåvirkninger

Background and objective

Copper is essential to modern society. As excellent electric and thermal conductor and because of its chemical resistance, it is used in a variety of applications. Examples include wiring; electric motors and generators; heat exchangers; steam generators; roofing and cladding; and works of art. Copper production is very energy intensive and contributes to energy-related greenhouse gas emissions. Copper is a heavy metal and waste flows from copper production are toxic to living organisms. Recycling displaces consumption of mineral resources and the associated energy demand and impacts from primary metal production, but the extent of recycling is limited by the amount of scrap available. To get an idea of the future environmental impact of copper production, a solid understanding of the entire copper cycle is required, including the different applications of copper; the stocks in use; the lifetimes of copper-containing products; the different technologies of copper production and recycling; and the available mineral resources and energy supply. This knowledge helps to anticipate challenges that may arise in the future, for example, vastly increasing energy use because of decreasing ore grade; limited mineral resources, or geo-political dependencies.

These challenges are part of the topic material criticality. Critical materials are substances or chemical elements with a risk of supply restriction, that are crucial in different product supply chains, and whose production has a significant environmental impact (Graedel et al., 2012). There is growing scientific activity on quantifying criticality in terms of upstream scarcity, supply chain vulnerability, and downstream impacts. One example is the EU-FP7 project DESIRE "DEvelopment of a System of Indicators for a Resource efficient Europe", which amongst other things aims at collecting data, developing methodology, and quantifying the potential criticality of a set of materials. The results of this project shall inform policy makers of the EU on potential future problems related to critical materials and suggestions for how to handle these. The project shall also advance environmental science by improving our database, developing new methods, and strengthening international collaboration of researchers.

Aim and scope:

The aim of this MSc project is to give the student a broad understanding of the issue of criticality and to enable her to work independently on a given topic with scientific methods. A scenario analysis of environmental impacts of the future copper cycle shall link the student's efforts to the activities in the project, thus enabling mutual benefits and synergies.

The following tasks are to be considered:

1. **Literature study**
   What is the state of the art of modelling future copper demand and the environmental impacts of copper production? Perform and document a literature study on different models of the anthropogenic copper cycle and scenario analyses for future copper demand.
2. **Detailed, region specific process inventories**
   What technologies to produce copper are used in different world regions, and what are their specific energy demand and emissions?
3. **Energy - ore grade relation**
   How do emissions from mining and concentrating copper oxide change when the ore grade changes? Try to classify global copper ore resources according to their total volume, their ore grade, and their region.
4. **Scenario modelling (stock model supplied by the DESIRE WP6 project team)**
   Combine the models of the copper production chain from your project with the knowledge on region-specific emissions factors from task 2, the energy-ore grade relation from task 3, and the dynamic stock model developed for the DESIRE project. Perform a sensitivity analysis and a scenario analysis covering the following parameters: i) future in-use stock levels of copper; ii) product lifetime, iii) end-of-life collection and recovery rate, iv) geographic distribution of copper mining and production, and v) different energy mixes.
5. **Documentation**
   Document your findings according to EPT's standards for MSc theses. The thesis body shall not exceed 50 pages excluding references. Additional material can be supplied as supplementary information.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14. January 2014

Olav Bolland
Department Head

Edgar Hertwich
Academic Supervisor

Research Advisor: PostDoc Stefan Pauliuk

Preface and Acknowledgements

This thesis is the final product of my M.Sc. in Mechanical Engineering at the Norwegian University of Science and Technology. Regarding a central topic of the thesis, energy demand, the *energy intensity* [MJ/ton] is an established term. However, this master`s thesis has chosen to divide energy demand to *electricity* demand and *diesel* demand. *Electricity intensity* is not an established term, but is utilized in the thesis as electricity demand per kg [kWh/kg].

The work of my thesis is conducted with guidance by supervisor professor Edgar Hertwich and co-supervisor postdoctoral Stefan Pauliuk. In addition I would like to dedicate extra thanks to Ph.D. candidate Erik Løhre Grimsmo, M.Sc. Andreas Nordby Meese, professor emeritus Kenneth A. Root and Ph.D. Per Jostein Stavnebrekk for valuable input and proofreading of my work.

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Sammendrag

I denne masteroppgaven har man sett på fremtidens kobberressurs- og miljøproblem(er) relatert til samfunnets økende kobberetterspørsel. Ved å analysere den menneskeskapte kobbersyklusen har det blitt modelert scenarier som har tidsperspektiv frem til 2050. Disse scenariene er bygd på "Special Report on Emissions Scenarios" (SRES)-rammeverket. Parametrene som er vektlagt i scenariomodelleringen er; kobber-i-bruk vekst, økning av hvor mye av kobberet fra i-bruk fasen som blir resirkulert og gjenvunnet, økning av hvor grønn energien på strømnettet er, samt økning av kobberetterspørsel. Livssyklusanalyse, og scenarie- og sensitivitetsanalyse har vært metodene brukt for å se på; når kobberressursene tilgjengelig ikke tilfredstiller samfunnets kobberetterspørsel, hvor mye elektrisitetsbehovet for kobberproduksjon øker i fremtiden, samt hvor mye drivhusgassutslipp det er knyttet opp mot produksjon av kobber. Dette er blitt gjort både for et globalt marked, samt seks ulike regionale marked. I etterkant av arbeidet er det blitt oppdaget feil i scenariemodelleringen. Dette må taes i betraktning når man leser resultatene for spesifikke årstall. Resultatene er for øvrig riktige dersom man kun ser dem i sammenheng med de fire (fem) parametrene brukt i analysene; kobber-i-malm grad (og tilhørende avfall-malm forhold), andel av kobberetterspørselen som er tilfredstilt av resirkulert kobber, kobberetterspørsel og energimiks (hvor mye kullkraft, gasskraft, vannkraft, vindkraft etc. i prosent strømmen på nettet består av). Scenarieresultene er presentert og diskutert, men sensitivitetsanalysene er vektlagt da disse har størst analyseverdi. De viktigste resultatene følger.

Mengden kobberressurser tilgjengelig er tilstrekkelig til å tilfredstille samfunnets kobberetterspørsel i første halvdel av dette århundre. På den andre siden krever dette at man for eksempel reduserer tapet av kobber når kobber gjenvinnes og resirkuleres. Man kan også utvikle materialer som kan erstatte kobber i noen produkter. Dette vil være med på redusere kobberetterspørselen.

Det er forventet at kobberprosenten i malm som prosesseres vil synke i fremtiden. På grunn av dette antas økningen av elektrisitetsbehovet per kg kobber produsert for de prosessene som påvirkes av denne nedgangen å være maksimalt 66 % (i.e. kobber-i-malm prosent = 0.41). Dette er mye mindre enn hva tidligere publisert litteratur har antatt (200-700%). Elektrisitet-kobber-i-malm forholdet er negativt eksponensielt, slik at minking av kobber-i-malm prosent er mer kritisk lengre ut i fremtiden.

Man kan forvente en økning fra dagens utslipp på 81 MT CO_2-eq. årlig opp til 290 MT CO_2-eq. i 2050 dersom man kun ser på økning av kobberetterspørselen. Dersom man i tillegg legger på effekten av forventet minkende kobber-i-malm og økende mengde avfall ift malm, er utslippet 390 MT CO_2-eq.. Om energimiksen blir grønnere og andel av kobberetterspørselen som er tilfredstilt av resirkulert kobber blir høyere, kan det årlige utslippet i stedet bli 170 MT CO_2-eq..

For å redusere det totale utslippet globalt bør økningen som skyldes kobberproduksjon kompenseres ved å bruke kobber som en investering i for eksempel vindmøller, samt å minske kobbertap vedrørende resirkulering. Hvordan man kan sørge for å ha tilfredstillende menge kobberressurser tilgjengelig også et godt stykke ut i fremtiden, samt å moderere økningen av utslipp fra kobberproduksjon og utslipp fra samfunnet generelt er politisk relevant. Oppdatert og fremtidsrettet informasjon er av høy interesse for å ta de riktige beslutningene. Studier som inkluderer skifting av ansvar fra produsenten til forbrukeren kan føre til at politikere kommer til å tenke annerledes når de skal komme med lover og regler for å moderere utslippet.

Abstract

This master`s thesis has discussed two problems of modern society; shortage of copper resources and an increase of electricity use and global warming potential (GWP) from copper production in the future.

Unlike most studies regarding environmental impacts from copper production, this study is; comprehensive considering that it includes a dynamic life cycle and is forward-looking regarding a number of factors which have high relevance for the result. The methodology of life cycle analysis (LCA) is utilized together with scenario building, and scenario and sensitivity analysis. The scenario and sensitivity parameters utilized in the analyses are based on the scenario building, which has in hindsight shown to have been conducted with errors. This should be taken into consideration when reading the results for electricity use and GWP for a certain year. The results are on the other hand correct if one sees them in relation to the scenario and sensitivity parameters utilized. The central results of this master thesis follow:

To extend copper depletion time beyond 2050 requires action. A medium in-use stock growth and high end-of-life collection and recovery rate increase could be mentioned as initiatives. Regarding direct electricity intensity of primary copper production, it will increase in the future since a declining ore grade is expected. With an ore grade of 0.41, the estimated energy intensity is 7.1 kWh/ kg refined copper. The increase compared to today is not as crucial as expected by others (200-700 %), but remarkably high for mining and beneficiation (i.e. 66 %). The rate of environmentally cruciality, due to an increase of the demand in electricity, will increase in the future as the energy-ore grade relation is not linear, but negatively exponential. On the other hand, the annual generated GWP from global copper production is dependent of a) the GWP-intensity (kg CO_2-eq. /kg) and b) the annual copper demand. It is expected to increase from today`s 80 MT CO_2-eq. to 290 MT CO_2-eq. (demand sensitivity parameter for 2050), or 390 MT CO_2-eq. (demand, ore grade and stripping ratio parameter values for year 2050). Extended producer- and consumer responsibility aiming to decrease the copper demand is essential to moderate or decrease the annual GWP caused by the copper production. The less the copper demand increase is, the less the GWP increase is. However, actions aiming to increase the recycling efficiency and making the energy mix less GWP-intensive will be almost equally effective, or in some cases more effective. The rate of *moderation* could be in the order of magnitude 100-120/200-220 MT CO_2-eq. (less than MT 290/390 CO_2-eq.).

Globally, society has a goal to reduce the annual generated GWP. This study has observed that the GWP-intensity of copper production and annual generated GWP caused by copper production is expected to increase. That increase should be compensated in other industries if society`s goal is to be reached. A solution might be to use copper “more wisely”- like an investment. Trying to reduce the generated GWP caused by other industries, e.g. the electricity industry might be a place to start. A reduction in generated GWP caused by the electricity industry is solved by investing in e.g. wind mill parks. On the other hand, the renewable electricity industry demands more copper per kWh produced than the conventional electricity industry, so if we should invest in *less* emission intensive electricity in the future, an increased RIR is important to extend copper depletion time.

The fact that copper will be more CO_2-intensive, and emissions will rise, contrary to what is needed to curb global warming are very policy relevant. New updated information and interesting observations concerning the environmental aspect of copper production are constantly published. Feeding policy makers with the most recent research, and introducing them to precautionary actions to avoid future issues – would probably change the way policy makers think regarding the copper cycle, copper production and how we use it today. For example, introducing qualitative and quantitative sectorial targets, and introducing emission trading where the emissions are addressed to the consumer instead of the producer, might change the way policy makers think. This might be crucial to reach society`s global goal of reducing the annual GWP.

Used abbreviations:

Abbreviation	Explanation
GWP	Global warming potential
RIR	Recycling input rate
EOL	End of life
LCA	Life cycle analysis
GDP	Gross domestic product

1. Introduction

1.1 Problem Description

The environmental impact of the anthropogenic copper cycle (figure 1.1) is likely to increase in the future due to an expected increase in copper demand and production in the order of several million tons (bullet point 1) (Ayres et al., 2002). On the other hand, copper is a finite resource (Gordon et al., 2005), so increased copper production means less copper ore resources available in the future. This secondly leads to a decline in the percent of Cu in the mined ore (i.e. ore grade), more complex ore bodies and finer grained ore bodies in the future (Norgate and Jahanshahi, 2011) (bullet point 2). As a consequence of declining ore grade (in addition to increased copper demand) energy demand and global warming potential (GWP) from copper production is expected to increase in the future (Norgate and Jahanshahi, 2011) (bullet point 3). On the other hand, a greener energy mix (higher share of renewable energy power) and higher recycling input rate (higher input of recycled copper to satisfy copper demand) is expected in the future (United Nations Environmental Programme, 2014, Harmsen et al., 2013). This could affect the expected increase in GWP from copper production. The overall goal of this thesis is to understand the impact of total demand, scrap availability, and ore grade on future copper availability and the environmental impact of copper production. Figure 1.2 explains how different parameters will affect global warming potential from copper production. Each of the three bullet points are now addressed in more detail.

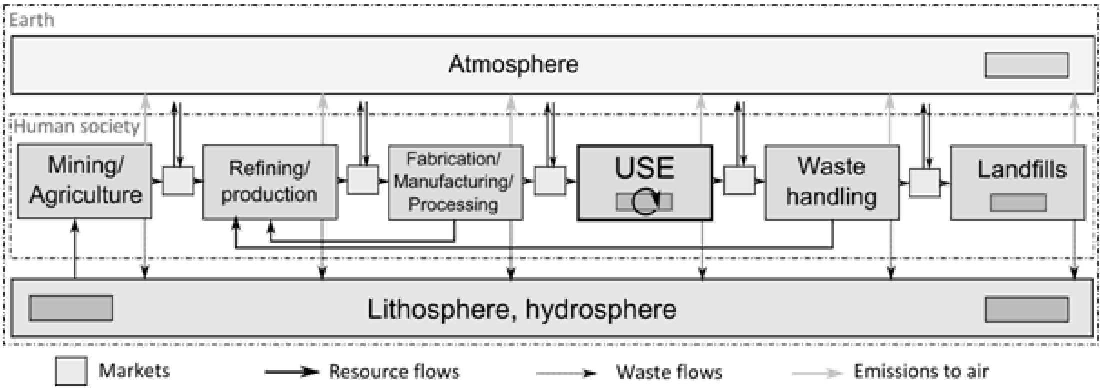


Figure 1.1: The Anthropogenic copper cycle (Pauliuk, 2013)

1. The demand in copper has remained strong for the past 100 years (Northey et al., 2013) and is expected to grow in the next 100 years (Ayres et al., 2002). Since 1900, the demand in refined copper has increased by 3.4 % annually - from less than 500 thousand tons to over 20 million tons in 2012 (International Copper Study Group, 2013). The increase in the demand in copper is a result of emerging economies and an increasing complexity of products (Harmsen et al., 2013). As a consequence of the increased consumption and demand in copper, the copper production is assumed to increase by 3.6 % annually between 2010 and 2030 (Norgate and Jahanshahi, 2011). Copper is widely used in e.g. building construction (i.e. electric power, plumbing, architecture, communications, building plant), as well as electrical and electronic equipment (e.g. power utility, cooling, electronic, telecommunication) (Kishita et al., 2012). In the next decades, the copper demand is expected to increase the most in the following categories; building construction, electrical and electronic equipment, and transportation equipment (Kishita et al., 2012). The increase regarding building construction is partly due to the rapid industrialization in China as well as India in the next decades (Northey et al., 2013). In addition, we expect a world population growth from 6,609 million in 2007 to 9,150 million in 2050 and a world GDP [billion 2000 USD] increase from 39,493 in 2007 to 133,299 in 2050 (Kishita et al., 2012). This will indirectly increase the demand for electrical and electronic equipment, as well as transportation equipment. More specifically, regarding power utility and electric power, the expected increase in the demand for copper might be an indirect consequence of the

increased demands for electricity (e.g. between 2000 and 2010, the consumption of electricity by households, rose in the EU-27 by 18.0 % (European Commission Eurostat, 2014)). It may also be an indirect consequence of the global focus in shifting the generation of energy from fossil fuels to renewable resources e.g. wind mills (Vidal et al., 2013). The copper-usage intensity (kg/kWh generated electricity) is typically four to six times higher for renewable energy (RE) sources than for fossil fuels or nuclear (BBF Associates and Ph.D. Konrad J.A. Kundig, 2011). Renewable energy requires a multitude of installations to extract the energy compared to fossil fuels (Harmsen et al., 2013). Investments in renewable energy will directly increase the copper demand.

2. The growth in copper use may cause a copper scarcity (Harmsen et al., 2013). Copper scarcity may obstruct the progress of human activities. However, increased recycling, optimal copper use design of copper equipment and decreased copper losses in the copper cycle, may extent the copper depletion time (i.e. when the copper demand is greater than the possible copper production). On the other hand, copper ore scarcity is likely to result in deteriorating ore quality (Harmsen et al., 2013) since the copper ore which has the best quality (i.e. highest % of copper) is mined first to obtain the highest economical profit (Northey et al., 2013).
3. The expected increase in environmental impacts of copper mining are to a great extent because the expected ore grade decline (Northey et al., 2013, Harmsen et al., 2013). The gross energy requirement of copper is expected to be 2-7 larger in 2050 than it is today (Harmsen et al., 2013). The increase is depending on technological progress of mining and beneficiation, the recycling rate and the future electricity demand (Harmsen et al., 2013). The declining ore grade will in addition to increase the water and energy demand, increase the rate of waste rock removal, tailings generation, area of local habitat disturbance, and demand of diesel and explosives (Northey et al., 2013). This will in turn increase the global warming potential from copper production (Northey et al., 2013).

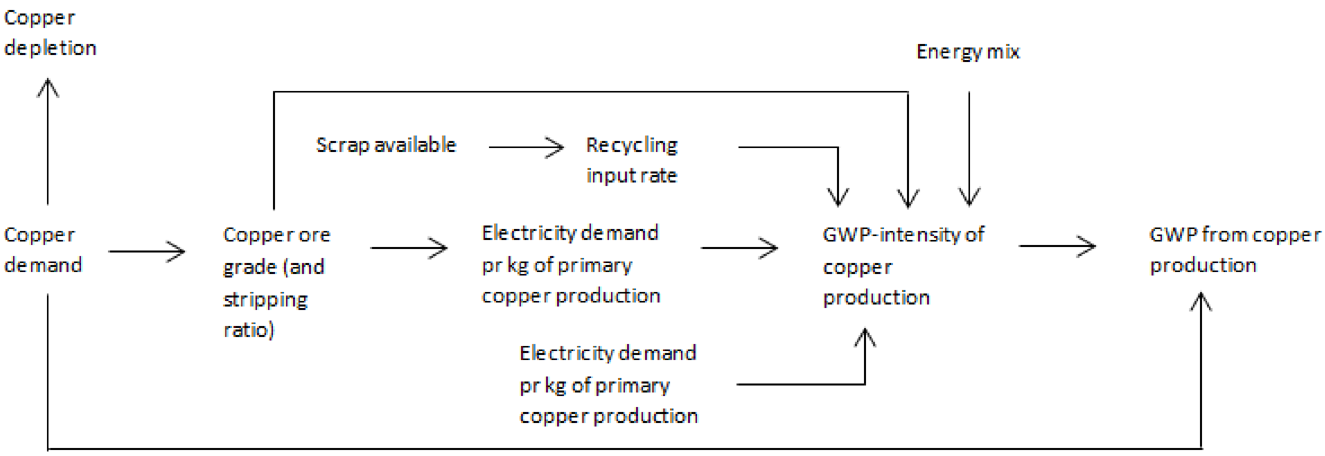


Figure 1.2: Overview of how different parameters affect copper production`s environmental impacts

A higher demand in copper and the following less copper ore resources available and the raise in environmental impacts enhance the motivation of quantifying *copper depletion, and future electricity demand and global warming potential.* How and why the environmental impacts increase could inform policy makers on potential future problems related to copper production and suggestions for how to handle these.

1.2 Existing Literature

The literature study presents published studies relevant for the topic of this thesis. According to the thesis title; “The Environmental Impact of the Future Anthropogenic Copper Cycle”, three issues are in focus of this review. Those are 1) *The anthropogenic copper cycle in general; today and into the future, 2) Copper* *depletion and the quality of the copper ore resources in the future and* 3) *Life Cycle Assessment (LCA) of copper production.*

1) *The anthropogenic copper cycle in general; today and into the future*

A detailed dynamic analysis of global copper flows (Glöser et al., 2013) including global stocks, postconsumer material flows, recycling indicators and uncertainty evaluation is recently conducted. Recycling efficiencies, copper stocks in use, and dissipated and landfilled copper at a global level is also considered. The work was based on historical mining and refined copper production data in the period 1910-2010 and a unique data set of recent global semifinished goods production and copper end-use sectors. Generally, the copper cycle model conducted shows how copper flows in the technosphere, and has qualitative similarities to the models presented by "The Center for Industrial Ecology to quantify global stocks and flows (STAF) of important materials used in the 20th century"(Glöser et al., 2013). The model offers a rather high level of detail: 17 different end-use sectors have been considered and the study claims that it is possible to distinguish between the average lifetime of copper in products and the average age of copper scrap leaving the use phase in the model. The results showed that the global stock in use reached approximately 350 TG by 2010 (1 TG=1 MT), where the use group building construction accounts for most of it (55 %). The stock in landfills reached 140 TG, and the annual generated end-of-life flow increased to above 10 TG/annually in 2010. To obtain consistency of the model in terms of material balance, a calculation method was developed to estimate the yearly global collection rates of end-of-life (postconsumer) scrap as well as the scrap fraction. The calculation method was based on mass balance theory. 8 different recycling indicators over time were calculated based on the flows extracted from the model. The model did also distinguish between 6 scrap types. The indicators were Recycling Input Rate (RIR), End-of-Life Recycling Input Rate, Overall Recycling Efficiency Rate, End of Life Recycling (Efficiency) Rate, Overall Processing Rate, End of Life Processing Rate, End of Life Collection Rate and Old Scrap Ratio. By conducting a sensitivity analysis of the calculated recycling indicators with regard to the effect of uncertainties in the input data; *average life time* and *percentage of new scrap* within the total waste fraction was considered to have the *highest uncertainty*. The main indicator for the recycling rate was estimated to be 45 % (+-5%) on an average basis.

In 2009, Gerst presented a study of the multilevel global copper cycle over the *next* 100 years applying the material cycle model, a novel dynamic in-use stock model and the SRES "Special Report on Emissions Scenarios" Scenarios (Gerst, 2009). Achieving a long-term resource sustainability, development of methods "that explore future material cycles and their environmental impact" (Gerst, 2009), is essential. He considered stocks and flows of 14 different copper-containing technologies. 4 scenarios were built assuming either lower or higher degree than the 2009-level of; globalization, environmental consciousness, population growth, decline in average household size, urbanization and economic growth. The SRES Scenarios were modelled for the industrialized world and the developing world. Between 2010 and 2020, it is expected that the developing world will have a higher in-use stock of copper than the industrialized world, in contrary to previously. The developing world is expected to have in-use stocks between 600 TG and 950 TG in 2050, in contrary to the industrialized world which is expected to have an in-use stock between 300 TG and 350 TG. Regarding the in-use stock per capita results, the industrialized world is expected to have an in-use stock per capita between 200 kg/cap and 270 kg/cap (2050), in contrary to the developing world which is expected to have an in-use stock per capita between 50 and 125 kg/cap. According to the scenario which assumed no material substitution or technological change in copper products, the results for 2100 is that the global in-use stock will be approximately as large as the copper resources which are known available in 2009. He did also discover that the stock dynamics will change due to dematerialization.

2) *Copper depletion and the quality of the copper ore resources in the future:*

Several scenario analyses to estimate copper depletion time were conducted in 2002 by Ayres et al. (Ayres et al., 2002). The work was based on the SRES Scenario framework, with three main assumptions: economic growth, evolution of consumption in relation to income behavior (the intensity of use curve) and old scrap recycling efficiency. All model scenarios suggest that mining will peak sometime in the 21st century. Scenario 4 and 8, which is most interesting in this context, is based on the IPCC scenario B1 (Intergovernmental panel on climate change, 2014a), which assume more globalization and environmental consciousness, a slower growth in GDP/capita. Scenario 4 and 8 are in addition based on an intensity of use curve (IU-curve) that is scaled down over time at the rate of 0.25% per year from 1997 on. The earliest peaks occur between 2050 and 2060 (scenarios 4 and 8) with an annual production of 50 MT, while the latest one peaks after 2080 at a production level above 60MT annually.

The “coming copper peak” is also discussed very recently (Kerr, 2014). The article presents the study on copper peak, and discusses the future after the peak: Steve Mohr have developed “a mathematical model for projecting production of mineral resources taking into account expected demand and the amount thought to be still in the ground”(Kerr, 2014). The model is based on Hubbert curves drawn for peak oil production. Based on the known mine sites compiled by (Mudd et al., 2012), Northey, Mohr and Mudd investigated the coming copper peak. According to their work, the mines will not meet the world’s demand for copper much longer. Assuming today`s recycling input rate, the copper production is only expected to meet the demand for the next 2 to 3 decades. This will “drive prices sky-high, trigger increased recycling, and force inferior substitutes for copper on the marketplace in the future” (Kerr, 2014). Increasing the amount of copper accessible (i.e. new copper ore deposit discoveries), the peak production is extended until 2045. On the other hand, if one includes social and environmental constraints on production which limit the primary copper annually produced, the copper depletion time will occur in the early 2020s. Lastly, the article suggests that copper substitutions are possible, but substitutions some places are easier than in others.

On the other hand, the quality of the ore can be described by the %Cu in ore (i.e. ore grade). Future copper ore grade decline have been modelled (Northey et al., 2013). The modelling work was based on a detailed assessment of copper resources and mining, and discusses copper depletion in addition to economic and environmental issues in the future. Scenarios were modelled using the Geologic Resources Supply-Demand Model (GeRS-DeMo).The scenarios produced were further used to estimate the cumulative grade-tonnage curves for each country and deposit type into the future, from 2010. Based on the curves, Northey et al. were able to estimate the future rate of copper ore grade decline. Global mined copper ore has an average ore grade about 0.62% Cu (2010). According to the curve, the ore grade is approximately 1.2% Cu (model mean) today. In 2030, the ore grade is estimated to be approximately 0.8%Cu (model mean), while in 2050, the ore grade is estimated to be approximately 0.6%Cu (model mean). According to the model, Chile and Peru are able to continue to grow their production for some time. The results indicate that the ore grade decline may be less than what has historically been the case (Northey et al., 2013). The results from the scenarios indicate further that there are sufficient identified copper resources available for the next twenty years. However, as the developing world experiences economic growth, the copper demand will increase. The economic and environmental impacts associated with increased production rates, and following declining ore grades, could limit the copper industry expansion. Regarding that, it is important to discuss a possible peak in mined copper production since it might occur this century. On the other hand, the report claims that economic and environmental issues related to energy consumption, water consumption and GHG emissions might play a greater role in the future than the availability of deposits.

3) LCA of copper production

Several Life Cycle Assessments of copper production can be found among literature available. The literature published in the last couple of years is emphasized.

3.1) Focusing on energy demand and global warming potential

In 2007 Norgate, Jahanshahi and Rankin (Norgate et al., 2007) conducted a study which assess the environmental impact of several metal production processes, including copper production. The GWP from producing 1 kg pyro metallurgical produced copper was 3.3 CO_2-eq. (i.e ore grade = 3 %), and 6.2 CO2-Eq. producing 1 kg hydrometallurgical produced copper. The study discuss factors influencing the environmental impacts, in which ore grade, electricity energy source, fuel types, and material transport, as well as process technology were emphasized.

Norgate and Haque (Norgate and Haque, 2010) investigates how the mining and mineral processing steps contributes to energy and greenhouse gas impacts. In the case of copper, optimizing the crushing and grinding processes will be most effective regarding efforts to reduce the increased greenhouse gas emissions from copper mining and processing. The energy for copper mining and processing is 26.2 MJ/kg copper (i.e. assuming the copper concentrate/copper ratio is 3.15), in which the crushing and grinding contributes 39.4 %. On the other hand, the GWP-intensity for copper mining and processing is 2.0 kg CO_2-eq. /kg copper (assuming the copper concentrate/copper ratio is 3.15), in which crushing and grinding contributes 46.8 %.

The International Copper Association has also conducted a global Life Cycle Assessment of copper production (Russ and Jewell, 2011). The goal was to create a recent, high quality LCA for copper which includes both primary and secondary copper. They compiled a “cradle-to-gate” life cycle inventory, and had a global geographical scope for both pyro metallurgical and hydrometallurgical productions with the reference period 2005-2009. Ten companies and 35 sites were involved in the project. Although the study focus was mines in South America, the study included all regions beside Africa and South East Asia. The LCA considered only 29% of global production sites, which were claimed to be representative for the total global production. The findings presented were; The life cycle stages mining and concentrate production were the dominant contributors to GWP, and the differences between the energy mixes applied had considerable effects on the results.

Norgate and Jahanshahi have also been discussing where in the copper production the focus should be to reduce the greenhouse gas footprint of primary metal production (Norgate and Jahanshahi, 2011). A life cycle assessment of the main metal production processes for today, as well as predicted global metal production rates, was conducted. In the analysis they included important factors such as declining ore grades and liberation size. The results from their life cycle assessment showed that the focus should be on the metal extraction stage, and hence having a focus on improved energy efficiency. Declining ore grades, as well as more complex ore bodies in the future arr expected to increase the energy required.

However, several equations to calculate the energy-intensity and GWP-intensity of pyro metallurgical copper production is presented in the literature, e.g. Norgate et al. (Norgate and Jahanshahi, 2011) and Northey et al. (Northey et al., 2012). The equations depend on the ore grade only, but since the ore grade is expected to decline in the future – the equations give estimates on future energy demand and GWP from copper production if we assume other effecting factors to stay constant. The energy-intensity is expected to increase from approx. 4.5 kWh/kg refined copper (ore grade = 1) to approx. 6.5 kWh/kg refined copper if the ore grade decreases to 0.5. The GWP-intensity is expected to increase from approx. 1.5 CO2-eq./kg refined copper (ore grade = 1) to approx. 2.3 CO_2-eq./kg refined copper if the ore grade decreases to 0.5.

Considering Norgate and Jahanshahi`s (Norgate and Jahanshahi, 2011) ore grade estimate in 2030 to be 0.7 – the energy-intensity in 2030 will increase to 5.3 kWh/kg refined copper and GWP-intensity will increase to 1.9 CO_2-eq./kg refined copper.

Harmsen et al. analyzed the gross energy requirement (GER) from copper production and the effect it has on energy return on investments of wind turbine technologies (Harmsen et al., 2013). The study focuses on renewable energy scenarios. The GER is expected to increase by a factor of 2-7, depending on the technological progress, the recycling rate and the future electricity demand. Even when the recycling is high, the increasing in-use stock of copper will moderate the effect of recycling. The study suggests that the GER of increasingly scarce materials has the potential to give "more meaningful indications for abiotic depletion in LCA studies than the current mineral reserve based practice" (Harmsen et al., 2013).

3.2) Improvements of LCA inventory

Higher ore grade resources are mined first as these represent richer returns (Northey et al., 2013). After those resources are mined, ore with a lower ore grade is mined. This leads to a gradual decline in average Cu ore grade mined. In addition to lower ore grade, increased mine size will effect; the amount of waste rock and tailings generated, and electricity, diesel and explosives demand. Regarding the inventory, the amount of overburden and tailings, and the demand of electricity, diesel and explosive should in other words be dependent on the ore grade (Northey et al., 2013).

The Fossil Energy Demands of Primary Nonferrous Copper Production is discussed by (Swarts and Dewulf, 2013). By including the effects of ore grade changes and changes in primary metal extraction technology they were able to model energy demand of copper production. The model was conducted by applying available literature distinguishing between different mining and mineral processing methods. Energy demand were both modeled and analyzed and expressed in fossil energy equivalents (FEE) per kilogram of primary copper. Considering underground mining, the mass of ore mined is claimed to be the determining factor for the energy demand. For open pit mining the amount of waste material which has to be moved is claimed to be the greatest factor determining the energy demand. To improve the model, the study suggests including the use of explosives and steel used in the comminuting and the production of sulfuric acid. On a global level, it is claimed that increasing energy demand for copper production is caused by number of factors, not only the changes in ore grade (Swarts and Dewulf, 2013). Different extraction technologies will result in different energy demands.

1.3 Research Gaps

There are few recently (Kerr, 2014, Northey et al., 2013) conducted comprehensive studies regarding future analysis on copper depletion time. In addition, a comprehensive future-oriented LCA study on copper production regarding a number of dynamic parameters, with respect to year, is not yet conducted and published. Ore grade, copper availability and demand is constantly changing (Gordon et al., 2005). That will affect the inputs that are expected to change with deteriorating ore grade, e.g. overburden and tailings, electricity, diesel and explosives demand. In addition, recycling input rate and energy mix are also expected to change with time. The overall potential for copper recycling is limited by the total scrap availability, and has significant impact on the carbon and energy footprint of copper production.

Providing updated and multitudinous literature on copper resource limitations and environmental impacts from future copper production is essential to make the best appropriated policies regarding the anthropogenic copper cycle.

1.4 Research Questions

1. Under which scenarios will the existing copper resources be depleted and when?
2. How does electricity intensity and GWP of copper production change throughout the first halve of the 21st century as the copper ore grade declines?

1.5 Goal, Scope and System Boundary of Current Study

Goal:

The overall goal of this thesis is to understand the impact of total copper demand, copper scrap availability, and copper ore grade on future copper availability and the environmental impact of copper production. When this is understood, the research questions could be answered.

Scope:

Impact scope: Current work will investigate the *future anthropogenic copper cycle* regarding; copper depletion time, the electricity demand and global warming potential for copper production in the first halve of the 21st century as the copper ore grade declines. This will cover the two research questions.

General process scope: The investigation is conducted by modelling scenarios for copper demand, in-use stock, EOL collection and recovery rates, and energy mix. The variables are included to cover the largest flow changes by amount in the *whole* copper cycle. The parameters which are emphasized to be affected by the variable changes are; copper ore grade, overburden to ore stripping ratio and recycling input rate (% input of recycled copper to satisfy copper demand). Recycling is included to capture a more realistic picture of the anthropogenic copper cycle. The mentioned parameters will be *quantified* for a time period and will thus be dynamic with respect to year. A dynamic copper ore grade, overburden to ore stripping ratio and recycling input rate will in turn affect the process inventory to be dynamic with respect to year.

Global process scope: The intent of the parameter quantification is to estimate global copper depletion and to perform; life cycle analyses (LCA) together with scenario and sensitivity analyses for future global copper production`s environmental impacts. The effect of import and export is excluded in this master`s thesis. As a consequence of import and export exclusion, the region specific production amount and ore grade decline is either over- or underestimated. Regarding copper depletion, electricity intensity and global warming potential *only* global averages is therefore satisfactory. However, regional differences are *only discussed in brief* regarding copper depletion and global warming potential per kg copper produced.

Regional process scope: Life cycle analyses and scenario analyses regarding future copper production`s environmental impacts will also be conducted uniquely for six different regions. Similarities and differences regarding copper production technologies, process requirements, emission factors and global warming potential per kg copper produced for the six different regions are *presented in brief.*

Temporal scope: The global temporal scope is from year 2015 to 2050, and the regional temporal scope is from year 2015 to 2025. The relatively short time scale is chosen to increase the total accuracy of the results.

Functional unit: The functional unit in the process LCA model is 1 kg refined copper (99.95-99.97 %Cu by weight), and the global impacts are quantified by multiplying the impact of 1 kg by the final global copper demand in kilos.

System boundary of the process LCA model:

The system boundary of the process LCA model is from “cradle” to “entry gate” of the copper cycle which includes the copper flow from the life cycle stages Earth and Biosphere, and Recycling, till the copper flow going to the copper marked (e.g. copper fabrication) (please see figure 1.1 for better understanding the stages as a part of the whole copper cycle). Due to the fact that copper production contributes the most of the environmental impacts from the anthropogenic copper cycle (Norgate and Haque, 2010) – the system boundary of this master`s thesis` process LCA model cover only copper production. However, the process model includes both primary production; the pyro metallurgical and the hydrometallurgical process route, and secondary production (figure 1.3).

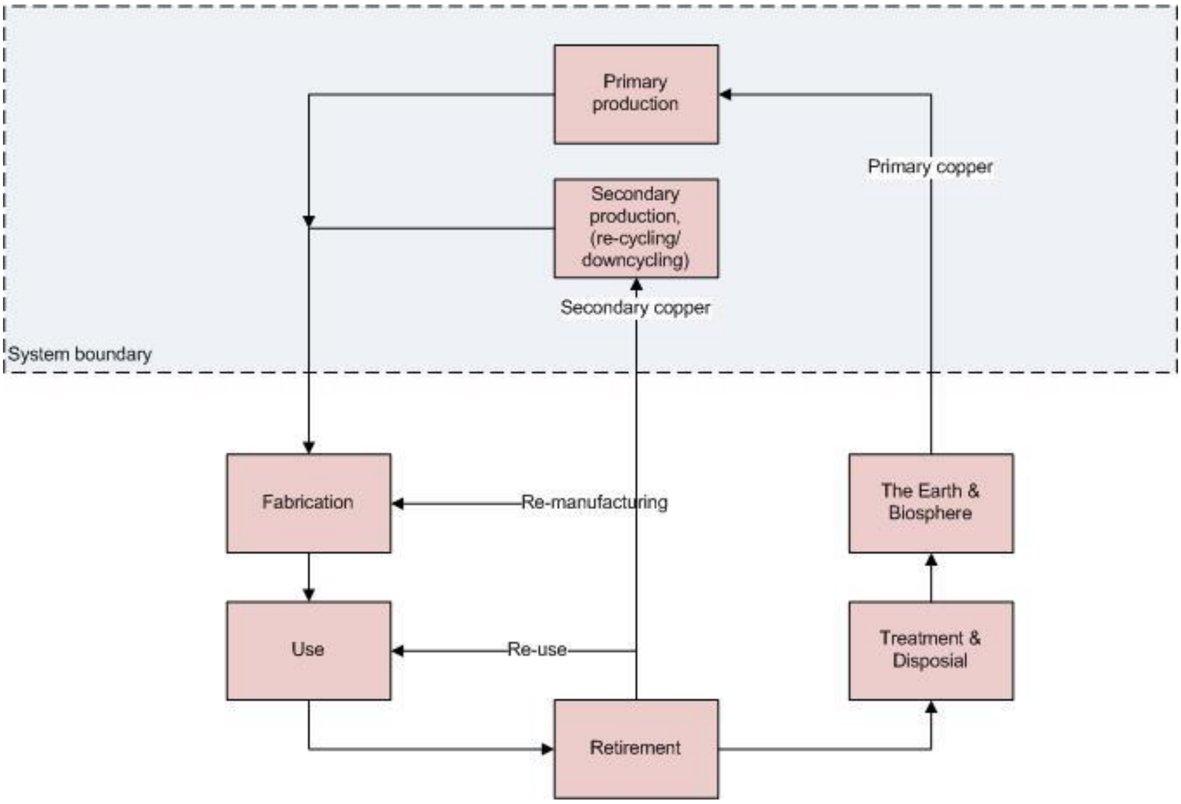


Figure 1.3: Defining the system boundary of the process LCA model

System boundary of the scenario process model:

The work with the scenario building comprises, on the other hand, the entire anthropogenic copper cycle (figure 1.1) including final copper demand (copper into use) and EOL flows. The anthropogenic copper cycle may be divided into several life cycle stages; mining/agriculture, refining/production, fabrication/manufacturing/processing, use, waste handling and landfills. All of the stages in the life cycle interfere with the atmosphere and the lithosphere (e.g. emissions)

2. Material and Methodology

All relevant materials and methodologies for the thesis are presented in this section. The presented materials cover copper production (section 2.1), assumptions (section 2.2), an overview of global ore resources categorized by its ore grade and region (Mudd et al., 2012) (section 2.3), expected increase in direct energy- and GWP-intensity for copper mining and beneficiation (Northey et al., 2012) (section 2.4), regions considered (section 2.5) in the regional study and regional breakdown of copper production technologies (section 2.6). Section 1.4 posed questions about copper resource depletion and impacts from copper production in the future, and this could be answered by the methodologies; life cycle analysis (LCA), and scenario and sensitivity analysis. Due to that, the methodologies presented in section 2 are LCA and the accompanying data quantification (section 2.7), as well as scenario building for the scenario and sensitivity analyses (section 2.8). At last, the parameter values utilized in the analyses are presented (section 2.9).

2.1 Copper Production

Copper production covers two life cycle stages in the anthropogenic copper cycle; mining/agriculture and refining/production (figure 1.1). They contributes the most of the environmental impacts of the anthropogenic copper cycle (Norgate and Haque, 2010).

2.1.1 Production Description

(Ayres et al., 2002)

Copper production depends on copper resources, which is either primary or secondary resources. While primary copper resources exist as minerals in copper ore in copper deposits located in the ground, secondary resources are recycled copper. Recycled copper is treated in such a way that it obtains the same characteristics as primary copper. The percent of input from secondary copper production in the final copper product is defined as the recycling input rate (RIR). Please read table 2.1 for nomenclature.

The copper ore are either sulfides or oxides. While the molecules in sulfide copper ore contains sulfur atoms, oxide copper ore contains oxygen atoms. Sulfide ores also contain iron atoms. The process route after mining depends on the type of ore mined, which makes the type of ore mined important considering factors such as economy and environment. There are two main processing routes utilized to produce primary copper; the pyro metallurgical and the hydrometallurgical route. The main difference between the process routes is; how unwanted minerals and tailings are separated from the copper concentration. This is either achieved by a certain temperature (i.e. pyro metallurgical method) or certain chemicals (i.e. hydrometallurgical method). Almost all sulfide ore are treated by the pyro metallurgical process route. The exothermic reaction heat from the oxidation of the iron and sulphur is utilized in the *smelting* stage(s). Due to that, it is more suitable to treat oxide ores and sulfide ores, which contain low levels of iron, by the hydrometallurgical method.

Copper production`s process chain is presented in figure 2.1. Regarding primary production the final process output from the two process routes is aggregated. The output of each process route has similar copper purities. The output amount of one process route compared to the other represents the pyro metallurgical/ hydrometallurgical share of primary copper. Regarding the final product of the LCA process model, the output of primary and secondary production is aggregated after the aggregation of pyro metallurgical and hydrometallurgical processed copper, and the last process step in the secondary production route. This is done to represent the RIR. The final product (i.e. functional unit) is 1 kg refined copper (99.96%Cu).

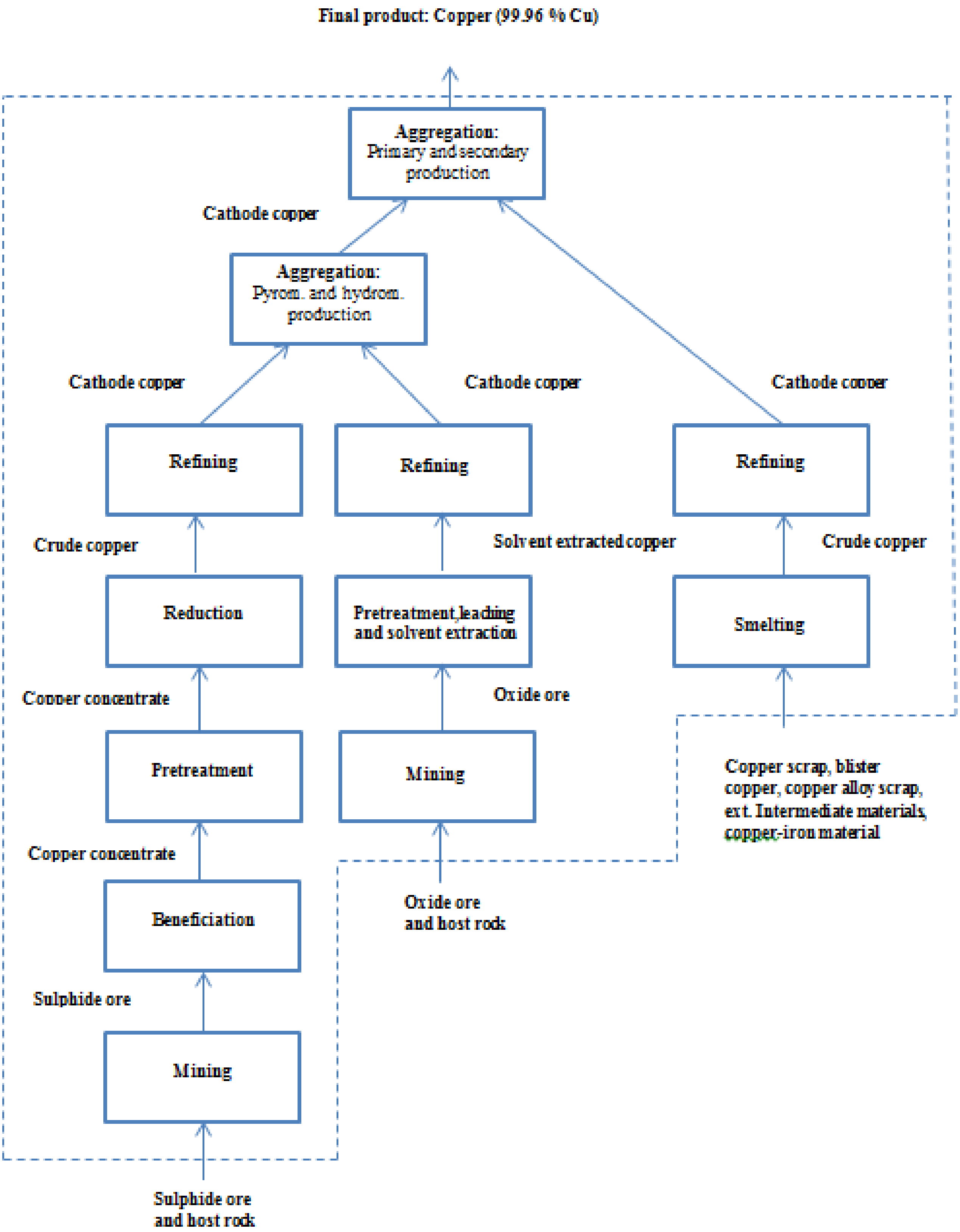


Figure 2.1: The LCA process model in detail

The % of Cu in copper ore *deposit rock* (mining input) distinguishes to the % of Cu in copper *ore*. The larger the difference is, the larger the overburden to ore stripping ratio is.

Table 2.1: Nomenclature, production description (ProtectEquador, 2014, International Copper Study Group, 2014, Bergverkhistorie, 2014)

Copper ore	Copper ore is a type of rock that contains copper minerals with important elements including copper metals. Copper ore appears as ore bodies within a host rock. The composition of the ore is usually a mineral body comprising metal bearing particles, unwanted minerals and gangue which is the worthless material that surrounds it and is closely mixed with the wanted mineral. The shape of the ore bodies vary both within a copper deposit, and from deposit to deposit.
Copper deposit	A collection of copper ore bodies captured in a host rock. Copper deposits are the source of copper ore.
Copper ore grade	The weight percent of Cu in copper ore.
Overburden (also called waste or spoil)	The material that lies above an area with economic or scientific interest. In mining, it is most commonly the rock, soil, and ecosystem that lie above a coal seam or ore body. Overburden is removed during surface mining.
Tailings (also called mine dumps, culm dumps, slimes, tails, refuse, leach residue or slickens)	Sulphuric materials left over after separating the valuable fraction from the uneconomic fraction (i.e. tailings) of an ore. Tailings distinct from overburden.
Overburden to ore stripping ratio	The ratio between overburden and ore. The stripping ratio increase with depth of the ore body.

2.1.2 The Process Operations in Primary Copper Production

The pyro metallurgical process route is by the LCA process model divided into five main stages; mining, beneficiation, pretreatment, reduction and refining (figure 2.1).

The mining stage composes the operations; drilling, blasting, and loading and haulage. The copper ore flow out of the mining stage is "a mineral body comprising metal bearing particles, unwanted minerals and gangue which is the worthless material that surrounds and is closely mixed with the wanted mineral" (Norgate and Haque, 2010). Beneficiation includes the operations; crushing and grinding, and separation. Copper concentrate is the valuable product out of beneficiation (Norgate and Haque, 2010). Pretreatment includes the operations; drying, and roasting which is an oxidation operation. Oxidation of the concentrate is necessary for the reduction process stage to be able to separate the high-grade copper sulphide *matte* from the slag which is the unwanted by-product from the smelting process (Ayres et al., 2002, Mischa Classen et al., 2007). The reduction process comprises the operations; smelting and converting, and produces the product named blister copper. Blister copper is then refined by three operations; fire refining, electrolytic refining and remelting of cathodes. Copper is the final product having a Cu wt% between 99.95 and 99.97%. (Mischa Classen et al., 2007).

The hydrometallurgical process route is by the process model divided into three main stages, mining, "pretreatment - leaching - solvent extraction" and refining.

Mining is identical to pyro metallurgical mining (Mischa Classen et al., 2007). The following pretreatment process, which includes grinding and separation, is not that common in the hydrometallurgical process route. While leaching is a recovering stage (i.e. extracting minerals from a solid producing a leach liquor containing soluble salts), solvent extraction is a solution cleaning stage (i.e. where precipitation of impurities and filtration or selective enrichment of copper takes place). Refining comprises the operations electro winning and remelting of cathodes (Mischa Classen et al., 2007, Ayres et al., 2002).

Some of the processes in both process routes are elaborated in appendix A. The requirements of all of the processes (i.e. energy and materials) and emission factors are also presented in appendices F and H.

2.1.3 The Process Operations in Secondary Copper Production

Copper from secondary production is a product of processing used copper. The processes of importance regarding the inventory is smelting and refining. The other processes; cleaning, sorting, stripping, shredding, magnetic separation are necessary before smelting, but not included in the process model. Smelting is conducted by the same process as primary production (i.e. reduction). Secondary production refining is also similar to the primary production process refining. The requirements of all of the processes (energy and materials) and emission factors are also presented in appendices F and H.

2.2 Assumptions

General assumptions are presented in this section, while the specific numerical assumptions (i.e. mostly important to reproduce the work) is presented in appendix G. The general assumptions are divided into assumptions regarding present and future anthropogenic copper cycle.

2.2.1 Present Anthropogenic Copper Cycle

Regarding the copper production process model the assumptions made is presented in table 2.2.

Table 2.2: General assumptions, the copper production model

The area of concern:	**Elaboration:**
Process model:	Pyro metallurgical processed copper has the same quality and contain the same percent of Cu as hydrometallurgical processed copper. The output of the two process routes is aggregated after last process step. On the other hand, primary copper has the same quality as secondary copper. The output of primary and secondary production is aggregated. No technological and time variations of the quality and percent of Cu in the mass out of all processes, except from mining.
Within the system boundary	Regarding the pyro metallurgical process route, there are only copper losses in the beneficiation and reduction process. Regarding the hydrometallurgical process route, there are only copper losses in the aggregated process of Pretreatment, Leaching and Solvent Extraction. Regarding secondary production, there are only losses in the smelting process stage.
Ore deposit	It is assumed that the deposit with the ore which has the largest ore grade is mined first.
Recycling input rate:	The recycling input rates among all regions are assumed to be equal (i.e. three different recycling rates for each region). 35 % recycling is assumed in the base case (Glöser et al., 2013).
Energy mix:	UNEP data valid (United Nations Environmental Programme, 2014)
Demand:	Data from World Copper Factbook 2013 (International Copper Study Group, 2013) valid.

The production requirement and emission data (comprising the *inventory*, please read the methodology of LCA in section 2.7) is based on the EcoInvent inventory and the assumptions made by the EcoInvent providers (Mischa Classen et al., 2007). However, there are some values made dynamic, with respect to year, by current work. Those values are electricity, overburden, tailings, diesel and explosives. The assumptions conducted regarding those are presented in table 2.3.

Table 2.3: General assumptions, the requirement data

The area of concern:	Elaboration:
Ore grade dependency	Only mining and beneficiation is dependent of the ore grade.
Percent of Cu in deposit	Only dependent on ore grade and stripping ratio.
Electricity/kg Cu in the output:	The electricity is only dependent on the ore grade. Since mining and beneficiation are the only processes dependent on ore grade, electricity demand vary for mining and beneficiation only. The energy intensity (i.e. generated on site and from grid) is assumed to be equal to the electricity intensity (i.e. from grid). The inventory does not include energy generated on-site, except for diesel. An overestimation of the electricity intensity is likely. However, we have compared the electricity demand to the electricity demand Norgate and Haque assumed in their work with energy and GWP of mining and processing (Norgate and Haque, 2010). While, Norgate and Haque`s assumed electricity demand was 4.6 kWh/kg Cu (i.e. ore grade = 0.99), the electricity demand in this study is 4.3 kWh/kg Cu (i.e. ore grade = 0.99).
Overburden and tailings/kg Cu in the output:	The overburden in the mining process is directly dependent on the Cu percent in the ore deposit and in the ore. The ratio between the ore grade and the % of Cu in the deposit is assumed to depend on the stripping ratio. On the other hand, the tailing amount is only dependent on ore grade, the amount of ore per copper concentrate mass out of beneficiation, in addition to the amount of concentrate.
Diesel/kg Cu in the output and explosives/kg Cu in the output:	Diesel and explosive demand is only dependent on the size of the input mass of mining per kg Cu out of the mining process. Since there are no Cu losses in the mining process, the diesel and explosive demands are only dependent on the input mass of mining per kg Cu in the input mass.

Regarding the inventory for Oceania, it is assumed to be the same as the inventory for Australia, which is already conducted by the EcoInvent providers. Regarding the inventory for Africa, EcoInvent has not conducted one. The global inventory is utilized for Africa since Africa`s global share of copper mining production is approximately 9 % only, and even less for copper smelter and refined copper production (International Copper Study Group, 2013). The assumption is controversial, but the best solution in this case.

2.2.2 Future Anthropogenic Copper Cycle

This section presents assumptions regarding changes modelled for the future anthropogenic cycle and future copper production process model. This is utilized in the scenario building in section 2.8. The parameters generated by the scenario building based on the assumptions are presented in section 2.9. Regarding the ore grade change, the effect of declining ore grades on the hydrometallurgical process` background- to-foreground demands is neglected for simplicity. This is because the share of hydrometallurgical produced copper to pyro metallurgical produced copper is below 10 % and seems to have reached a maximum few years ago (International Copper Study Group, 2013). The share is thus kept constant for simplicity. Table 2.4 shows an overview of the rest of the assumptions made regarding the quantification of the scenario and sensitivity variables.

Table 2.4: General assumptions, quantifying the scenario and sensitivity variables

Life time increase:	The life time increase is assumed to only effect the in-use stock growth to a small extent. The in-use stock already modelled by (Gerst, 2009) did not account for technology lifetimes. How much “technology lifetimes” effects the in-use stock growth for all three scenarios was assumed based on the Scenario storylines and the type of use in the future for each of the scenarios. The life time increase is assumed to be high for scenario B1 and B2, and low for scenario A1. Regarding A1: Free flow of goods from all over the world, as well as the very rapid economic growth, will affect a low increase of lifetime of copper products. Free flow of goods from all over the world will lead to an increase of the share of total products available which is produced in countries which produce products which have lower quality than in industrialized countries. Even though the lifetime increase is low, the amount of new products into the use phase will result into a high in-use stock *growth*.
Scrap pool:	The literature data utilized in the scenario modelling covered only four regions. In contrary, this master thesis considered six regions. Due to that, a global scrap pool is introduced. It is assumed that all copper scrap generated independent of location is the same. The amount of scrap available for EOL collection and EOL recovery for each region marked was decided by their regional final demand share of the global demand.
Final demand share among the regions:	Final demand shares among the regions are assumed to be constants until 2025. Final demand shares are the same as in 2012 (International Copper Study Group, 2013). It is assumed that the industrialization of some regions we see today will not change before 2025. The numerical values are presented in the appendix G.
EOL collection rate and EOL recovery rate growth:	The EOL recycling rate equals EOL collection rate multiplied by EOL recovery rate. It is distinguished between low and high increase towards 2050. The EOL recycling rate growth equals the difference between today`s and 2050`s, divided by the number of years between today and 2050. EOL recycling rate "base case" equals 46 %, EOL recycling rate in 2050 with low increase (20 %) equals 66 % and EOL recycling rate in 2050 with high increase (30%) equals 77 %.
Stripping ratio increase:	A stripping ratio increase is the same as saying the ratio between percent of Cu in deposit and ore grade decreases. It is assumed that drilling deeper and deeper for more ore means that the stripping ratio will increase. Dr. Sharif Jahanshahi confirms by mail that the assumption is good (Jahanshahi, 2014). It is assumed that it will increase with 2 % each year. This means, we assume a global stripping ratio of 1.8 in 2016, and 2.5 (Scenario B1 and B2) and 3.6 (Scenario A1) in 2050.

2.3 Global Copper Ore Resources

An overview of global copper ore resources (Mudd et al., 2012) is presented in figure 2.2 covering > 90% of the known (2012) ore deposits. The ore resources are categorized by their ore grade. Most of the copper ore existing in deposits have ore grade below 1.

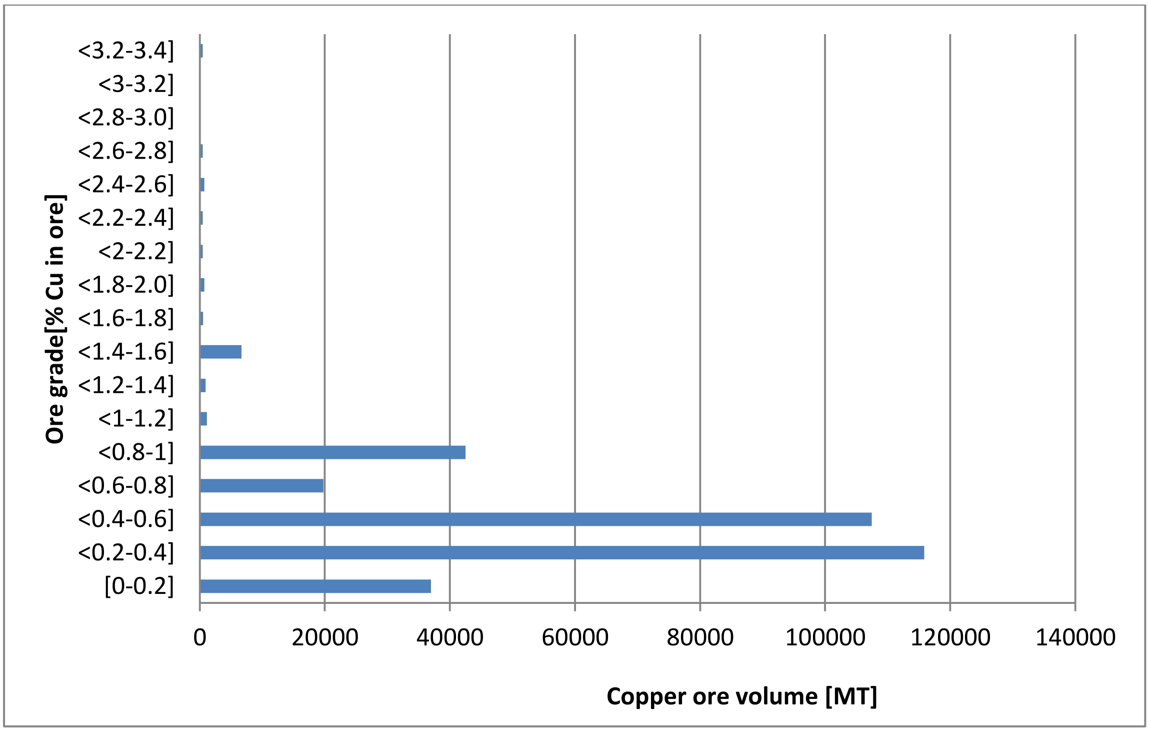


Figure 2.2: Global copper ore resources (Mudd et al., 2012)

The global ore resources categorized by their ore grade *and* regional location are presented in figures C1 to C6 in appendix C. As the figures present, the ore resources which have the highest ore grade are located in Africa, Europe and Asia. On the other hand, the largest ore resources by ore volume are located in Latin America and North America.

2.4 Energy Intensity and GWP-intensity for Mining and Beneficiation

Northey et al. have presented (Northey et al., 2012) two equation approximations (primary copper production energy- and GWP-intensity) based on primary data published by copper production mines, operations and companies. The equations show how pyro metallurgical copper production`s energy- and GWP-intensity change with ore grade. While the energy demand calculated by equation 2.1 is the direct energy demand of the processes *within* the process model per kg refined copper, the GWP calculated by equation 2.2 is the GWP-intensity of copper production including emission generated by third party material suppliers. Regarding equation 2.1, the factor value 0.273 represents the converting factor from GJ/ton (which is presented in the article (Northey et al., 2012)) to kWh/kg (i.e. which is the desired unit for our process model (i.e. regarding the software utilized)). The equations are valid for an ore grade (i.e. x in the equations) between 0.2-4.2, and are given below:

$$\text{Energy intensity [kWh/kg refined copper]} = 15.697 \cdot x^{-0.573} \cdot 0.273 \qquad (2.1)$$

(correlation coefficient = 0.71)

$$\text{GWP-intensity [kg CO}_2\text{-eq./kg refined copper]} = 1.5548 \cdot x^{-0.606} \qquad (2.2)$$

(correlation coefficient = 0.28)

Regarding this work, the energy intensity equation is utilized to estimate the *electricity* intensity of primary copper production. The GWP-intensity equation is on the other hand utilized to compare this work`s GWP-intensity result (mining and beneficiation contribution) to Northey et al.`s. The equations are on the same form, only the constants differ. The exponent of *x* is also quite similar. By looking at figure 2.3 and 2.4, the form of the plots has few differences.

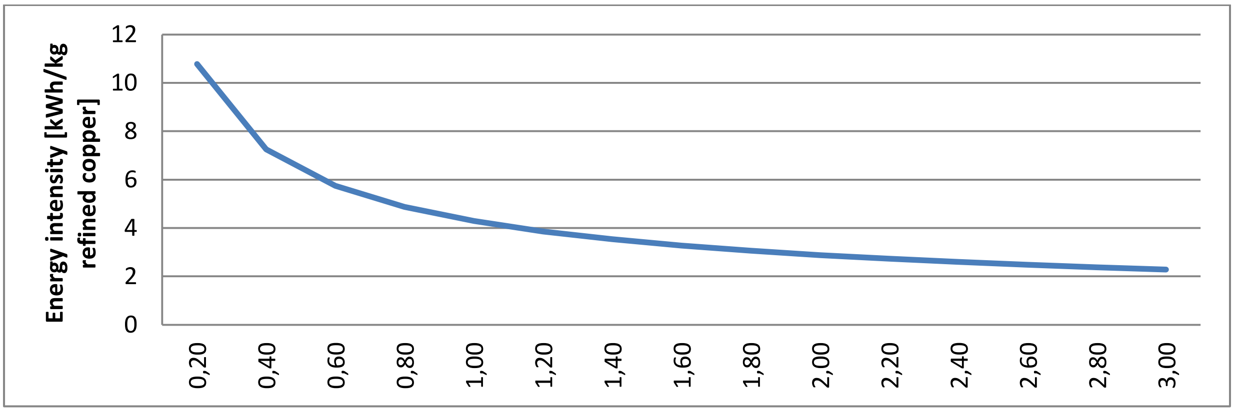


Figure 2.3: Primary copper production`s energy intensity of mining and beneficiation as a function of ore grade (Northey et al., 2012)

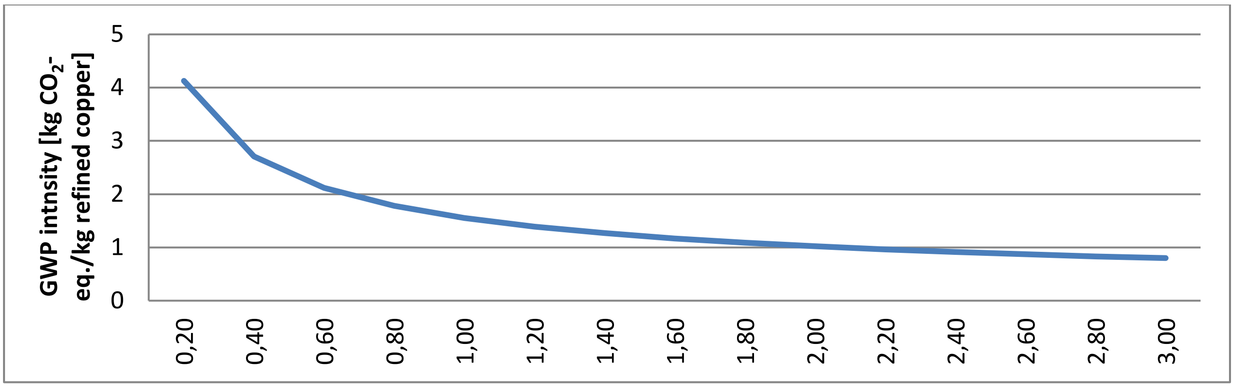


Figure 2.4: Primary copper production`s GWP Intensity of mining and beneficiation as a function of ore grade (Northey et al., 2012)

Regarding the precision of the equations, the correlation coefficient (i.e. the correlation between the intensity and ore grade) of the energy equation is 0.71, and 0.28 for the GWP equation. There is a strong correlation between energy intensity and ore grade (Northey et al., 2013). On the other hand, there is a low correlation between GWP intensity and ore grade. The energy intensity equation is more valid for utilization, than the equation calculating the GWP. In the discussion section, the energy equation is validated by comparing the result with the direct electricity demand assumed in some of Norgate and Haque`s work (Norgate and Haque, 2010). In the result section, the GWP result utilizing the GWP-equation is compared to the GWP results generated by this master`s thesis.

Based on Northey et al.`s work and ore reservoir data (Mudd et al., 2012), and assuming that the ore having the largest ore grade is mined first globally – the expected increase in direct energy intensity and GWP-intensity of mining and beneficiation into the future are presented. The data points represent the energy-/GWP-intensity for each copper deposit mined chronologically (i.e. highest ore grade first – lowest ore grade last). The x-axis in figure 2.5 and 2.6 is the accumulated copper volume in copper ore deposits which will be mined in the future (i.e. accumulated from the year the ore data was collected). The ore reservoir data covered by the figures include ore deposits which have an ore grade higher than 0.2 (Mudd et al., 2012), since the equations utilized are not valid for ore grades below (Northey et al., 2012).

Figures 2.5 and 2.6 show that the energy- and GWP-intensity will increase steadily to almost 6-fold by the time we have mined and processed all copper ore available (i.e. ore grades down to 0.2, which is the lowest ore grade the energy- and GWP-intensity equation are valid for). The energy-intensity and GWP-intensity with dynamic ore grade is compared to the energy-intensity and GWP-intensity with the constant ore grade EcoInvent have assumed (Mischa Classen et al., 2007). The figures illustrate the importance of dynamic ore grade when a future-oriented LCA of copper production is conducted.

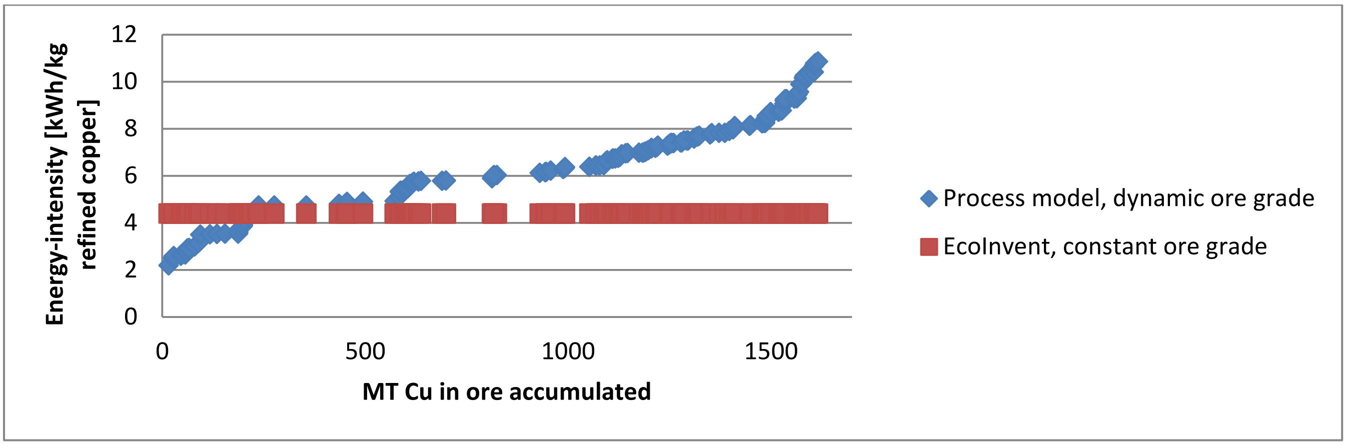


Figure 2.5: Global mining and beneficiation, energy intensity (Northey et al., 2012, Mudd et al., 2012)

Central assumption regarding figure 2.5: ore deposits are mined with gradually decreasing ore grade.

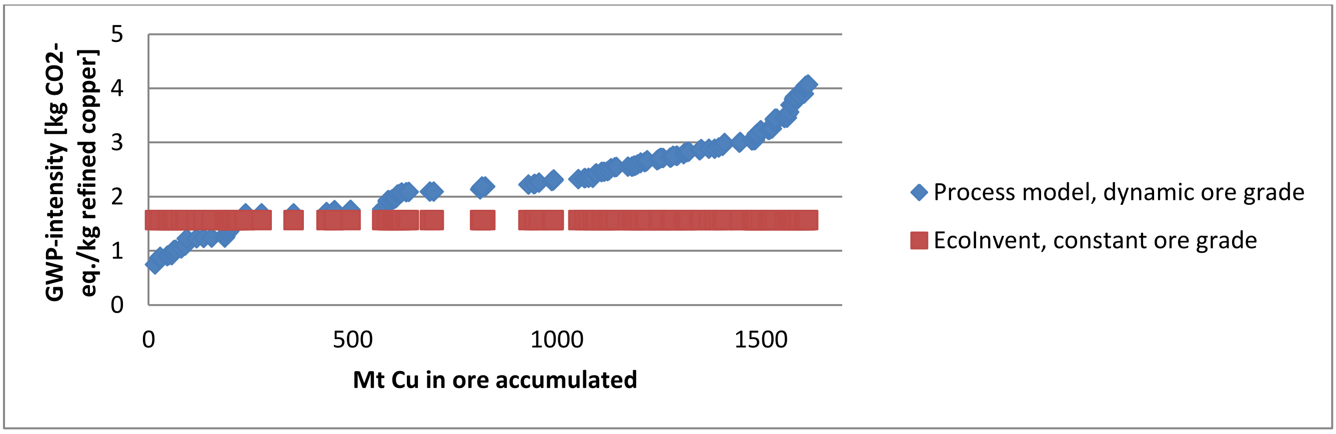


Figure 2.6: Global mining and beneficiation processing, GWP-intensity (Northey et al., 2012, Mudd et al., 2012)

Central assumption regarding figure 2.6: ore deposits are mined with gradually decreasing ore grade.

2.5 Regions considered

This master`s thesis considers *mainly* a global average of copper depletion and environmental problems regarding copper production. However, the work has also considered region differences. Figure 2.7 and table 2.5 elaborates which regions this study has considered, and from which countries in a specific region the ore data are collected. The copper ore data covers > 90 % of the discovered copper ore (Mudd et al., 2012).

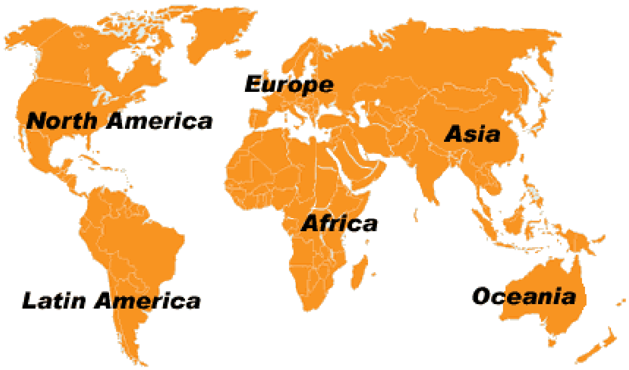


Figure 2.7: The regions considered in the region scenario analyses (EOXSales, 2014)

Table 2.5: Region-Country overview (Mischa Classen et al., 2007)

Region	Countries considered
North America	USA and Canada
Latin America	Chile, Peru, Argentina, Panama, Brazil, Venezuela, Bolivia, Equador, Dominican Republic and Mexico
Europe	Sweden, Finland, Romania, Poland, Spain, Portugal, Greece, Turkey, Norway, Ireland and UK
Africa	South Africa, Zambia, DRC (Congo), Zimbabwe, Botswana, Namibia, Eritrea, Burkina Faso, Tanzania, Mauritania, Burundi, Algeria and Mozambique
Asia	China, Indonesia, Mongolia, Pakistan, Philippines, India, Iran, Afghanistan, Laos, Saudi Arabia, Thailand, Vietnam, Russia, Kazakhstan and Kyrgyzstan
Oceania	Australia, Papua New Guinea and Fiji

2.6 Regional Breakdown of Technologies

Table 2.6 presents the copper production technologies assumed for the six regions presented in section 2.5 (Mischa Classen et al., 2007).

Table 2.6: Regional breakdown of copper production technologies

	Europe	Oceania	Asia	Latin America	North America	Africa
Open Pit	70.00 %	70.00 %	70.00 %	70.00 %	70.00 %	70.00 %
Underground	30.00 %	30.00 %	30.00 %	30.00 %	30.00 %	30.00 %
Froth flotation	100.00 %	100.00 %	100.00 %	100.00 %	100.00 %	100.00 %
Reverberatory furnace	6.20 %	23.70 %	22.80 %	23.30 %	23.30 %	23.70 %
Flash smelting furnaces	76.00 %	60.70 %	75.70 %	53.90 %	53.90 %	60.70 %
Other	17.80 %	6.20 %	1.50 %	5.20 %	5.20 %	6.20 %
Leaching and extraction	0.00 %	9.40 %	0.00 %	17.60 %	17.60 %	9.40 %
Electrorefining	100.00 %	90.60 %	100.00 %	82.40 %	82.40 %	90.60 %
Electrowinning	0.00 %	9.40 %	0.00 %	17.60 %	17.60 %	9.40 %

A compilation of Region specific Emission Factors is found in appendix H.

2.7 Life Cycle Analysis and the Accompanying Data Quantifications

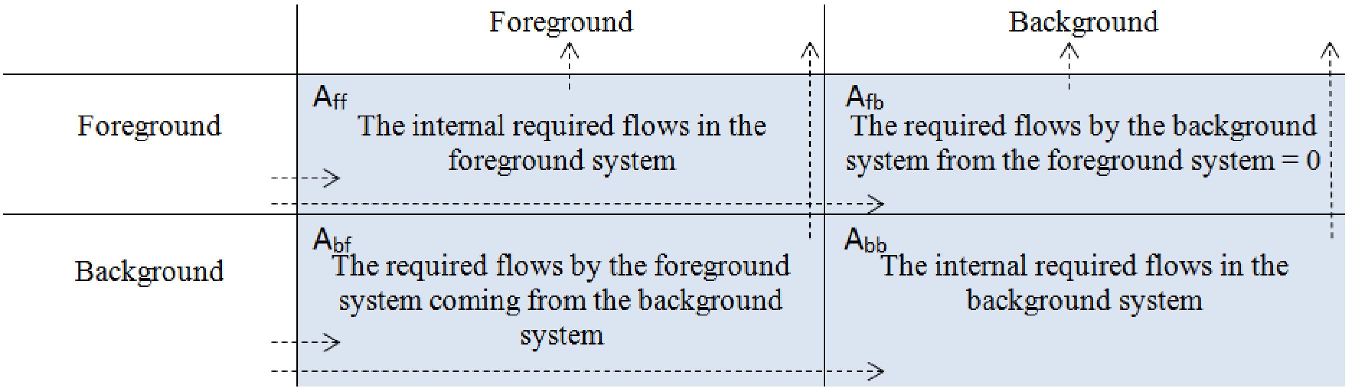
Life cycle analysis (LCA) is utilized together with scenario building (section 2.8) as the tools to conduct the scenario and sensitivity analyses (parameter value overview presented in section 2.9) to answer research question #2. Research question #1 is only answered by scenario analyses.

LCA is an analytical methodology to calculate environmental impacts throughout a life cycle (Strømman, 2010). This is why it is utilized in this work calculating global warming potential from copper production. The comprehensive methodology of LCA includes four main steps (European Commission Eurostat, 2010):

- Goal definition and scoping stage
- The inventory stage
- The impact assessment stage (the contribution analysis)
- The improvement assessment stage

In the first stage one sets the boundaries of the analysis; what the analysis will include and not include (a detailed flow chart of this work is presented in appendix D). An *inventory* contains; the energy and material demands of the processes, waste handling, as well as the stressors from the processes (the inventory of this work is presented in appendices F and H). In order to address stressors to individual impact categories, the contribution to an impact is divided by the contribution of a reference stressor to the same impact (Strømman, 2010). This makes it easy to present each impact category by a characterization factor (e.g. CO_2-eq.). This master`s thesis applies the process based hierarchical ReCiPe midpoint method (Goedkoop et al., 2008).

In LCA, "the foreground system" is separated from "the background system". While the foreground system covers the processes within the system boundary, the background system covers the processes outside the system boundary. However, in order to calculate the impacts based on the inventory, an A-matrix must be conducted. The A-matrix is the *requirement matrix* which is divided into four sections as figure 2.8 presents. The arrows in the figure show the directions of the flows. The flow values are per output of each process (Strømman, 2010).



	Foreground	Background
Foreground	A_{ff} The internal required flows in the foreground system	A_{fb} The required flows by the background system from the foreground system = 0
Background	A_{bf} The required flows by the foreground system coming from the background system	A_{bb} The internal required flows in the background system

Figure 2.8: The A-matrix utilized in the process based LCA

2.7.1 Conducting the Inventory and the A-matrix used in Process Based LCA

The foreground section of the A-matrix is conducted by the copper yield assumptions made by the EcoInvent providers (Mischa Classen et al., 2007). The background to foreground part of the A-matrix was conducted by utilizing existing EcoInvent inventory (Mischa Classen et al., 2007) and scale it (i.e. in order to be the size of the input per kg Cu in the output of each process). Deciding how to deal with the byproduct was also a part of the work. Overburden, and tailings, in addition to diesel, explosive and electricity demand was replaced by dynamic data (i.e. dynamic with respect to ore grade). This is recommended in several articles (Northey et al., 2013, Mudd et al., 2012). The ore grade was calculated for certain years (section 2.9.1), utilizing a number of assumptions (please read the general and specific assumption section).

a) *Mass balance theory*

In a system where the mass is constant, the flow *in* has to have the same mass as the flow *out* of the system.

$$\mathrm{m_{in}} = \mathrm{m_{out}} \tag{2.3}$$

b) Scaling

The values in the A-matrix has to be per unit output (Strømman, 2010). Regarding this master`s thesis` process model it is per kg copper (i.e. 99.96 wt-percent Cu) in the output. In other words, we want to track 1 kg of copper with 99.96 wt-percent Cu from mining to refining and know the size of the energy and material demands, and waste management per kg copper in a certain process output. However, the data in the EcoInvent inventory has the unit "per copper containing *mass* out of each subprocess". A scaling process of the already existing inventory is necessary to conduct the A-matrix correctly. New data are calculated by multiplying by the value "copper containing mass pr. kg copper out of a subprocess". This way the new data has the unit "pr. kg Cu out of the subprocess". Appendix B shows an example of the calculation principle.

c) Dealing with byproducts

The byproducts are assumed to replace a process which produces the byproduct as main product. Those byproducts registered in the EcoInvent database for copper production are included in the inventory, but with negative sign in the inventory. Those not registered are neglected. The fact that they are not registered could indicate that the product does not have a market value.

d) Dynamic background to foreground values

Most of the "background to foreground system"-requirements are provided by the EcoInvents inventory, and scaled as mentioned in b). However, some of the "background to foreground system"-requirements are calculated as follows:

d1) Electricity demand calculations for mining and beneficiation (pyro metallurgical process route)

The energy intensity (i.e. generated on site and from grid) is assumed to be equal the electricity intensity (i.e. from grid). The inventory does not include electricity generated on-site, except for diesel. An overestimation of the electricity intensity is likely. However, the electricity demand has been compared to the electricity demand Norgate and Haque assumed in their work with energy and GWP from mining and processing (Norgate and Haque, 2010). While Norgate and Haque assumed an electricity demand of 4.6 kWh/kg Cu (i.e. ore grade = 0.99), the electricity demand in current study is 4.3 kWh/kg Cu (i.e. ore grade = 0.99). The deviation is small. Therefore the energy intensity equation is utilized to calculate electricity demand:

If *x* is the ore grade, and 0.278 is the converting factor from GJ/t Cu to kWh/kg, the mining and beneficiation electricity demand [kWh/kg Cu] is calculated as (Northey et al., 2012):

$$15.697 \cdot x^{-0.573} \cdot 0.278 \tag{2.4}$$

The difference between mining and beneficiation electricity demand is assumed to be equal to the one EcoInvent assumes in their inventories (Mischa Classen et al., 2007).

$$\frac{Electricity\ demand\ mining}{Electricity\ demand\ of\ mining\ and\ benefication} = 0.1455 \tag{2.5}$$

d2) Overburden and tailings handling calculations for mining and beneficiation (pyro metallurgical process route)

The calculation principle is presented in this section, but an example of the calculation principles are presented in appendix B.

If x is the ore grade, and y is the % of Cu in the copper ore deposit rock (please see figure 2.9), the overburden amount [output of the mining process/kg Cu in mining output] is calculated as equation 2.6.

$$\frac{1}{y}-\frac{1}{x} \tag{2.6}$$

If x is the ore grade, a is the amount of ore, and b is the amount of copper concentrate (i.e. output of the beneficiation process), the tailings amount (i.e. output of the beneficiation process) is calculated as equation 2.7.

$$\frac{a}{b}\cdot\frac{1}{x}-b \tag{2.7}$$

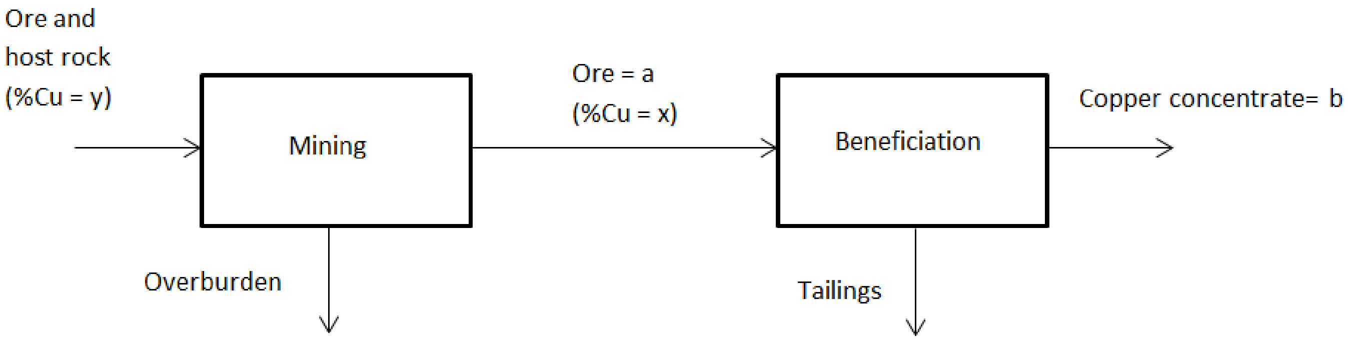


Figure 2.9: The relation between x, y, a and b

The ratio between the ore grade and the % of Cu in the copper ore deposit rock is assumed to only depend on the overburden to ore stripping ratio. This way, the overburden is indirectly dependent on the stripping ratio and ore grade only.

d3) Overburden/tailings handling calculation for mining, pretreatment, leaching and solvent extraction

Overburden and tailing out of mining, pretreatment, leaching and solvent extraction is aggregated to one flow and addressed to mining. If y is the % of Cu in the deposit, c is the % of Cu out of solvent extraction and d is the copper yield in all those processes together – overburden/tailings is calculated as equation 2.8.

$$\frac{1}{y}-\left(\frac{1}{c}\right)\cdot d \tag{2.8}$$

d4) Diesel and explosive demand calculations for mining and beneficiation (pyro metallurgical process route)

If c is the amount of diesel [MJ] per kg mining input (i.e. deposit rock), and y is the %of Cu in the deposit rock, the diesel demand [MJ/kg Cu] is calculated as equation 2.8.

$$c\cdot\frac{1}{y} \tag{2.8}$$

If d is the amount of explosives [kg] per kg mining input (i.e. deposit rock), and y is the % of Cu in the deposit, the explosives demand [kg/kg Cu] is calculated as equation 2.9

$$d \cdot \frac{1}{y} \tag{2.9}$$

The % of Cu in copper ore deposit rock (i.e. “y”) could be expressed as a function of the ore grade and stripping ratio (i.e. overburden to ore stripping ratio) (equation 2.10). The so-obtained increase of the stripping ratio would affect the inputs that depend on the percent of copper in the copper ore deposit rock.

$$y = \frac{x}{stripping\ ratio + 1} \tag{2.10}$$

2.7.2 The Contribution Analysis

The contribution or impact assessment stage in LCA comprises several quantification steps. The steps from the requirement matrix to the impact vector and –matrix are elaborated. Sets, vectors and matrices used in contribution analysis are explained in table 2.7.

Table 2.7: Sets, vectors and matrices utilized in the contribution analyses

Sets	pro		number of processes
	str		number of stressors
	imp		number of impact categories
Matrices and Variables	A	pro x pro	matrix of inter process requirements
	y	pro x pro	vector of external demand of processes
	x	pro x 1	vector of outputs for a given external demand
	L	pro x pro	The Leontief inverse, Matrix of outputs per unit of external demand
	S	str x pro	matrix of stressors intensities per unit output
	e	str x 1	vector of stressors generated for a given external demand
	E	str x pro	matrix of stressors generated from each process for a given external demand
	C	imp x str	characterization matrix
	d	imp x 1	vector of impacts generated for a given external demand
	D_{pro}	imp x pro	matrix of impacts generated from each process for a given external demand

To calculate the midpoint impacts (e.g. d-vector and D_{pro}-matrix), we need to calculate; the total output out of each process (the x-vector), emission vector (e-vector), characterization matrix (C-matrix) and stressor intensity matrix (S-matrix)

The x-vector is calculated by multiplying the “Leontief inverse”-matrix (L-matrix) by a dynamic final demand vector(y) which tells us how much the final demand is (eq. 2.12). Equation 2.11 shows how L-matrix is calculated. The elements (L_{ij}) in the Leontief inverse matrix tells us; the size [kg] of the process i`s output per unit [kg] external demand of process j (Strømman, 2010). This is in contrary to the A-matrix which tells us the size of the input in each process per unit [kg] output of each process (Strømman, 2010).

$$L = (\mathrm{I} - \mathrm{A})^{-1} \tag{2.11}$$

Where I is the identity matrix.

$$x = L \cdot y \tag{2.12}$$

(Strømman, 2010)

The e-vector is calculated by multiplying “the stressor intensity matrix” (s-matrix), provided by the inventory, with the x-vector. The s-matrix describes which environmental stressors (i.e. *str*) which is associated with a unit output of each process (i.e. *pro*).

$$e = \left[\begin{pmatrix} s_{11} & \cdots & s_{1,pro} \\ \vdots & \ddots & \vdots \\ s_{1,str} & \cdots & s_{str,pro} \end{pmatrix}\right] \begin{bmatrix} x_1 \\ \vdots \\ x_{pro} \end{bmatrix} = \begin{bmatrix} e_1 \\ \vdots \\ e_{str} \end{bmatrix} \tag{2.13}$$

(Strømman, 2010)

The midpoint impacts are calculated by multiplying the characterization matrix (C-matrix) by the e-vector. The characterization factors in the C-matrix “allow us to convert emissions of different substances with the same type of environmental impact into equivalents” (Strømman, 2010). The C-matrix tells us how much a stressor is affecting a impact relative to a reference stressor, which allows the different emissions to be aggregated in midpoint impacts like equation 2.14 presents.

$$d = \left[\begin{pmatrix} c_{11} & \cdots & c_{1,str} \\ \vdots & \ddots & \vdots \\ c_{imp,1} & \cdots & c_{imp,str} \end{pmatrix}\right] \begin{bmatrix} e_1 \\ \vdots \\ e_{str} \end{bmatrix} = \begin{bmatrix} d_1 \\ \vdots \\ d_{imp} \end{bmatrix} \tag{2.14}$$

(Strømman, 2010)

How much each process contributes to each impact category is calculated as equation 2.15 presents:

$$D_{pro} = CSx \tag{2.15}$$

where:

$$x = \left[\begin{pmatrix} x_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & x_n \end{pmatrix}\right] \tag{2.16}$$

(Strømman, 2010)

2.7.3 Calculating the Environmental Impact

Impact data are obtained using external data (EcoInvent) and assessment methods (ReCiPe), in addition to the software tool *Arda*. Arda is developed at the Norwegian University of Science and Technology. In this context Arda needs two types of inputs, input from the user and input from a background system. The user provides Arda with a functional unit, foreground to foreground data, as well as background to foreground and direct stressor data. Those inputs are compiled in an ArdaTemplate (i.e. Microsoft Excel). The functional unit (i.e. y-vector) and foreground to foreground data (i.e. A_{ff} part of the A-matrix) is compiled in the first sheet. Each of the foreground processes are labeled with a number starting at 10001. This way the background requirements could be linked to the foreground by remembering which foreground process the codes belong to. The data regarding the background is provided by the EcoInvent database. Each requirement and stressor from the background is labeled with a numbered code which is found in the

EcoInvent database. The “background to foreground”-requirements (i.e. A_{bf} part of the A-matrix) is compiled in sheet two by utilizing the foreground process code and the background requirement code. The direct stressors (i.e. S-matrix) is compiled in the third sheet by utilizing the same code system, with exception of that the stressors have another code database than the background requirements.

Among others, Arda provide us with the total impact vector (i.e. d-vector [# of impacts considered x 1]) divided by foreground and background, along with an impact matrix (i.e. D_{pro} [# of impacts x # of processes]).

In addition, Arda is able to perform both structural path analysis (i.e. comparing paths and analyze how much of the emissions from a process in the background that can be explained by a certain path of process interrelations leading to the final demand) and Taylor expansion series (i.e. comparing tiers). Comparing pathways along with tiers makes it possible to indicate the largest contributors in the background system.

2.7.4 Quantifying Uncertainties of the Inventory Data

Quantifying the uncertainties is recommended when conducting an LCA (European Commission Eurostat, 2010), because it supports the robustness of the LCA results (European Commission Eurostat, 2010).

Uncertainty considerations and estimation by EcoInvent

The process requirements are presented by “mean values” in the EcoInvent inventory. Mean values are uncertain for many reasons; measurement uncertainties, process specific variations, temporal variations, temporal and/or spatial approximations etc. (Frishknecht and Jungbluth, 2007). When there are only one or few sources of information, which is the case the EcoInvent inventory, a so-called pedigree matrix for uncertainty estimation of the mean value is applied. Six characteristics are all given a score between 1 and 5 (five quality levels). Each input and output flow is given a set of six indicator scores (one for each characteristic), which is in second hand given six uncertainty factors. The uncertainty factors are based on expert judgments (Frishknecht and Jungbluth, 2007).

The square of the geometric standard deviation (95% interval – SDg95) is calculated as presented in equation 2.17:

$$SD_{95} = \sigma_g^2 = \exp^{\sqrt{[\ln(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_6)]^2+[\ln(U_b)]^2}} \qquad (2.17)$$

Where:

U_1= Uncertainty factor of reliability

U_2 =Uncertainty factor of completeness

U_3 =Uncertainty factor of temporal correlation

U_4 = Uncertainty factor of geographic correlation

U_5 =Uncertainty factor of other technological correlation

U_6 =Uncertainty factor of sample size

U_b =Basic uncertainty factor

Please read (Frishknecht and Jungbluth, 2007) for elaboration about the scoring and factoring

There are some factors that are neglected applying this uncertainty assessment, and those are:

- missing information in the inventory table
- inappropriate modeling for the necessary inputs and outputs (in particular flow demand from the background database)
- mistakes imposed by human errors

(Frishknecht and Jungbluth, 2007)

Uncertainty estimation in this master`s thesis

There are some values in the inventory which is calculated by this master thesis` author. Those values should optimally have an uncertainty factor. In some cases, this was not possible as the calculation of the values was based on scenario building assumptions. The problem is elaborated further in the following bullet points.

- Uncertainty of the energy equation is listed as the correlation coefficient in literature (Northey et al., 2012).
- The overburden and tailing amounts are calculated based on; ore grade, % of Cu in rock, Cu in the concentrate and copper yield estimations. Those estimations have no numerical uncertainty. The uncertainty of overburden and tailings are therefore listed as NN.
- The diesel and explosive amounts are calculated based on % of Cu in deposit rock and the diesel demand per kg deposit rock into mining. The diesel demand per kg rock into mining is calculated based on the diesel demand per kg Cu in beneficiation, as well as the ratio between copper in deposit rock and copper in ore. Those estimations have no numerical uncertainty. The standard deviation of diesel demand listed by the EcoInvent providers (Mischa Classen et al., 2007) is 1. The uncertainty of diesel and explosives are therefore listed as NN/1.

2.8 Scenario Building for the Scenario and Sensitivity Analyses

In order to make the study dynamic, with respect to year, this master`s thesis has built/modeled scenarios concerning the whole anthropogenic copper cycle. Based on the *scenario building*, it is possible to begin quantifying the parameters which are expected to change in the future for a number of chosen scenarios. This master`s thesis utilizes those parameter values in a number of *scenario and sensitivity analyses*. The results of the scenario and sensitivity analyses, *together* with the methodology of LCA (section 2.7) will hopefully answer the research questions. Due to that, scenario building is presented before the parameter quantification process.

The parameters of concern is ore grade, stripping ratio, recycling input rate (dependent on copper demand, in-use stock growth, lifetime increase and EOL collection and recovery rate), energy mix and copper demand into the future. They are quantified on a yearly basis. The quantification process and an overview of the parameter values are presented in detail in section 2.9. The relation between the specific parameter change, methodologies utilized and research questions are further elaborated:

Firstly, varying recycling input rate and copper demand will both effect copper depletion (addressed to research question #1). On the other hand, declining ore grade will impact the electricity intensity (addressed to the first part of research question #2). Lastly, varying ore grade, stripping ratio and recycling input rate will affect the A-matrix and in turn the d-vector and D_{pro}-matrix (please see equations 2.11 to 2.16 in section 2.7.2). This is addressed to the second part of research question #2. Because the ore grade, stripping ratio and recycling input rate vary differently for each scenario, a number of A-matrices, L-matrices (equation 2.11), x-vectors (equation 2.12), e-vectors (equation 2.13), d-vectors (equation 2.14) and D-matrices (equation 2.15) will be conducted. This means that a unique set of matrices and vectors will be conducted for each year for each scenario.

Scenario vs sensitivity analyses in this master's thesis

While the scenario analyses explore the future where the five dynamic parameter values all have changed, sensitivity analysis investigates how current results are affected by each of the parameters. Three scenario analyses for a global and six regional markets are conducted. The sensitivity analyses are conducted by looking at the change due to *one* parameter at a time (Lederkilden, 2014). The value of the other parameters is kept constant and equals the values in the base case (based on literature on how the present/recent past is). This is with exception of ore grade and stripping ratio which are investigated as a whole because ore grade and stripping ratio are highly related to each other. Four sensitivity analyses for a global market are conducted.

This way current work is able to investigate the electricity intensity, GWP-intensity and GWP from *future* in addition to present copper production.

2.8.1 Theory of Scenario Building

Scenario building is a useful tool when exploring the future (The International Training Center, 2014a), “because it allow for an internally consistent framework to define deeply uncertain assumptions about the future” (Gerst, 2009). A scenario distinguishes from forecast and back cast, by exploring an alternative future (figure 2.10). Forecasting predicts a most likely future and back casting assess feasibility of a desired future (Kemp-Benedict, 2014). The work of the scenario builder starts by developing storylines for the future (Kapur, 2005). A storyline describes how the variables of concern in the scenario will change. In addition, the scenario’s driving forces is quantified where it is possible (Kapur, 2005).

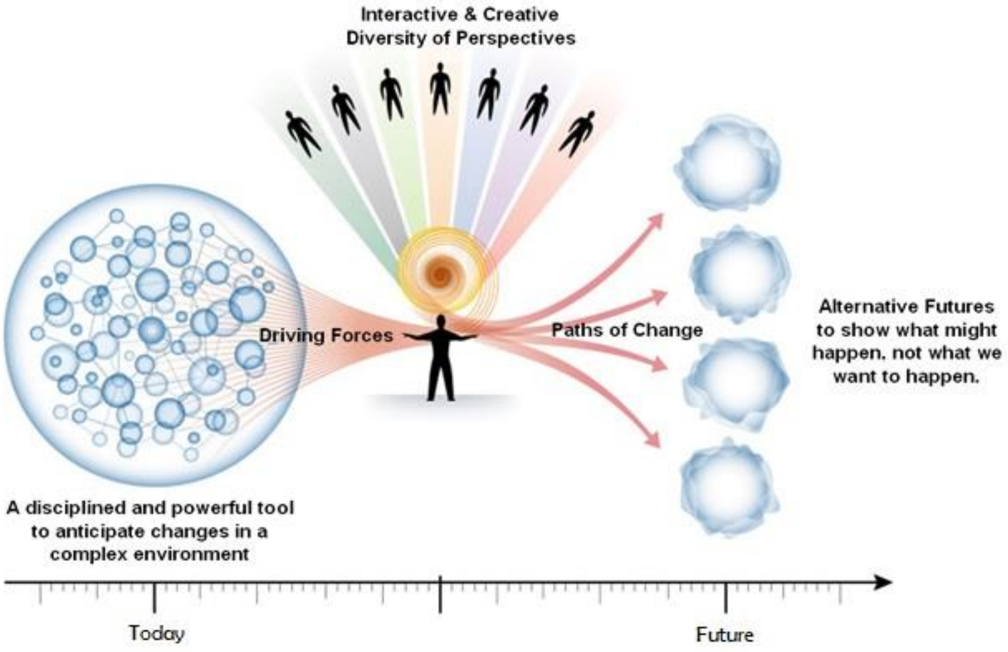


Figure 2.10: The methodology of scenario building (The International Training Center, 2014b)

When developing the future scenarios for energy use and environmental impact from copper production the following methodology (Kapur, 2005) is adopted.

1. Use of the Intergovernmental Panel on Climate Change (IPCC) emission scenarios for Greenhouse gases (GHG) as the background framework;
2. Selection of spatial units of analysis and temporal scale;
3. Formulation of scenario storylines for energy use and environmental impact from copper production;
4. Quantification of the scenarios.

2.8.2 The IPCC Scenario Framework

(Kapur, 2005, Intergovernmental panel on climate change, 2014a)

The Intergovernmental Panel on Climate Change (IPCC) has developed a framework for environmental related scenarios development. The framework builds upon two scenario themes; globalization (global vs regional) and environmental consciousness (economic vs environmental) generating a two-dimensional tree (figure 2.11), which symbolizes a family of four scenarios. Each of the scenarios describes future worlds. They differ by the rates of growth among regions and over time. Six driving forces for each of the scenarios are represented as the roots of the three. The drivers range; from very rapid economic growth and technological change to high levels of environmental protection, from low to high global populations, and from high to low GHG emissions. The family of four scenarios is widely known and respected, and is called the SRES (Special Report on Emissions Scenarios) scenarios namely A1, A2, B1 and B2.

In the SRES report IPCC states: “It is recommended that a range of SRES scenarios with a variety of assumptions regarding driving forces be used in any analysis” (Kapur, 2005). Therefore, this master`s thesis utilizes the SRES scenarios.

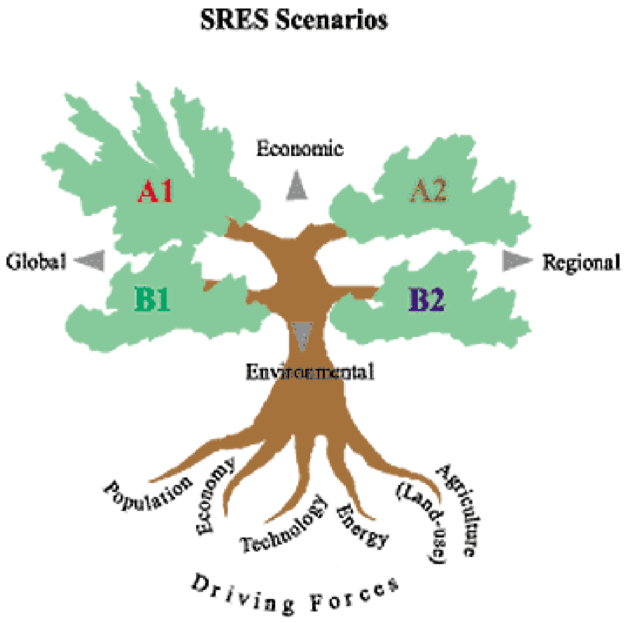


Figure 2.11: The SRES Scenarios (Intergovernmental panel on climate change, 2014b)

2.8.3 Spatial Units of Analyses and Temporal Scale

Which regions and which countries the present work has considered are described in detail in section 2.5. The time scale chosen for the scenario analyses are the period 2015–2025 for the regional analyses and 2015-2050 for the global analyses. The larger temporal scale, the lower is the accuracy for the latest years considered. The relatively short time scale is chosen to increase the overall accuracy of the results.

2.8.4 Scenario Storylines

The basis of the scenario storylines of present work is the same as the IPCC’s SRES storylines (Kapur, 2005, Intergovernmental panel on climate change, 2014a). The variables included in this work are carefully chosen with intentions to investigate the future electricity use and environmental impacts from copper production. The scenario themes and variables are presented in table 2.8 and 2.9, where table 2.9 elaborates the meaning of the variable. The storylines presented in table 2.10 explains the choices regarding the variables specific for this work, presented in table 2.8.

Table 2.8: The scenario themes and variables

	A1	A2	B1	B2
Scenario themes				
Globalization	higher	lower	higher	lower
Environmental consciousness	lower	lower	higher	higher
Variables specific for this work				
In-use stock growth	high	high	medium	medium
EOL collection & EOL recovery rate increase	low	low	high	high
“Green” energy mix	low	low	high	high
Final demand growth	high	high	high	high

A2 is not considered further as it is considered unlikely in this context because it assumes less globalization *and* less environmental consciousness. Therefore, only the three developed SRES scenarios, namely A1, B1 and B2 is utilized in this master thesis.

Table 2.9: Elaboration of the scenario variables

Variables	**Elaboration**
In-use stock	The amount of copper in stock (i.e. in use)
EOL collection & EOL recovery rate	EOL = end of life. EOL collection rate = how much is collected of the used copper products going to waste (i.e. in percent). EOL recovery rate = how much is recovered by the recycling industry (i.e. in percent).
Energy mix	The share among the input of energy generation (e.g. coal, natural gas, hydropower, wind power etc.).
Final demand	The external copper demand

Table 2.10 presents a general elaboration (Kapur, 2005) of the A1, B1 and B2 storylines, in addition to focus on four unique data variables (table 2.9) chosen for this scenario modeling. This makes the scenario results useful regarding the research questions of the thesis.

Table 2.10: Scenario storylines (Kapur, 2005)

Scenario name:	Storyline:
A1:	This scenario represents a future world of very rapid economic growth. High rate of global linkages and cooperation. The world’s population peaks to approximately 8.7 billion by the middle of the century. A1 also assumes a rapid introduction of new and more efficient technologies. The differences between the income levels of developed and developing countries will converge, but gaps will persist. Cultural and social interactions are assumed to increase. (Kapur, 2005) Free flow of goods from all over the world – including an increase of production in countries producing products having lower quality than industrialized countries, as well as a very rapid economic growth, in which global GDP will increase. This will affect a high growth of in-use stock. The low environmental consciousness will affect a low increase in the EOL collection & EOL recovery rate and low rate of “green” energy mix. The very rapid economic growth will affect a high final demand growth.

B1:	High rate of global linkages and cooperation. The world’s population peaks to approximately 8.7 billion by the middle of the century. It represents a convergent world where environmental consciousness is high. High economic growth is assumed, as well as rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The scenario emphasizes global solutions to economic, social, and environmental sustainability.(Kapur, 2005) A more homogeneous world having a high environmental consciousness and low material intensity, as well as an introduction of clean and resource-efficient technologies will increase the in-use stock at a medium rate. Non-fossil energy sources demand a higher rate of copper (i.e. wiring) per produced kWh. This will increase the in-use stock of the copper use group “infrastructure”, and is the main reason of a medium in-use stock growth instead of a low in-use stock growth which one could assume. More environmental consciousness will cause a high EOL collection & EOL recovery rate increase and a high rate of “green” energy mix. The economic growth and the focus of clean and resource-efficient technologies will also affect a high final demand growth.
B2:	In contrast to A1 and B1, B2 assume a lower economic growth and technological change. It also assumes that global population continues to increase. Less rapid and more diverse technological change is assumed in the B2 scenario. Local solutions take place when it comes to economic, social, and environmental sustainability issues. Scenario B2 do also assume trade barriers, but have a focus on the environment protection and social equity.(Kapur, 2005) A more homogeneous world having a high environmental consciousness and low material intensity, as well as an introduction of clean and resource-efficient technologies will increase the in-use stock at a medium rate. Non-fossil energy sources demand a higher rate of copper (i.e. wiring) per produced kWh. This will increase the in-use stock of the copper use group “infrastructure”, and is the main reason of a medium in-use stock growth instead of a low in-use stock growth which one could assume. More environmental consciousness will cause a high EOL collection & EOL recovery rate increase and a high rate of “green” energy mix. The economic growth and the focus of clean and resource-efficient technologies will also affect a high final demand growth.

2.9 Parameter Values Utilized in the Analyses

Based on the *scenario building* (section 2.8), it is possible to begin the process of quantifying five unique data parameters which are expected to change in the future for a number of chosen scenarios; copper ore grade, stripping ratio, recycling input rate (RIR), energy mix and copper demand. Section 2.9.1 presents how they are quantified, and section 2.9.2 presents an overview of the values by number in tabular form.

2.9.1 Quantification Process

Copper is a continuous material flow in the life cycle of copper, in which virgin material is the cycle`s only input. Losses appear in the waste- and recycling stages as figure 2.12 shows. Nomenclature is given in table 2.11.

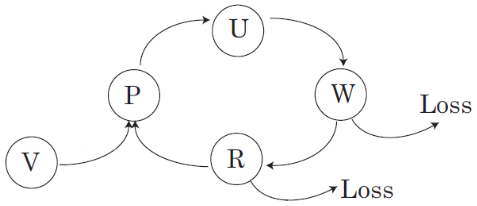


Figure 2.12: The life cycle of a material (Strømman, 2010)

Table 2.11: Nomenclature, material cycle

Symbol	Copper Cycle Appellation
V	Virgin material (i.e. primary copper)
P	Production
U	Use
R	Recycling
W	Waste

Two of the five unique data parameters; ore grade and RIR are quantified of the author based on the material cycle model (Gerst, 2009) (equation 2.18), the mass balance theory and the specific variables for this work, presented in table 2.8. Nomenclature is given in table 2.12.

$$D_{i,j,t} = S_{i,j,t} - S_{i,j,t-1} + O_{i,j,t} \tag{2.18}$$

Table 2.12: Nomenclature, material balance

Symbol	Copper Cycle Appellation
D	Demand
S	In-Use Stock
O	Rate of discarded stock
i	Copper-containing technology
j	World region
t	time

In short, the quantification process is based on; ore reservoir data (Mudd et al., 2012), the scenario storylines of this master thesis (table 2.10), future final copper demands (Ayres et al., 2002) and copper in use-stocks conducted by earlier scenario analyses (Gerst, 2009). The *global* in-use stock is the sum of the four regions REF, ASIA, OECD90 and ALM (see Appendix E for name description).

One of the other five unique data parameters, *stripping ratio*, is only based on the specific variables for this work, presented in table 2.5 and mailing correspondence with Dr. Sharif Jahanshahi (Jahanshahi, 2014).

The former and future *energy mixes* for six world regions and the global average (United Nations Environmental Programme, 2014) are collected from literature. Regarding the energy mixes for the future, the baseline and blue map scenarios (see Appendix E for name description) have been the basis. The *future demand* in copper for four regions is also collected from literature (Ayres et al., 2002). Regarding the future demands, those are based on the SRES framework. The global demand is the sum of the four regions REF, ASIA, OECD90 and ALM (see Appendix E for name description).

Regarding the quantification process of ore grade and RIR, it is now elaborated in detail. It should be noted that the writer have calculated both primary copper production of year *x* and copper outflow of use phase of year *x*, by utilizing copper demand of year *x*. In hindsight after the scenario modelling and analyses took place, I understand that this is not the correct way to calculate the copper material outflow. The copper flow depends, in fact, on the amount of copper that was put into use 30 years ago or so (Harmsen et al., 2013), and is now discarded, and average in-use stock growth (i.e. average over the years the products in the output was a demand). Anyway, the presented methodology was utilized to quantify the parameters ore grade and RIR:

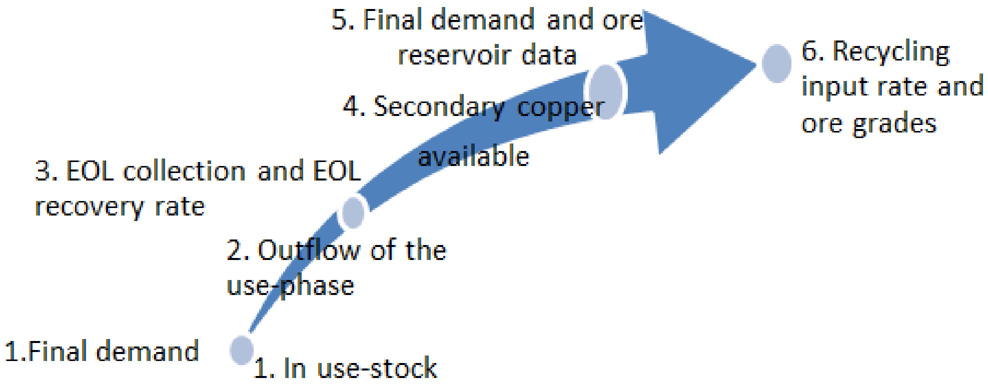


Figure 2.13: Sketch presenting the idea behind the parameter value quantification process

Figure 2.13 illustrates the working process, and is elaborated in the numerical points. Equation 2.19 to 2.22 presents how the material flows in the copper cycle are quantified (Gerst, 2009). The variables were calculated on year-to-year basis.

1. Final demand and in-use stock
   Data for annual *final demands* and annual *in use-stocks, for four regions-OECD90, ASIA, REF and ALM*, for a number of scenarios were collected from literature and matched with our scenarios for the same four regions. The four regions are defined in "Spatial units of analysis and temporal scale". The matching was done based on the storylines of the scenarios in the literature and this master thesis` scenarios storyline (please read appendix E for elaboration).
2. Outflow of the use-phase
   By utilizing material flow analysis and the mass balance theory – annual outflow of the use-phase for scenario A1, B1 and B2 for the same four regions was calculated. Current study wanted to study all continents – Europe, Asia, Africa, Oceania, North America and Latin America. Transforming the four-region data to six—region data was conducted carefully. The definition scrap pool was introduced. It was assumed that all copper scrap generated independent of location is the same. The amount of scrap available for EOL collection and EOL recovery for *each* region market was decided by their regional final demand share of the total global final demand.

$$\begin{gathered}\textit{Copper outflow of use}_{\ (year\ x)} = \\ \textit{final copper demand}_{\ (year\ x)} - \textit{copper in-use stock growth, this year compared to} \\ \textit{previous year}\end{gathered} \tag{2.19}$$

3. EOL collection and EOL recovery rate

The annual regional outflow of the use-phase, and the annual regional EOL collection and EOL recovery rates, was utilized to calculate the secondary copper available for the final demand marked (point 4).

4. Secondary Copper Available
   100 % of the secondary copper available is assumed to be used, to satisfy the copper final demand.

$$\textit{Secondary copper available}_{\textit{(year x)}} = \textit{copper outflow of the use phase}_{\textit{(year x)}} * \textit{copper EOL collection \&recovery rate}_{\textit{(year x)}} \tag{2.20}$$

5. Final demand and ore reservoir data
   The annual amount of secondary copper available and the annual final demand was utilized to calculate the primary copper produced by utilizing equation 2.19, 2.20 and 2.21, to get equation 2.22.

$$\textit{primary copper produced}_{\textit{(year x)}} = \textit{final copper demand}_{\textit{(year x)}} - \textit{secondary copper available}_{\textit{(year x)}} \tag{2.21}$$

$$\textit{primary copper produced}_{\textit{(year x)}} = \textit{final copper demand}_{\textit{(year x)}} - (\textit{final copper demand}_{\textit{(year x)}} - \textit{copper in-use stock growth}_{\textit{(year x)}}) * \textit{copper EOL collection \&recovery rate}_{\textit{(year x)}} \tag{2.22}$$

The annual primary copper demand was further utilized together with the ore reservoir data to calculate the annual averaged ore grade of the ore mined annual – for six regional industries and markets and a global industry and market. This is further presented in point 6.

6. RIR and ore grade

The annual amount of secondary copper available and the annual final demands (generated in point 2) was further utilized together with the ore reservoir data to calculate the RIR (International Copper Association, 2013).

$$\textit{Recycling input rate} = \frac{\textit{Secondary Copper available (year x)}}{\textit{Copper demand (year x)}} \tag{2.23}$$

Modelling the annual averaged ore grade for year *x* is conducted by combining ore grades of ore in deposits mined at year *x*. Finding the ore grades of the ore mined at year *x* is done by combining primary copper demand at year *x* and ore reservoir data.

$$ore\ grade\ (year\ x) = \sum_{n=1}^{\infty} oregrade\ deposit\ \#n \cdot \frac{amount\ of\ ore\ mined\ having\ ore\ grade\ in\ deposit\ \#n}{amount\ mined\ (year\ x)} \tag{2.24}$$

2.9.2 Overview of the Parameter Values

As section 2.8 explains, in addition to the parameter values generated by this master`s thesis, the thesis has considered two parameters; energy mix and copper demand which are collected from literature. The parameter values are utilized to answer research question #1 and the first part of research question #1 (regarding electricity intensity), and to generate the LCA vectors and matrices in equation 2.11-2.15

(section 2.7) in order to answer the rest of research question #2. This section will present all global parameter values. The regional parameter values are presented in appendix I.

Base case variables:

Table 2.13: Global ore grade and stripping ratio, base case

Ore grade [% Cu in ore]	Stripping ratio [kg overburden/kg ore]
0.99	1.75

Table 2.14: Global recycling input rate, base case

Recycling Input Rate
35 %

Table 2.15: Global energy mix, base case

Energy mix	
Coal	32 %
Gas	26 %
Oil	9.9 %
Nuclear	8.2 %
Hydro	20 %
Wind++	3.6 %

In table 2.15 and 2.19, wind++ refers to wind, ocean, geothermal, solar and biomass.

Table 2.16: Global copper demand, base case

Demand [MT]
18

Scenario and sensitivity analysis values:

Table 2.17: Global ore grade, analysis values

	Ore grade [% Cu in ore]		
	A1	B1	B2
2020	1.47	1.72	1.72
2030	0.85	0.87	0.87
2050	0.41	0.54	0.56

Table 2.18: Global stripping ratio, analysis values

	Stripping ratio [kg overburden/kg ore]		
	A1	B1	B2
2020	2.0	1.9	1.9
2030	2.4	2.1	2.1
2050	3.6	2.5	2.5

Table 2.19: Global energy mix, analysis values

Energy mix				
		A1	B1	B2
2020	Coal	33 %	31 %	31 %
	Gas	26 %	17 %	17 %
	Oil	6.7 %	4.0 %	4.0 %
	Nuclear	7.0 %	17 %	17 %
	Hydro	19 %	17 %	17 %
	Wind++	9.0 %	14 %	14 %
2030	Coal	34 %	23 %	23 %
	Gas	25 %	15 %	15 %
	Oil	4.2 %	2.6 %	2.6 %
	Nuclear	6.1 %	19 %	19 %
	Hydro	18 %	18 %	18 %
	Wind++	13 %	23 %	23 %
2050	Coal	30 %	12 %	12 %
	Gas	32 %	15 %	15 %
	Oil	1.9 %	0.6 %	0.6 %
	Nuclear	6.1 %	24 %	24 %
	Hydro	16 %	14 %	14 %
	Wind++	15 %	34 %	34 %

Table 2.20: Recycling input rate, analysis values

	Recycling input rate		
	A1	B1	B2
2020	36 %	48 %	50 %
2030	26 %	46 %	55 %
2050	35 %	56 %	62 %

Table 2.21: Copper demand, analysis values

	Demand [MT]		
	A1	B1	B2
2020	31	31	31
2030	41	42	42
2050	61	65	65

3. Results

In section 1 two questions are addressed. One of them is; under which scenarios will the existing copper resources be depleted and when? The answer, estimated copper depletion, is presented in section 3.1. Section 3.2 and 3.3 are addressed to the second research question; How does electricity intensity and GWP of copper production change throughout the first halve of the 21st century as the copper ore grade declines? The results regarding research question #2 is divided into several result topics; electricity intensity, GWP-*intensity* of *primary* copper production, GWP-*intensity* of copper production, GWP from global copper production and regional differences in the GWP-intensity. This is to make the result- and discussion section as transparent and understandable as possible for the reader, and for future work. In addition to answer the research questions, possibilities to moderate the expected problems are also considered.

3.1 Estimated Time for Global Copper Depletion

“Copper depletion” occurs when the copper demand is greater than the possible production; either it is primary or secondary production. Based on the scenario work and scenario parameter values (section 2.8 and 2.9), possible copper depletion in the 21st century is investigated. Figure 3.1 presents how fast copper depletion is estimated to take place. The figure includes only the currently known reserves. According to Scenario A1 copper depletion will occur in 2070. The depletion time according to the B1 Scenario is year 2096, and according to the B2 Scenario, a depletion time will occur after year 2100.

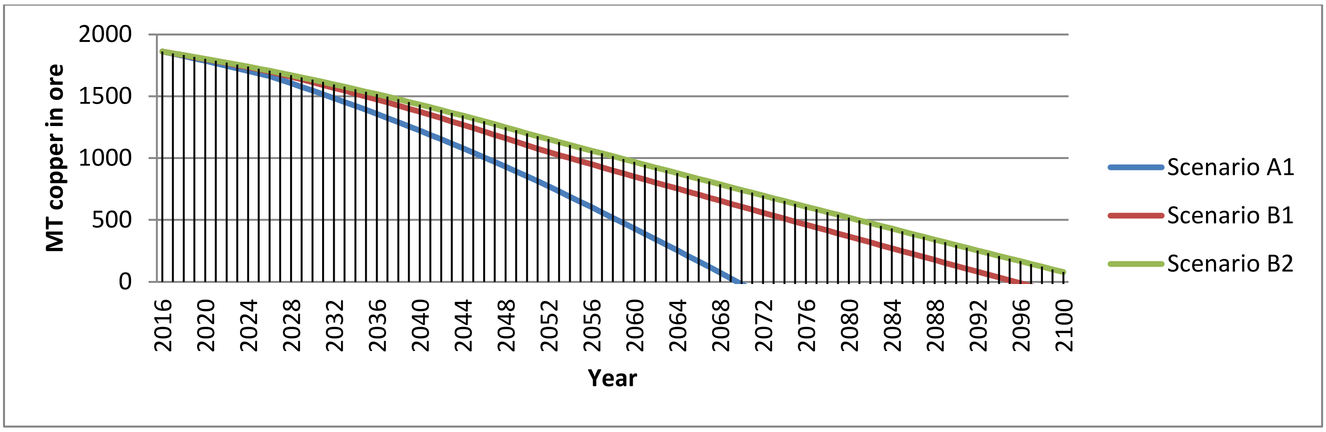


Figure 3.1: Copper depletion, globally [MT]

3.2 Global Primary Copper Production`s Direct Electricity Intensity

Global production, in contrary to region specific, is an optimal situation where we first mine the global ore available in deposits which demands less energy being mined and processed (i.e. deposits with ore having the largest ore grades).

According to the research question #2, changes in *the future* are most interesting. The electricity demand of the hydrometallurgical process route is therefore not presented as the electricity demand of those processes is assumed to not change.

There are (Northey et al., 2012) developed equations to calculate the direct energy intensity, among others, of the processes in the pyro metallurgical process route; mining and beneficiation. This master`s thesis has approximated direct energy intensity to be equal to the direct electricity intensity. This is elaborated in materials and methodology. *Direct* electricity intensity is, in contrary to electricity intensity, the electricity demand *within* the system. However, for simplicity in the rest of this master`s thesis, “direct electricity intensity” is written “electricity intensity”. Further, electricity demand for mining and beneficiation are assumed to be the only processes which depend on the ore grade. All input values of; pretreatment, reduction and refining are assumed to be independent of the ore grade. Due to that, the size of the electricity demand per kg Cu of those processes are based on the data provided by the EcoInvent inventory

(Mischa Classen et al., 2007), and the size of the output mass per kg Cu assumption made by the EcoInvent providers (Mischa Classen et al., 2007).

Ore grade dependency on electricity intensity is first presented (figure 3.2), before present (table 3.1) and future (table 3.2 and figure 3.3) electricity intensities are presented. The modelled ore grade decline was based on the scenario work (section 2.8 and 2.9).

Figure 3.2 illustrates the dependency of the ore grade on the direct electricity intensity. It is conducted by utilizing Northey et al.`s equation (Northey et al., 2012) and assumptions made by the EcoInvent inventory providers (Mischa Classen et al., 2007). The electricity intensity increases with declining ore grade for the processes mining and beneficiation.

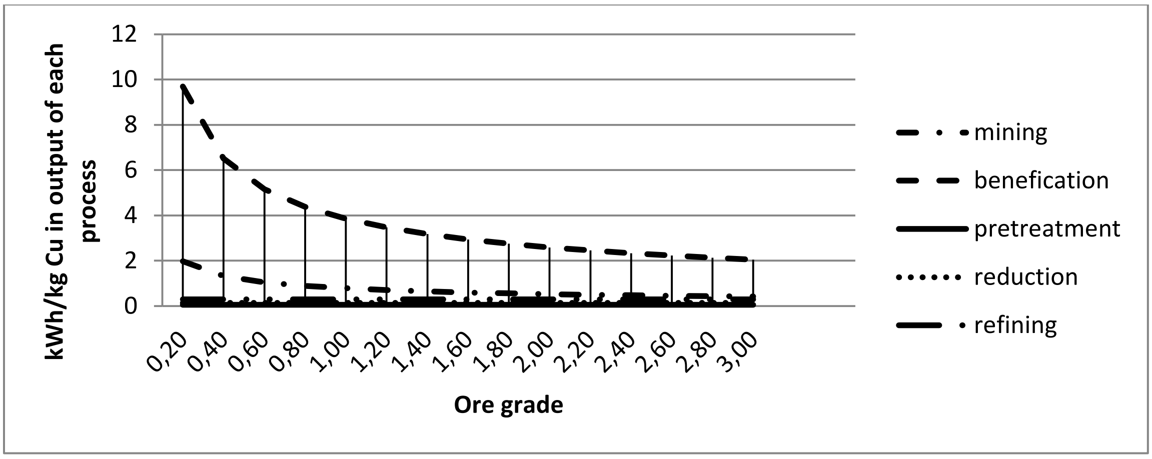


Figure 3.2: Ore grade dependency on electricity intensity

The present

The electricity intensity of present time is presented by a base case result which is conducted by utilizing the assumptions made by the EcoInvent inventory providers (i.e. ore grade = 0.99). Table 3.1 presents the results.

Table 3.1: Electricity intensity, base case primary copper production

Copper production process	Electricity demand [kWh/kg Cu in output of each process]
- Mining	0.79
- Beneficiation	3.87
- Pretreatment	0.06
- Reduction	0.14
- Refining	0.29

The future

The electricity demands per kg are presented in table 3.2. The ore grade values utilized in the electricity demand study was provided by the scenario work (please read section 2.8 and 2.9). However, the unit is per kg Cu in the output of each process. As table 3.2 illustrates, the electricity intensity for mining and beneficiation will increase in the future, but with different velocities regarding the three different scenarios considered.

Table 3.2: Electricity demand, sensitivity analyses, primary copper production

Scenario	Copper production process	[kWh/kg Cu in output of each process] 2020:	2030:	2050:
A1	- Mining	0.63	0.86	1.31
	- Beneficiation	3.09	4.23	6.47
	- Pretreatment	0.06	0.06	0.06
	- Reduction	0.14	0.14	0.14
	- Refining	0.29	0.29	0.29
B1	- Mining	0.58	0.85	1.11
	- Beneficiation	2.83	4.17	5.47
	- Pretreatment	0.06	0.06	0.06
	- Reduction	0.14	0.14	0.14
	- Refining	0.29	0.29	0.29
B2	- Mining	0.58	0.85	1.10
	- Beneficiation	2.83	4.17	5.40
	- Pretreatment	0.06	0.06	0.06
	- Reduction	0.14	0.14	0.14
	- Refining	0.29	0.29	0.29

Figure 3.3 compares the electricity-intensity for each process per kg *refined copper*. The highest increase by amount is observed for the beneficiation process. It seems that refining (electrolysis) is much smaller than beneficiation. This is a remarkable result which is discussed in section 4.2.

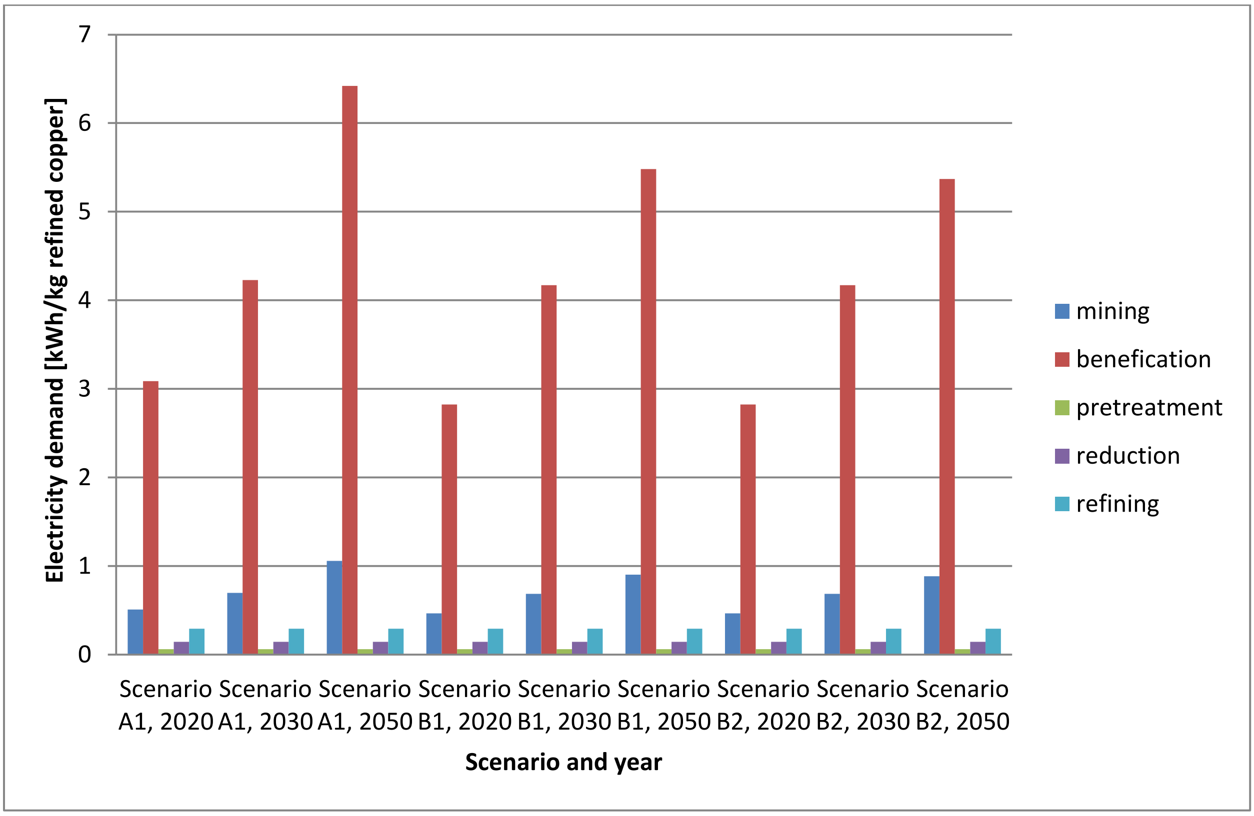


Figure 3.3: Overview of electricity demand in all scenarios

3.3 Global Warming Potential

Global warming potential [CO_2-eq.] generated from global copper production depends on global warming potential intensity [CO_2-eq./copper demand unit] and global copper demand. Both the intensity and demand are important when investigating global warming potential. The GWP-intensity is presented in two turns for better transparency regarding how the result is affected by the dynamic parameters and why. The

GWP-intensity of primary copper production depends on ore grade, stripping ratio and energy mix. On the other hand, the GWP-intensity of copper production (where the final product is an aggregation of primary and secondary produced copper) is dependent of ore grade, stripping ratio, energy mix and recycling input rate. They are presented in respectively section 3.3.1 and 3.3.2. Regarding research question #2, changes in global warming potential from global copper production due to a number of factors are easier to understand if we first investigate and discuss the GWP-intensity. Due to that, the GWP-*intensity* results are presented. Regarding 3.3.1, GWP-intensity of *primary* copper production is interesting because the overall changes in the GWP-intensity are mostly caused by the GWP-intensity of *primary* copper production because RIR is mostly beneath 50 %. Section 3.3.2 is interesting because it allows the author to investigate the effects of RIR *in addition* to ore grade and energy mix.

Section 3.3.3 presents the total GWP from global copper production which is the directly answer to research question #2. The GWP results include all factors of interest; ore grade, stripping ratio, energy mix, RIR and demand, regarding research question #2. To investigate regional differences, which provide a more location detailed answer of the question, section 3.3.4 is presented.

3.3.1 GWP-intensity, Primary Production

This section presents the GWP-intensity of primary production. The GWP-intensity [kg CO_2-eq./kg refined copper] of primary production is assumed to only depend on the factors; ore grade, stripping ratio and energy mix. While all of the factors affect the result linked to the pyro metallurgical process route, only energy mix affects the result linked to the hydrometallurgical process route. This, both process routes is presented

“The present” is presented before “the future”. “The future” is first presented by table 3.3. Subsequently, a comparance this study`s results to Norgate et al `s (Norgate et al., 2007) is presented in table 3.4. “The future” is first presented by figures 3.4 and 3.5 which illustrate the dependency of the ore grade for the global warming potential. The last one presents this study`s results and the results utilizing the GWP-intensity equation provided by Northey et al. (Northey et al., 2012). The sensitivity and scenario analyses are then presented. The scenario analyses are presented both graphically and in tabular format. The results` sensitivity to changes in ore grade, stripping ratio and energy mix are presented in tabular format.

The present:

The GWP-intensity of present time is presented by a base case result which is conducted by utilizing the assumptions made by the EcoInvent inventory providers and energy mixes of the year 2007 which is provided by the literature (United Nations Environmental Programme, 2014). The ore grade of the sulphide and oxide ore = 0.99, and the assumed global mix between pyro metallurgical and hydrometallurgical produced copper is 90.6% - 9.4%. Please read section 2.9 for an overview of the parameter values utilized.

Table 3.3 presents the GWP-intensity. The impacts from the two process routes are added to reflect the average global mix of the pyro metallurgical and hydrometallurgical production.

Table 3.3: GWP-intensity, base case primary copper production

Copper production process	GWP-intensity [kg CO_2-eq./kg refined copper]
- Mining (pyro m.)	1.34
- Beneficiation	2.41
- Pretreatment	0.12
- Reduction	0.75
- Refining (pyro m.)	0.34
- Mining (hydrom.)	0.53
- Pretreatment, Leaching and Solvent Extraction	0.24
- Refining (hydrom.)	0.26
Total	6.00

Table 3.4 compares the primary GWP-intensity result (ore grade sensitivity result), including all process stages, to another study (Norgate et al., 2007) which also have looked at primary GWP-intensity, including all process stages. The ore grade of 3 is utilized. This study`s result is higher than Norgate et al.`s result. The difference is discussed in section 4.2.

Table 3.4: Comparing a result to Norgate et al`s

	(Norgate et al., 2007)	This study
Ore grade (% Cu)	3	3
GWP-intensity primary copper	3.3 kg CO_2-eq./kg refined copper	4.6 kg CO_2-eq./kg refined copper

The future:

The GWP-intensity increases with declining ore grade. Figure 3.4 presents *how* the GWP-intensity of primary production increases with declining ore grade in the future (ore grade sensitivity results). Figure 3.5 compares this study`s results for mining and beneficiation (ore grade sensitivity results) and the results utilizing the GWP-intensity equation provided by Northey et al. (Northey et al., 2012).

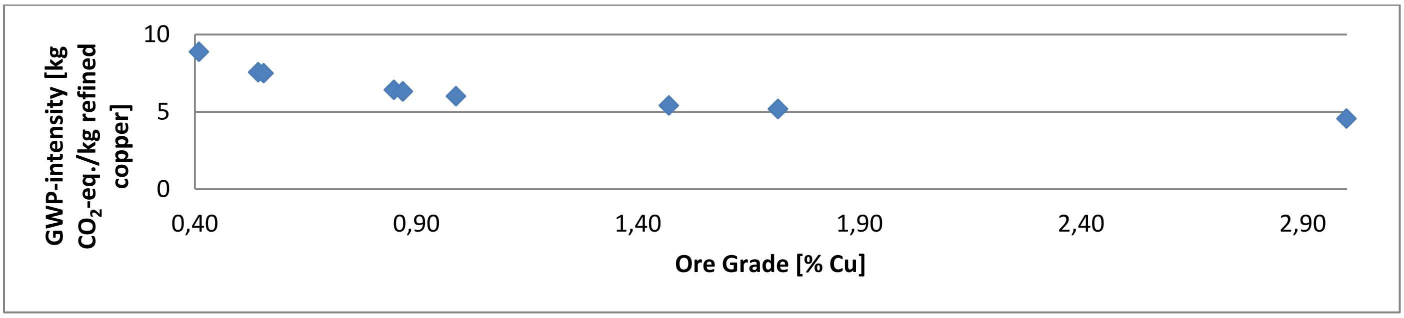


Figure 3.4: Primary copper production`s GWP-intensity, including all process stages

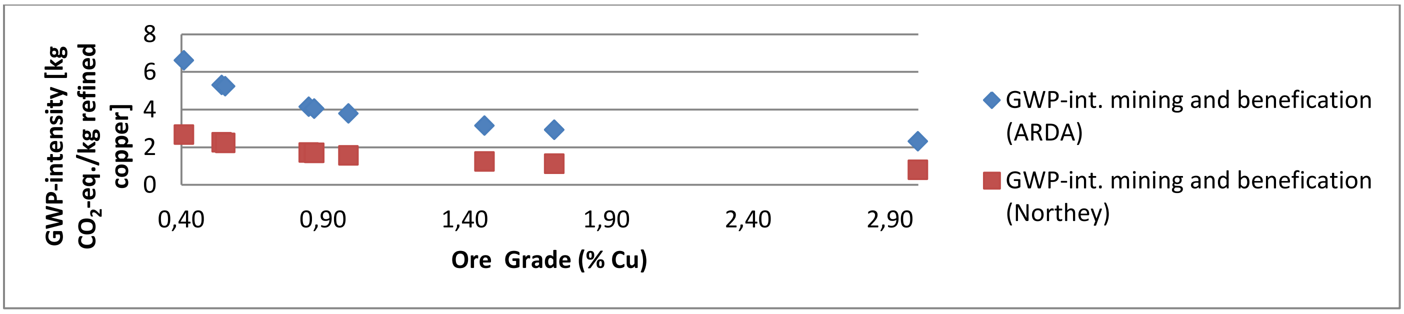


Figure 3.5: Primary copper production`s GWP-intensity, mining and beneficiation

The sensitivity analyses presented investigate how sensitive GWP-intensity is to changes in; ore grade and stripping ratio (table 3.5) and energy mix (table 3.6). The parameter values utilized are provided by the scenario work (see section 2.9 for the parameter values utilized). Ore grade decline and stripping ratio increase will raise the GWP-intensity of primary copper production in the future (table 3.5). On the other hand, greener energy mix will alone shrink the GWP-intensity of primary copper production in the future (table 3.6). Same energy mix is utilized in the B scenarios (blue map).

Table 3.5: Sensitivity to ore grade and stripping ratio, GWP-intensity, primary copper production

	GWP-intensity [kg CO_2-eq./kg refined copper]		
Scenario	2020:	2030:	2050:
A1	5.39	6.40	8.87
B1	5.17	6.30	7.55
B2	5.17	6.30	7.48

Table 3.6: Sensitivity to energy mix, GWP-intensity, primary copper production

	GWP-intensity [kg CO_2-eq./kg refined copper]		
Scenario	2020:	2030:	2050:
A1	5.89	5.81	5.63
B1	5.43	4.79	4.19
B2	5.43	4.79	4.19

The scenario analyses presented in this section explores alternative futures regarding GWP-intensities [kg CO_2-eq./kg refined copper] of primary copper production (see section 2.9 for an overview of the parameter values utilized).

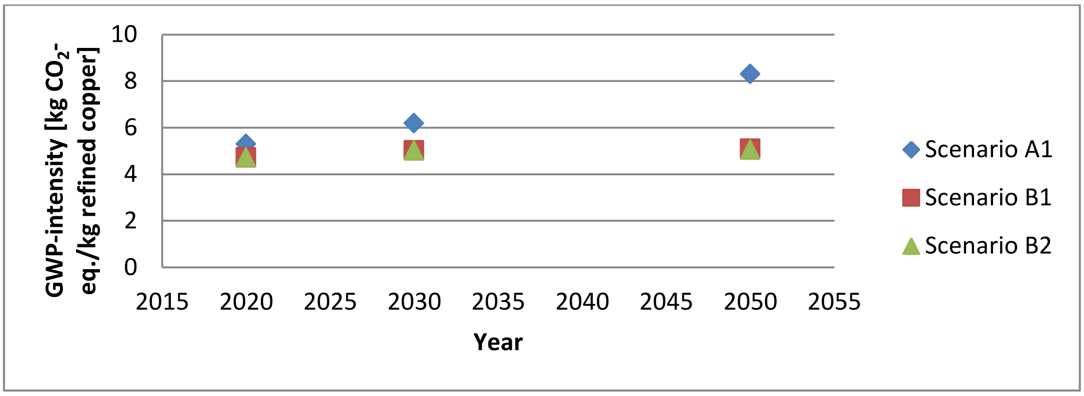


Figure 3.6: GWP-intensity primary production

According to figure 3.6, the GWP-intensity will increase in all scenarios. The GWP-intensity will increase more in the A1 Scenario, than in the B1 and B2 scenario. The B1 and B2 scenarios are almost equal for all years considered. The variable values utilized for those scenarios are very equal (see section 2.9 for parameter values utilized). However, the *expected increase* of GWP-intensity observed in table 3.5 may be *moderated*, or in some cases (scenario B1 and B2) the GWP-intensity for 2050 might be less compared to the base case and year 2020. By moderating, it is meant that the increase could be less than table 3.5 shows. Table 3.7 illustrates that in a better way.

Table 3.7: GWP-intensity, scenario analyses, primary copper production

	GWP-intensity [kg CO_2-eq./kg refined copper]		
Scenario	2020:	2030:	2050:
A1	5.29	6.19	8.30
B1	4.71	5.01	5.08
B2	4.71	5.01	5.04

3.3.2 GWP-intensity, Primary *and* Secondary Production Aggregated

This section presents the GWP-intensity [GWP/kg refined copper] of the copper production - primary and secondary production aggregated. It differs from section 3.3.1 where only GWP-intensity of *primary* production is considered. The GWP-intensity of copper production is assumed to depend on the factors; ore grade, stripping ratio, energy mix and *recycling input rate*. “The present” is presented before “the future” by table 3.8. “The future” is presented by the sensitivity and scenario analyses. The scenario analyses are presented both graphically and tabular format. The results` sensitivity to changes in ore grade, stripping ratio, energy mix and RIR are presented in tabular format.

***The present*:**

The GWP-intensity of present time is presented by a base case result which is conducted by utilizing the assumptions made by the EcoInvent inventory providers (e.g. ore grade = 0.99) (Mischa Classen et al., 2007), and energy mixes and demand of the year 2007 which is provided by the literature (United Nations Environmental Programme, 2014). Recycling input rate is also provided by the literature (Glöser et al., 2013) (i.e. 35 % for the base case). Please read section 2.9 for an overview of the parameter values utilized. The GWP-intensity result is presented in table 3.8.

Table 3.8: GWP-intensity, base case copper production

GWP-intensity [kg CO_2-eq./kg refined copper]
4.42

The future:

The sensitivity analyses presented in this section investigates how sensitive GWP-intensity is to changes in; ore grade and stripping ratio (table 3.9), energy mix (table 3.10) and recycling input rate (table 3.11). The parameter values utilized are provided by the scenario work (see section 2.9 for an overview of the parameter values utilized). Ore grade decline and increase in stripping ratio will raise the GWP-intensity of copper production in the future (table 3.9). On the other hand, greener energy mix (table 3.10) will alone shrink the GWP-intensity in the future. The results presented in table 3.11 are difficult to interpret since some values increase and some decrease. However, since the recycling input rate is only steadily increasing for scenario B2, only that scenario shows a decreased GWP-intensity for all the years presented.

Table 3.9: Sensitivity to ore grade and stripping ratio, GWP-intensity, copper production

	GWP-intensity [kg CO_2-eq./kg refined copper]		
Scenario	2020:	2030:	2050:
A1	4.02	4.67	6.28
B1	3.87	4.61	5.42
B2	3.87	4.61	5.38

Table 3.10: Sensitivity to energy mix, GWP-intensity, copper production

	GWP-intensity [kg CO_2-eq./kg refined copper]		
Scenario	2020:	2030:	2050:
A1	4.34	4.27	4.15
B1	4.00	3.55	3.16
B2	4.00	3.55	3.16

Table 3.11: Sensitivity to Recycling Input Rate, GWP-intensity, copper production

	GWP-intensity [kg CO_2-eq./refined copper]		
Scenario	2020:	2030:	2050:
A1	4.35	4.84	4.39
B1	3.81	3.90	3.47
B2	3.72	3.50	3.19

The scenario analyses presented in this section (figure 3.7 and table 3.12) explore alternative futures regarding GWP-intensities [kg CO_2-eq./kg refined copper] of copper production (see section 2.9 for the parameter values utilized).

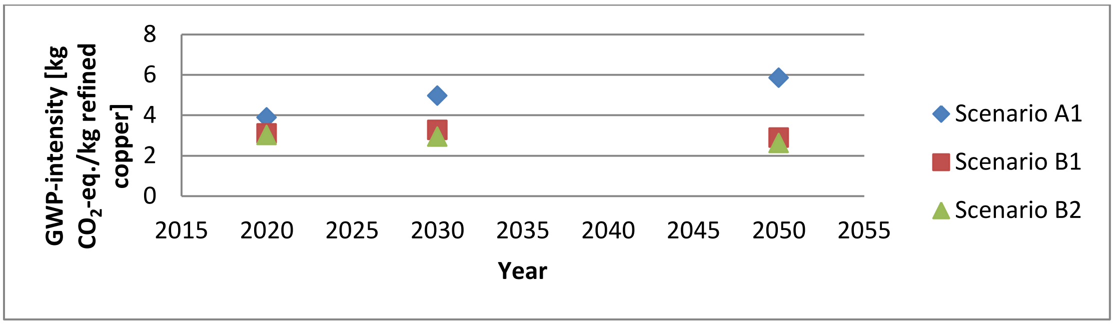


Figure 3.7: GWP-intensity copper production

According to figure 3.7, the GWP-intensity increases in scenario A1 from 2020 till 2050. On the other hand, the GWP-intensity will not deviate by much toward year 2050 in scenario B1 and B2. However, the expected increase of GWP-intensity observed in table 3.9 may be *moderated*, or in some cases (scenario B1 and B2) it might decrease instead of increase. By moderating, it is meant that the increase could be less than table 3.9 shows. Table 3.12 illustrates that in a better way.

Table 3.12: GWP-intensity

	GWP-intensity [kg CO_2-eq./kg refined copper]		
Scenario	2020:	2030:	2050:
A1	3.89	4.96	5.85
B1	3.09	3.26	2.88
B2	3.02	2.93	2.62

3.3.3 GWP from global Copper Production

This section presents the global GWP [MT CO_2-eq] from global *copper production*. It differs from section 3.3.1 and 3.3.2 where only the GWP-*intensity* is considered. The GWP from global copper production is assumed to depend on the factors; ore grade, stripping ratio, energy mix, recycling input rate and *demand*.

“The present” is presented before “the future” by table 3.13. “The future” is presented by the sensitivity and scenario analyses. The scenario analyses are presented both graphically and tabular format. The results` sensitivity to changes in ore grade, stripping ratio, energy mix, RIR and demand are presented in tabular format.

The present

The GWP from global production of present time is presented by a base case result which is conducted by utilizing the assumptions made by the EcoInvent inventory providers (Mischa Classen et al., 2007) and energy mixes of the year 2007 which is provided by the literature (United Nations Environmental Programme, 2014). Recycling input rate is also provided by the literature (Glöser et al., 2013), and is assumed to be 35 % for the base case. Please read section 2.9 for an overview of the parameter values utilized.

Table 3.13: GWP, base case, global copper production

GWP [MT CO_2-eq.]
81

The future

The sensitivity analyses presented in this section investigate how sensitive GWP is to changes in; ore grade and stripping ratio (table 3.14), energy mix (table 3.15), recycling input rate (table 3.16) and demand (table 3.17). The parameter values utilized are provided by the scenario work (see section 2.9 for the parameter values utilized). Ore grade decline and stripping ratio increase and an increase in copper demand will both raise the GWP from global copper production in the future (tables 3.14 and 3.17). On the other hand, greener energy mix will alone shrink GWP from copper production in the future (table 3.15). The results presented in table 3.16 are difficult to interpret since some values increase and some decrease. However, since the recycling input rate is only steadily increasing for scenario B2, only that scenario shows a decreased GWP for all the years presented.

Table 3.14: Sensitivity to ore grade and stripping ratio, GWP, global copper production

	GWP [MT CO_2-eq.]		
Scenario	2020:	2030:	2050:
A1	74	86	110
B1	71	84	99
B2	71	84	98

Table 3.15: Sensitivity to energy mix, GWP, global copper production

	GWP [MT CO_2-eq.]		
Scenario	2020:	2030:	2050:
A1	79	78	76
B1	73	65	58
B2	73	65	58

Table 3.16: Sensitivity to Recycling Input Rate, GWP, copper production

	GWP (MT CO_2-eq.)		
Scenario	2020:	2030:	2050:
A1	80	89	80
B1	70	71	64
B2	69	64	58

Table 3.17: Sensitivity to copper demand, GWP, copper production

	GWP [MT CO_2-eq.]		
Scenario	2020:	2030:	2050:
A1	140	180	210
B1	140	190	290
B2	140	190	290

By multiplying the GWP-intensity for 2050 (ore grade parameter and stripping ratio value as the A1 scenario, table 3.9) with the global copper demand for A1 scenario in 2050, one gets 390 MT CO_2-eq.. This is the case where energy mix and RIR has not changes from “the base case”.

The scenario analyses presented in this section explore alternative futures regarding GWP [MT CO_2-eq.] from copper production (please read section 2.9 for the parameter values utilized).

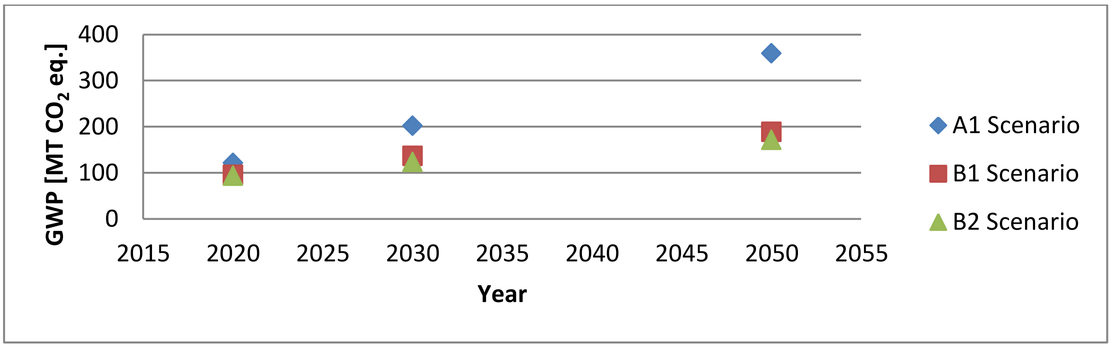


Figure 3.8: GWP from global copper production

Figure 3.8 and table 3.18 illustrate that the GWP is expected to increase in the future even if we recycle more and have greener energy mix. On the other hand, the expected increase of GWP in the future observed in table 3.17 may be moderated. By moderating, it is meant that the increase could be less than table 3.17 shows. Table 3.18 illustrates that in a better way

Table 3.18: GWP, scenario analyses, global copper production

	GWP [MT CO_2-eq.]		
Scenario	2020:	2030:	2050:
A1	120	200	360
B1	100	140	190
B2	90	120	170

3.3.4 Copper Production`s GWP-intensity in six Regions

To achieve a more detailed answer regarding regional differences of research question #2, the GWP-intensities in six regions are presented. Producing copper ore which has the highest ore grade, region by region, is more realistic than assuming that copper ore which has the globally highest ore grade, is mined first at all times.

On the other hand, the regional copper production is assumed to satisfy its own copper demand, which is a market that excludes import and export. Since such a market is fictitious, direct comparison among the regions, without considerations, is not appropriate.

“The present” is presented before “the future” by table 3.19. “The future” is presented by the scenario analyses (tables 3.19-3.25).

The present

The GWP-intensity result of present time is presented by a base case result which is conducted by utilizing the assumptions made by the EcoInvent inventory providers (Mischa Classen et al., 2007) and energy mixes of the year 2007 which is provided by the literature (United Nations Environmental Programme, 2014). The parameter values utilized in the base case are presented in appendix I. The unit is kg CO_2-eq./kg refined copper. The GWP-intensity is highest in Africa, Asia and North America.

Table 3.19: Regional GWP-intensity, base case

	Europe	Africa	Asia	Latin America	North America	Oceania
1 kg copper	2.40	5.71	5.75	3.64	5.72	4.45
1 kg primary copper	3.14	6.39	7.97	4.04	7.92	4.94
1 kg secondary copper	1.33	1.53	1.43	1.12	1.46	1.43

The future

The scenario analyses explore alternative futures regarding GWP-intensities [kg CO_2-eq./kg refined copper] of copper production (please read appendix I for the parameters utilized).

Table 3.20: GWP-intensity, Europe

		Scenario A1	Scenario B1	Scenario B2
2020	1 kg copper	2.38	1.91	1.84
	1 kg primary copper	3.03	2.59	2.59
	1 kg secondary copper	1.24	1.18	1.18
2025	1 kg copper	7.30	2.26	2.03
	1 kg primary copper	11.2	3.48	3.07
	1 kg secondary copper	1.20	1.12	1.12

Table 3.21: GWP-intensity, Africa

		Scenario A1	Scenario B1	Scenario B2
2020	1 kg copper	3.38	2.88	2.73
	1 kg primary copper	4.47	4.25	4.25
	1 kg secondary copper	1.47	1.40	1.40
2025	1 kg copper	3.24	2.64	2.59
	1 kg primary copper	4.39	4.03	4.03
	1 kg secondary copper	1.44	1.33	1.33

Table 3.22: GWP-intensity, Asia

		Scenario A1	Scenario B1	Scenario B2
2020	1 kg copper	4.59	3.44	3.32
	1 kg primary copper	6.43	5.47	5.41
	1 kg secondary copper	1.38	1.26	1.26
2025	1 kg copper	4.45	3.34	3.26
	1 kg primary copper	6.43	5.59	5.59
	1 kg secondary copper	1.36	1.22	1.22

Table 3.23: GWP-intensity, Latin America

		Scenario A1	Scenario B1	Scenario B2
2020	1 kg copper	2.94	2.25	2.13
	1 kg primary copper	3.98	3.40	3.40
	1 kg secondary copper	1.13	1.02	1.02
2025	1 kg copper	2.89	2.10	2.06
	1 kg primary copper	4.02	3.27	3.27
	1 kg secondary copper	1.14	0.99	0.99

Table 3.24: GWP-intensity, North America

		Scenario A1	Scenario B1	Scenario B2
2020	1 kg copper	4.43	3.41	2.66
	1 kg primary copper	6.15	5.42	5.42
	1 kg secondary copper	1.42	1.27	1.27
2025	1 kg copper	5.07	3.03	2.96
	1 kg primary copper	7.42	5.00	5.00
	1 kg secondary copper	1.40	1.18	1.18

Table 3.25: GWP-intensity, Oceania

		Scenario A1	Scenario B1	Scenario B2
2020	1 kg copper	3.22	2.71	2.58
	1 kg primary copper	4.28	4.04	4.04
	1 kg secondary copper	1.36	1.30	1.30
2025	1 kg copper	3.08	2.43	2.39
	1 kg primary copper	4.20	3.73	3.73
	1 kg secondary copper	1.34	1.22	1.22

4. Discussion

The master`s thesis main topic was future copper resource scarcity and environmental problems related to society's increasing demand in copper. The results of section 3 have shown; copper depletion (section 3.1), and electricity- (section 3.2) and GWP-intensities (section 3.3.1, 3.3.2 and 3.3.4) and GWP (section 3.3.3) from global copper production today and in the future. Those results led the author to the research questions. In this section the author address each of the research questions in turn, followed by a discussion regarding the copper cycle in a global context, and limitations of current study and suggestions for future work and studies.

Regarding research question #2, the discussion is divided into several result topics. The structural order of the result topics is the same as presented in the result section (sections 3.2 and 3.3.1-3.3.4). The different result topics are included of same reasons as it was included in section 3. A number of observations regarding each result topic is presented and discussed.

In addition to answer the research questions, possibilities to moderate the expected problems have also been considered.

Regarding the discussion of the results presented in section 3, the scenario modelling error should be taken into consideration. The result for a specific year may be wrong, so the results are discussed mainly regarding the parameter values. The writer has discussed “future” electricity intensity and impact by value and how it will increase/decrease. How large the electricity intensity and emission is in 2020, 2030 and 2050 is only considered illustrating the development in brief, not the actual picture in 2020, 2030 and 2050.

4.1 Research Question #1

Under which scenarios will the existing copper resources be depleted and when?

“State of art”-update

Copper resources are both primary and secondary. Understanding the copper cycle is essential when tackling the issue of potentially limited copper resources. The copper cycle`s only *new* input is primary copper, and its only output is copper waste and losses regarding production and EOL collection and recovery. Globally there are approximately 340 000 MT copper ore available at present, containing approximately 1900 MT copper. The rate of how much primary copper one mines depends on; how large the global copper demand is and how much secondary copper there is available. The rate of secondary copper available depends further on; how large the material flow out of the use phase is and the size of the end-of-life (EOL) collection and recovery rates. The material flow out of use phase depends further on; earlier year`s copper demand and average in-use stock growth (i.e. average over the years the products in the output was a demand). In other words, stock size and lifetime determine scrap availability. On the other hand *net* in-use stock growth is only dependent on the input to the copper cycle, which is primary copper.

Global copper resource limitations

The results presented in section 3 showed that according to scenario A1, the depletion time for copper is 2070. Scenario A1 assumed a high final demand growth, high in-use stock growth and the EOL collection & EOL recovery rate increase was low. The depletion time according to the B1 Scenario was year 2096, and according to the B2 Scenario, a depletion time will occur after year 2100. The B1 and B2 Scenario assume a high final demand growth, a medium in-use stock growth and a high EOL collection & EOL recovery rate increase. Overall, the only variable value difference between B1 and B2 was the in-use stock growth, which was slightly less for the B2 Scenario. In general, this affects the amount of output of the use-phase, which in turn affects the amount of secondary copper available. Due to that, and since the copper demand was the same in scenario B1 and B2, the primary copper demand was larger for the B1 scenario.

According to all three scenarios, copper will not be a limited resource in at least the first 70 years of the 21st century. Those results confirmed earlier studies (Northey et al., 2013, Ayres et al., 2002). Ayres et al. estimated that the copper peak production will occur between 2050 and 2080. Northey et al., on the other hand estimate that there are sufficient identified copper resources available for at least the next twenty years. On the other hand, this is to some point in contrary to a recent published article written by (Kerr, 2014). According to a new model which considers projected copper production peaks, copper production will peak between 2030 and 2040. It is mainly explained by that it takes a lot of copper to satisfy exponentially growing demand (Kerr, 2014). However, the considered scenarios in *this* work assume relatively high EOL recycling rates (76 % in 2050). Achieving an upward copper production as long as possible *do* require medium in-use stock growth and a high EOL recycling rate increase compared to today. Increasing the EOL recycling rate is only possible if everyone do an effort by avoiding losses from use and waste handling. This is only achievable if the society facilitates collection of copper containing products and improves waste handling processes with the goal of limiting the copper losses.

Regional differences

This study has also considered six regional depletion times. The results presented in section 3 have shown that those regions having relatively large copper reserves compared to annual copper demand, experience copper depletion later than those regions that do not. This was expected. Latin America, Asia and North America have reserves which respectively correspond to 50 %, 20 % and 10 % (Mudd et al., 2012) of the total global reserves. Their copper demand compared to the global demand is respectively 3 %, 60 % and 10 % (International Copper Study Group, 2013). As the results showed; Latin America experience copper depletion later than year 2100, Asia between 2035 and 2040, and North America between 1964 and 1979. According to (Northey et al., 2013) the copper production will peak in China, Democratic Republic of Congo, Peru, Chile and Spain between the year 2040 and 2050. On the other hand, the copper production will peak in Australia, Canada and USA between the year 2050 and 2100. The differences to this master thesis` result are probably a result of excluding import and export. For example Latin America produces more than its own copper demand.

The region comparison was somewhat unfair because those regions which already have a large in-use stock have a great benefit. Other regions will have a large in-use stock growth in the next decades. A larger in-use stock growth may directly mean a smaller copper output value from use, and indirectly a smaller amount of secondary copper available. If the demand is constant, and if we assume the amount of secondary copper available equals the material flow of secondary copper to use - a greater amount of secondary copper available will indirectly cause a lower amount of primary copper resources mined annually. Regions such as Asia and Africa do not have the benefit of a huge in-use stock. Their in-use stock growth is expected to be huge in the next decades.

Other options for extending the copper depletion time

The copper resources are limited, therefore it is important to improve and optimize its utilization. Copper losses regarding the production chain, and waste and recycling should be avoided. On the other hand, the copper demand is expected to increase. However, something should be done about the way we are living – the use and throw society belongs to yesterday. Increasing the responsibility of the consumers and businesses could be an excellent initiative to moderate the annually increase of copper demand. This may be done by shifting the perspective of emission studies *from* producer perspective *to* consumer perspective, or through an attitude campaign.

Despite earlier studies indicating limited copper resources, large amounts of deep sea copper reserves have lately been discovered (Avner, 2014). If it turns out to be technological possible and economically feasible, there are huge possibilities to extend copper depletion considerably.

Central conclusion to research question: Regarding the 21st century, copper resources will be depleted under scenarios A1 (year 2070) and B1 (year 2096). A1 assumes high final demand growth, high in-use stock growth and the EOL collection & EOL recovery rate increase is low. The B1 and B2 Scenario assume a high final demand growth, a medium in-use stock growth and a high EOL collection & EOL recovery rate increase. Overall, the only variable value difference between B1 and B2 is the in-use stock growth, which is slightly less for the B2 Scenario.

4.2 Research Question #2

How does electricity intensity and GWP of copper production change throughout the first halve of the 21st century as the copper ore grade declines?

“State of art”-update
Compared to other LCA studies which have investigated energy and global warming potential from copper production, this study has considered a few dynamic, with respect to year, parameters. Recently published studies have discussed the importance of declining ore grade on energy demand and greenhouse gas emissions (Northey et al., 2013, Harmsen et al., 2013, Norgate and Jahanshahi, 2011). Discussions on the direct effects of declining ore grade such as increased material demand and material handling has also been a hot topic in those studies. The effects emphasized in those studies were electricity demand, diesel demand, explosive demand and overburden/tailings handling. Those were emphasized in this master`s thesis as well. In addition to dynamic inventory, this study also considered actual scrap generated at an annual basis, a dynamic energy mix, copper recycling input rate (dependent of in-use stock growth, lifetime increase and EOL collection and recovery rate increase) and copper demand.

Result topic # 1: Direct electricity intensity for the pyro metallurgical process route:
An energy intensity equation (equation 2.1) from the literature was utilized to achieve the results for direct electricity intensity. This equation`s only unknown was ore grade. Suggestions to include other factors are presented in section 4.4. However, the ore grade values modelled in this study was based on copper ore resource data and annual primary copper demand modelled for the scenarios.

Observation #1: The mining and beneficiation electricity intensity was estimated to increase from 4.3 (i.e. ore grade 0.99) to 7.1 kWh/kg refined copper if the ore grade declined to 0.41 (i.e. year 2050).

The estimated electricity intensity when the ore grade was 0.41 (i.e. year 2050) was 7.1 kWh/ kg refined copper, compared to 4.3 kWh/kg refined copper when the ore grade was 0.99 (figure 2.3). This is an increase of 66 %. Mining and beneficiating copper ore with lower ore grade required more electricity by amount. This was presented in section 1. However, (Harmsen et al., 2013) estimated the increase in 2050 compared to today to be 200-700 %. Harmsen et al. included both the energy demand in the foreground *and* background system (i.e. including energy requirement for the production and transport of materials and infrastructure needed in the different copper processing steps). However, the ore grade values modelled in their work was not presented. On the other hand, the ore grade values in our process model were modelled based on a higher EOL collection and recovery rate than Harmsen et al. assumed was realistic (70 %).

Observation #2: The change in electricity intensity is not proportional to the change in ore grade

The electricity-ore grade relation is not linear. The lower the ore grade values were at decline-start and decline-end, the larger the electricity increase was. For example when the ore grade declined from 1.72 to

0.87 the electricity intensity increased by 48 %. When the ore grade declined from 0.87 to 0.54 (which was almost 1/3 of the decline from 1.72 to 0.87) the electricity increased by 31 %. A decline of the ore grade of 0.1 had larger consequences regarding electricity demand when the ore grade at decline-start was low, than a decline of the ore grade of 0.1 when the ore grade at the decline-start was high. At some point, mining ore which contains less and less copper is not economically feasible regarding the electricity increase.

Observation #3: The ore grade decline affected the electricity intensity increase of the beneficiation process the most

This observation was slightly on the side of the research question, but was presented nevertheless since it was interesting to discuss why the overall electricity demand increased. The observation in seen in figures 3.2 and 3.3, and table 3.1 and 3.2 as a whole. However, the observation was based on studying ore grade values between 0.41 and 1.72. The increase of electricity intensity of beneficiation was only compared to the electricity increase of mining, since those processes were the only ones assumed to be affected by a decline of the ore grade. The results of section 3 showed that electricity demand of mining, where the ore grade was 0.99, was 0.8 kWh/ kg Cu in the output of mining. On the other hand, the result for beneficiation was 3.9 kWh/ kg Cu in the beneficiation output. When the ore grade was 0.54, the electricity demand of mining was 1.2 kWh/ kg Cu in the mining output, while it was 5.8 kWh/ kg Cu in the beneficiation process. The ore grade decline affected the electricity intensity of the beneficiation process to increase the most by the real value.

However, the observation may have been a consequence of assuming that the share of mining electricity compared to mining- and beneficiation electricity was only 15 %. On the other hand, the observation confirmed existing literature presented in the literature study in section 1 regarding that the demand in beneficiation *is* affected the most by a decline of the ore grade. Declining ore grade affected an increase of the amount crushed and grinded, which are the sub processes of beneficiation, per kg Cu in the output. The input into mining is on the other hand “deposit rock” containing ore and overburden rock. The electricity demand of mining depended in other words *more* on the amount of rock in the input per kg Cu in the output (i.e. which is somehow related to the overburden to ore stripping ratio), than the ore grade.

Regarding electricity demand of beneficiation, the electricity efficiency of crushing and grinding has been reported to be as low as 1 % (Norgate and Haque, 2010). This indicates huge potentials to optimize the electricity efficiency. On the other hand, the electricity efficiency depends on the upstream processes, and the technology of those processes. The coarser the ore input to beneficiation is the less is the electricity efficiency.

Validation of the result

The electricity demand of mining and beneficiating copper ore per kg Cu in the output mass of beneficiation was in this study 4.3 kWh. To get that result, Northey et al.`s energy equation was utilized with an ore grade equal to 0.99. Comparing the electricity intensity presented in the inventory Norgate and Haque utilized in their work with energy and GWP of mining and processing (Norgate and Haque, 2010) showed small differences. Their result was 4.6 kWh/kg Cu in the output mass of beneficiation, which was a difference of 7 % compared to this study`s result. On the other hand, electricity should also depend on the percent of Cu in the deposit, which affects the amount of overburden out of mining. However, the electricity demand of ventilation and dewatering (i.e. which is the only electricity demanding processes in mining) is negligible compared to crushing and grinding (Norgate and Haque, 2010). The mining processes loading and hauling demands diesel as energy source not electricity (Norgate and Haque, 2010).

Result topic #2: Primary copper production`s GWP-intensity

Observation #1: When the ore grade declined from 1.72/1.47 (two scenario ore grade values for 2020) to 0.54/0.41(two scenario ore grade values for 2050), the primary production GWP-intensity increased from 5.2/5.4 to 7.6/8.9 kg CO_2-eq./kg refined copper, *which was an increase of 46/65 %.*

The observation is seen in table 3.5. If we only considered a decline of the ore grade, GWP-intensity was expected to increase with 46/71 % (two different scenarios) from 2020 to 2050. However, the difference between 46 % and 65 % was significant. Regarding the increase of 46 %, the decline of the ore grade was from 1.72 to 0.54. The increase of 65 % was on the other hand a result of a decline of the ore grade from 1.47 to 0.41. The differences in GWP-intensity increase is further discussed in observation #2.

There are on the other hand possibilities to moderate the expected increase of the GWP-intensity of primary copper production, or in some cases have an overall lower GWP-intensity (compared to the base case and 2020 values). This observation is seen in figure 3.6 and table 3.7. The GWP-intensity could be 5.1/8.3 instead of 7.6/8.9 kg CO_2-eq./kg refined copper. The moderating is possible by investing in greener energy on the electricity grid. However, the size of moderation varies by degree for the different scenarios. The largest moderation is anyway remarkably high. However, there are doubts if the moderation is realistic. Regarding the scenario results for 2050, the GWP-intensity difference between two scenarios was almost 100 %, even though the ore grade difference was relatively small. The difference was quite remarkable. Observation 3 and section 4.3 presents and discusses the change in energy mix further. Result topic #3 also discusses investment in renewable resources to some extent.

However, the estimated GWP-intensity at tops (scenario parameters for 2050) was 8.3 kg CO_2-eq./ kg Cu. Comparing the GWP-intensity to the base case resulted in an increase of 38 % (i.e ore grade = 0.41). Compared to the increase of electricity intensity of 66 %, the GWP-intensity was less affected by the ore grade decrease. The GWP-intensity was in addition to ore grade, dependent on overburden to ore stripping ratio and energy mix. This probably effected the less increase compared to electricity-intensity. Figure 3.5 also illustrated that this study`s GWP-intensity estimations for mining and beneficiation was higher than what the GWP-intensity equation for mining and beneficiation indicated. The lower the ore grade was, the larger the deviation was between this study`s results and the GWP-intensity equation provided by Northey et al.. However, the correlation factor of the equation was 0.28. The correlation between the intensity and ore grade of the equation was extremely small. This means that the deviation of a researcher`s estimated GWP-intensity to the GWP-intensity equation might as well vary between low or extremely high.

Observation #2: The change in GWP intensity is not proportional to the change in ore grade

The observation is seen in figure 3.4. The GWP-intensity - ore grade relation is not linear. When the decline of the ore grade was from 1.72 to 0.87 (i.e. the decrease was equal to 0.85) and stripping ratio increase from 1.88 to 2.05 (i.e. the increase was equal to 0.17), the GWP-intensity increased from 5.17 to 6.40 kg CO_2-eq./ kg Cu (i.e. the decrease was equal to 1.23). However, a decline of the ore grade from 0.87 to 0.54 (i.e. the decrease was equal to 0.33) and stripping ratio increase from 2.05 to 2.50 (i.e. the increase was equal to 0.45, will affect the GWP-intensity to increase from 6.30 to 7.55 kg CO_2-eq./ kg refined copper (i.e. the decrease was equal to 1.25). A decline of the ore grade of e.g. 0.1 had larger consequences regarding GWP-intensity when the ore grade at decline-start was low, than a decline of the ore grade of e.g. 0.1 when the ore grade at the decline-start was high. This confirmed existing literature presented in the literature study in section 1. However, at some point, mining ore containing less and less copper is not economically feasible regarding the GWP-intensity increase.

Observation #3: Declined ore grade and increased stripping ratio may increase the GWP-intensity of primary copper in the future, while greener energy mix may decrease the GWP-intensity of primary production in the future.

The observation is seen in table 3.5 and 3.6. It was observed by the sensitivity analyses that declining ore grade and increasing the stripping ratio will influence a relative increase of primary copper production`s GWP-intensity. A decline of the ore grade of 49 % (from 1.72 to 0.87) and stripping ratio increase from 1.86 to 2.05 gave an increase of the GWP-intensity by 22 %. On the other hand, a less GWP-intensive energy mix will alone influence a relative decrease. A reduction of coal based energy generation (from 31 % to 23 %) and an increase of wind, ocean, geothermal, solar and biomass based energy generation (from 14 % to 23 %) gave a decrease of 12 % of the primary GWP-intensity. Even though decline of the ore grade is expected, the results showed that there are possibilities to moderate the expected increase of GWP-intensity from primary copper production, by focusing on greener energy. The difference in the size of moderation was due to that scenario A1 assumed “business as usual”-energy mix change, while the B scenarios assumed energy mix change was based on a blue map scenario aiming to decrease the society`s annually GWP.

Observation #4: According to the structural path analysis and Tailor expansion series when the ore grade was 0.54, beneficiation electricity demand contributes approximately 35% to GWP from primary production. This is an increase from approximately 25 % (i.e. when the ore grade was 0.99).

Electricity generated from hard coal (i.e. two different global locations), natural gas and oil, for the beneficiation process, contributed the most to GWP-intensity of primary copper production. Approximately 35 % of the total impact was due to those (i.e. when the ore grade was 0.54). This confirmed existing literature presented in the literature study in section 1. However, those 35 % was when the ore grade was very low. The percent was lower for a higher ore grade. This was explained in observation 2 and 3 for result topic #1, research question #2. As mentioned, there are huge potentials to increase the electricity efficiency of crushing and grinding, which contributes the most to beneficiation electricity demand. Secondly, electricity efficiency will affect the GWP-intensity of primary production.

On the other hand, heavy fuel oil (reduction, pyro metallurgical process route), natural gas burned in industrial furnace (refining, pyro metallurgical process route) and diesel, burned in building machine (mining, hydrometallurgical process route) contribute respectively 5.4 %, 2.1 % and 1.6 % (i.e. when ore grade was 0.54).

Refining electricity (electrolysis and electro winning) demand contributes only approximately 1-1.1 % (ore grade numbers between 0.99 and 0.54). This is somewhat surprising. Underestimations of demand in electro winning electricity may have caused the low percent contribution. Current work assume an electro winning electricity demand of 0.49 kWh/kg copper (Mischa Classen et al., 2007). (Cifuentes et al., 2006) presents results for electro winning between 0.94 and 1.39kWh/kg copper. Electrolysis electricity demand assumed in this work do on the other hand not vary much from other`s calculations (0.29 kWh/kg (Mischa Classen et al., 2007) versus 0.22 kWh/kg (Educypedia)).

Validation of the results by comparing them to other studies

Where the ore grade was modelled to 3.0, the GWP-intensity of primary copper was 4.6 kg CO_2-eq./kg refined copper. Australia`s CRIRO (The Commonwealth Scientific and Industrial Research Organization) has carried out studies on GWP-intensity of primary copper (Norgate et al., 2007). For an ore grade (% Cu) of 3, the GWP-intensity of producing 1 kg of copper was estimated to be 3.3 kg CO2-eq. The inventory utilized to generate those results included less by number than this study`s inventory, but approximately the same amount of direct electricity demand per kg Cu. However, by utilizing Northey and Haque`s modeled equation, which represented the GWP-intensity of mining and beneficiation, the result was quite interesting. The equation was based on sustainability reporting of actual copper production sites. With an ore grade of 3 %, the GWP-intensity was 0.8 CO2-eq..The result included only mining and beneficiation. However, the correlation coefficient of the GWP-intensity equation was 0.28 ((i.e. the correlation between the intensity and ore grade) (Northey et al., 2012). When the correlation coefficient between an input and an output is low, the uncertainty of the result (which depends on the input) is high. Since the equation is based on production sites, large technological and stressor differences among the sites may explain the low correlation coefficient.

Result topic #3: Copper production`s GWP-intensity

Copper production consists of primary *and* secondary production. GWP-intensity depends on e.g. ore grade, energy mix and recycling input rate. This work considered scenario A1, B1 and B2, but discussed the results in relation to the scenario and sensitivity parameter values generated by the scenario work (as the discussion introduction explains).

Observation #1: We could expect an increase of the GWP-intensity from 3.9/4.0 kg CO_2-eq./*kg Cu (A1 and B1 scenario ore grade parameter values for 2020) to 5.4/6.3 (A1 and B1 scenario ore grade parameter values for 2050). However, the GWP-intensity may decrease or the increase may be moderated to 2.9/5.9 kg* CO_2-eq./*kg Cu if the energy mix was greener and recycling input rate increased.*

The observation was seen in table 3.9, figures 3.7 and table 3.12. With an ore grade of 1.72 and stripping ratio of 1.86 the GWP-intensity of copper production was estimated to be 3.9 kg CO_2-eq./kg Cu. An ore grade of 0.87 and stripping ratio of 2.05 resulted in a GWP-intensity of 4.6 kg CO_2-eq. This means that a decline of the ore grade from 1.72 to 0.87 (49 %) and increase of the stripping ratio from 1.86 to 2.05 (10 %) generates an increase of the GWP-intensity of 19 %.

However, the GWP-intensity *may* decrease in the future (The B Scenarios) or the increase *may* be moderated (The A1 scenario) to 2.9/5.9 kg CO_2-eq./kg Cu *if* the energy mix *is* greener and recycling input rate *will* increase (caused by medium in-use stock growth, high lifetime increase and high EOL collection and recovery rate increase). A change in energy mix alone (i.e. coal based energy from 23 % to 13 % and an increase of wind, ocean, geothermal, solar and biomass based energy generation from 23 % to 34 %) will give a decrease of 11 % of the GWP-intensity. An increase of the recycling input rate from 35 % to 46 % will result in a decrease of 12 % of the GWP-intensity. Firstly, an overall decrease of GWP-intensity in the future is remarkably and somehow unexpected. The decrease is due the superposition effect of greener energy mix *and* higher recycling input rates. Greener energy mix is already discussed by earlier observation. Recycling input rates over 50-60 % in the future is, on the other hand, dramatic and remarkably. If it is actually technological possible and realistic is discussed in section 4.4.

On the other hand, the difference among the GWP-intensities in 2050 was remarkably (table 3.12). The difference was due to the large difference in energy mix and RIR in 2050 for the scenarios. Again, the superposition effect was conspicuous.

However, we cannot escape the problem of declining ore grade. Regarding the inventory, direct electricity demand was pointed out by literature as one of the main contributors to GWP-intensity. This was also discovered in observation #4 regarding primary copper GWP-intensity. However, new and emerging technologies providing a more energy effective grinding process of the copper ore *is* expected to provide a less GWP-intensive primary copper production (Northey et al., 2013).

Finding good solutions to moderate the expected increase of GWP-intensity, other than looking at the production processes itself, is not straightforward. We could moderate the increase by utilizing a greener energy mix and improving the RIR by improving the EOL-collection and recovery rate and avoid a huge in-use stock growth, and moderating the copper demand. On the other hand, a greener energy mix will indirectly affect the RIR and copper demand. Regarding the energy mix and copper demand, if the society invests in e.g. wind mills, which are a renewable energy resource, and are overall more copper intensive than conventional energy resources, the copper demand growth is expected to be larger. If the investments in renewable energy resources increase and if the copper demand should increase only moderately - the final demand growth considering other consumer groups should to be moderate. Regarding the RIR, improving the EOL collection and recovery rates could be done by optimizing the design for collection and recovery. On the other hand, the in-use stock growth of the electrical use-group is also expected to increase partly as a result of investments in renewable energy resources. The in-use stock growth will moderate the copper output of the use-phase. This might affect the secondary copper available and in turn, the RIR. If the RIR is low, the higher is the GWP-intensity – relatively speaking.

Result topic #4: The GWP from global copper production
Observation #1: The GWP from global copper production could increase up to 390 MT CO_2-eq. *(with demand, ore grade and stripping ratio parameters values for 2050) from 80 MT at present, but the increase could be moderated by the right actions down to 170 MT* CO_2-eq.

The observation was seen in table 3.13, by multiplying the highest GWP-intensity for 2050 (A1 scenario) with the A1 scenario`s demand value for 2050, figure 3.8 and table 3.18, all as a whole. The GWP from copper production depends in addition to GWP, on GWP-intensity (which depends on ore grade, energy mix and RIR). The sensitivity analyses showed that the increased demand and decline of ore grade affects an increase of total GWP from copper production. However, the increased copper demand affected more than what the decline of ore grade did. This was because the demand increase was considerably (i.e. approximately 250 % for all scenarios). Greener energy mix and increased RIR will on the other hand both alone decrease the GWP. Overall, greener energy mix and increased RIR (caused by medium in-use stock growth, high lifetime increase and high EOL collection and recovery rate increase) could moderate an expected GWP increase of 290 MT CO_2-eq. (demand sensitivity parameter values for 2050) or 390 MT CO_2-eq.(demand, ore grade and stripping ratio sensitivity parameter values for 2050). The rate of *moderation* could be in the order of magnitude 100-120/200-220 MT CO_2-eq. (less than 290/390 MT CO_2-eq.). Extended producer- and consumer responsibility aiming to decrease the copper demand is essential to decrease the GWP from global copper production. On the other hand, since the GWP-intensity vary that much due to different RIRs and energy mixes, actions aiming to increase the recycling efficiency and making the energy mix less GWP-intensive will be equally effective. Regarding the scenario results, changing the annual generated GWP in the future (2050) from potentially 390 MT CO_2-eq. to 170 MT CO_2-eq. by mainly greener energy mix and increased recycling input rate is remarkable, and to some extent unrealistic as discussed earlier.

Result topic #5: Copper production`s GWP-intensity among six regions producing copper for their own regional market
The ore grade difference among the regions is not discussed. The ore grade values are based on the scenario modelling which had errors and in addition excludes import and export among the regions. The observations will only confirm or weaken observations related to the global study, and the discussion will be more of a general kind. The observations was seen in tables 3.19-3.25.

Observation #1: The difference between some of the energy mixes, from 22 % hydropower in Africa to 62 % in Latin America for example, was one of main contributors to cause a difference in the GWP-intensity of 36 %.

Regional differences in primary GWP-intensity are expected due to regional differences in ore grades and stripping ratios, energy mixes, RIR and process inventory (including emission factors). On the other hand, regional differences among the secondary GWP-intensities is caused by the different regional energy mixes modelled since the secondary copper inventory is the same among the regions.

The difference in the GWP-intensity caused by differences in the energy mix might best be seen by the difference in the GWP-intensity for secondary copper where the energy mix is the only factor causing it. Comparing the results to the base case - the difference is largest (36 %) between Latin America and Africa. While Africa was assumed to have 17 % coal based energy, and 22 % hydropower based energy, Latin America was assumed to have 3 % coal based energy and 62 % hydropower based energy.

The effect of the energy mix used among the regions on the different GWP-intensities was also clearly observed when comparing copper production`s GWP-intensity for Latin America and North America. The difference in ore grade between the regions was modeled to be below 1 %. While the energy mix modelled for copper production in Latin America composed of between 53 and 68 % hydropower between 2020 and 2050 and among the scenarios - the percent is modelled to be between 13 and 14% in North America. The GWP-intensities for copper production in North America was ranging from 71 % to 129 % higher than in Latin America.

However, discussing the differences among the regional GWP-intensities makes little sense when the ore grade decline is caused by the regional copper demand, and not the global. Regions having huge copper demand, but few ore resources experience an overestimation of the ore grade decline. Opposite, regions having low copper demand, but large ore resources will experience an underestimation of the ore grade decline.

Observation #2: The effect caused by a decline of the ore grade from for example 1.08 to 0.85 *had potentials to be reduced to only an increase of 3.3 % by for example increasing the share of* energy from renewable resources from 47 % to 53 %.

Even though a decline of the ore grade is large, a greener energy could moderate the GWP-intensity increase. E.g. Asia, where the ore grade decline in one scenario was modelled to be 0.23 (from 1.08 to 0.85), the primary GWP-intensity increase was only 3.3 % In this scenario, the percent of energy from renewable resources had increased (from 47 % to 53 %), while the coal, gas and oil based energy had decreased (from 52 % to 48 %). The GWP-intensity of copper production may on the other hand decrease (by 2 %) from 2020 to 2025 in Asia due to the superposition effect of greener energy and higher recycling input rate.

Central conclusion to research question: Electricity intensity is expected to increase from 4.3 (i.e. ore grade 0.99) up to 7.1 kWh/kg refined copper (if ore grade = 0.41 in year 2050). GWP is expected to increase from 80 MT CO_2-eq. up to 360 MT CO_2-eq. due to an expected increase of GWP pr kg and an expected increase of the global demand. The GWP per kg primary copper is expected to increase up to 8.9 kg CO_2-eq. (i.e. ore grade = 0.41 and stripping ratio 3.6) from 5.4 kg CO_2-eq. (i.e. ore grade = 1.47 and stripping ratio 2.0). However, it could be moderated by increased renewable energy share in the energy mix. An expected increase to 7.6 (i.e. ore grade =0.54 and stripping ratio 2.5) or 8.9 kg CO_2-eq. (i.e. ore grade = 0.41 and stripping ratio 3.6) from respectively 5.2 (i.e. ore grade = 1.72 and stripping ratio 1.9) and

5.4 (i.e. ore grade = 1.47 and stripping ratio 2.0) could decrease or the increase may be moderated to respectively 5.1 (rate of greener energy mix = high) and 8.3 (rate of greener energy mix = low) kg CO_2-eq..

By investigating the GWP per kg copper it is possible to better see how the GWP will change. It is now possible to see the effects of increased recycling input rate as well. An increase of the GWP-intensity from 3.9/4.0 kg CO_2-eq./kg Cu (scenario parameters for 2020) to 5.4/6.3 (scenario parameters for 2050) is expected. However, the GWP-intensity may decrease or the increase may be moderated to 2.9/5.9 kg CO_2-eq./kg Cu if the energy mix becomes greener and recycling input rate increases (caused by medium in-use stock growth, high lifetime increase and high EOL collection and recovery rate increase).

At last, by investigating the global GWP it is possible to give the direct answer to the research question. The GWP from global copper production could increase up to 390 MT CO_2-eq. (with demand, ore grade and stripping ratio parameter values for 2050) from 80 MT at present, but the increase could be moderated by the right actions down to 170 MT CO_2-eq. The right actions are a high increase of renewable energy share in the energy mix, a medium in-use stock growth, high lifetime increase and high EOL collection and recovery rate.

4.3 The Copper Cycle in a Global Context

Two of modern society`s biggest issues are satisfying its demand today and into the future, in addition to an annual increase of induced global warming potential.

“State of art”-update

The modern society`s copper demand cannot be served by secondary copper only. Primary copper production is necessary. However, declining ore grade is expected in the future (Norgate and Jahanshahi, 2011, Northey et al., 2013). Due to that, a higher copper production GWP-intensity is expected. The ore grade decline is only dependent on the amount of primary copper produced annually (and future copper ore discoveries). Investigating the anthropogenic copper cycle towards 2050, we might see how the GWP-intensity of primary copper production will change. If the amount of primary copper produced annually is high, the ore grade decline will be larger compared to whether the amount of primary copper produced annually is low. On the other hand, secondary copper available may affect the increase of copper production`s GWP-intensity – which is also of importance.

Challenges

Globally we have a goal to reduce the annually generated GWP. This study has observed that the GWP-intensity of copper production and annually generated GWP caused by the copper industry is expected to increase. That increase should be compensated someplace else if our goal should be reached. A solution might be to use copper “more wisely”- like an investment. Trying to reduce the generated GWP caused by other industries, i.e. the electricity industry might be an excellent place to start. A reduction in generated GWP caused by the electricity industry is solved by investing in low-carbon electrical supply (for example wind power). On the other hand, wind power have environmental implications (Arvesen and Hertwich, 2011). It also demands a great amount of resources (e.g. copper) per kWh produced (Hertwich et al., 2014). Copper demand is typically four to six times higher for renewable energy (RE) sources than for fossil fuels or nuclear (BBF Associates and Ph.D. Konrad J.A. Kundig, 2011). If we should invest in *less* emission intensive electricity in the future, increased RIR is necessary to extent copper depletion time. However, investigating the future RIR towards 2050, we might see how the GWP-intensity will change towards 2050. Understanding how the RIR could be increased is essential to decrease the GWP-intensity. Stabilizing the in-use stock, increasing the EOL-collection and recovery rate and moderating the copper demand could together increase the factor. However, if the demand is incredibly high, a high RIR will not help moderating the amount of primary copper mined, the decline of ore grade, and secondly the GWP-intensity of primary production. On the other hand, a green energy mix might moderate the increase of GWP-intensity, but it will not *solve* the problem of declining ore grade and increasing GWP-intensity of primary production.

Satisfying societal demand for a material which has a high thermal and electrical conductivity, also in the future, might be solved by finding substitutions for copper (e.g. aluminum). The resistance of aluminum is higher, but aluminum has its benefits in weight and price. In products where a lower resistance has remarkable drawbacks (e.g. wiring regarding electricity transportation from energy generation plants) a substitution should be avoided. The energy amount annually delivered to the market will be less, and the amount CO2-eq. emitted per kWh electricity transported to the consumer will increase.

The fact that copper will be more CO_2-intensive, and emissions will rise, contrarily to what is needed to curb global warming are very political relevant. A sectorial target for copper should account for the rise. New updated information and interesting observations regarding the environmental aspect of the copper industry are constantly published. Feeding policy makers with the most recent research, and introducing them to precautionary actions to avoid future issues – would probably change the way policy makers think regarding the copper cycle, copper production and how we use it today. For example emission trading where the emissions are addressed to the consumer instead of the producer might change the way policy makers think. This might be crucial to reach Society`s global goal of reducing annual GWP.

4.4 Limitations of Current Study and Suggestions for Future Studies

An updated study on copper resource limitations and some of the environmental impacts from future copper production was conducted by current study. Updated and multitudinous literature is essential to make the best appropriated policies regarding the anthropogenic copper cycle. The knowledge gap discussed in section 1 was not entirely filled, but the gap was tightened. The research question; *Under which scenarios will the existing copper resources be depleted and when* was answered as best as possible. However, since the scenario modelling contained errors, the answer of the question was based on a possibly wrong groundwork. Research question #2; *How does electricity intensity and GWP of copper production change throughout the first halve of the 21st century as the copper ore grade declines*, was answered as best as possible. However, like in research question #1, since the scenario modelling contains errors, the answer of question #2 is also based on a possibly wrong groundwork. Answers for certain years could not be conducted by this work. However, how electricity intensity and global warming potential change, due to a number of factors, were investigated closely. This is overall achieved by first discussing the future impact by number, the future impact increase, and why it will increase, or in some cases decrease. Although the question could have been answered better regarding the regional differences. This could have been conducted for example by factor sensitivity on GWP-intensity and GWP. In addition, if there were different electricity equations for the regions available, the regional results could also be more accurate. However, there were none accidental discoveries which could be applied elsewhere.

Discussion regarding other limitations of current study and suggestions for future studies follows. It is divided into the subsections process model and method. The method subsection does also discuss the scenario parameters generated by this study.

4.4.1 Process Model

This master`s thesis`s process model has the potential to be improved for further work. The model could be optimized to reflect the true and real state of art in a better way.

This master`s thesis` global study was a "*best* case" study where the copper having the largest ore grade was assumed to be mined first. This is not the true and real state of art, and probably will never be it. The

GWP-intensity of global copper production would probably in fact be higher than this study has presented. Based on our study, a research including last years trends and statistics, would have given me results which would have been more likely.

Regarding the inventory, there are possibilities to improve the data. The inventory data utilized in a work by Norgate and Haque (Norgate and Haque, 2010) were derived from a number of published sources for copper ore, supplemented by data collected by them self. By comparing the inventory of current work with their inventory, differences are discovered. For example, copper ore per copper concentrate is twice the amount compared to Norgate and Haque`s inventory, and overburden, tailings and explosives in current study are approximately triple the amount. On the other hand, diesel demand is hundred times less in current study compared to Norgate and Haque`s inventory. In general, by proving global averages based on a larger amount of copper production sites might decrease the large differences among copper production inventories utilized in LCAs.

A possible improvement for further work is to generate more accurate amounts of ore available annually in the future. One way of obtaining that is by including an annual detection of ore resources based on research and earlier discovery statistics. In addition, including an annual realistic change in final demand share among the regions might also improve the regional models. This would provide more realistic results towards 2025.

The process model could be utilized for further work regarding total GWP emitted by the modern society, modelling scenarios where some of the copper is substituted with aluminum. Studying how much the savings related to “primary copper produced” and “ore grade decline” pays off compared to the extra costs related to electricity losses, might be of interest for further work.

Investigating the change of the GWP-intensity of producing 1 kg refined copper on the global market, by modelling various geographical distributions is not performed. Import and export among the regions are not considered in this study. In our process model, the ore grade modelled of the ore mined is based on each region`s primary copper demand and ore resources in each region at a certain year. When import and export is not considered when modelling the ore grades, global GWP-intensities based on regional GWP-intensities should be discussed with concern. If import and export is to be included, in addition to the responsibility perspectives (i.e. who to blame, the consumer versus producer) is important if the work should be of any relevance.

4.4.2 Method

Earlier LCA-studies has utilized a constant ore grade or have investigated few ore grades. Energy, material demand and electricity mix has also been constant in the inventory utilized. This study has presented a dynamic LCA-study, with respect to year, exploring future variations of the parameters. However, a dynamic study for the future copper industry has huge uncertainties compared to a LCA-study with known parameters which have relatively small uncertainties. On the other hand, a dynamic study may have a larger relevance to policy makers. A more robust analysis exploring a parameter variation and dependency of the future has better potentials to effect policy makers than static analysis.

A cost-benefit analysis could be conducted in order to investigate whether and where an optimization of the copper cycle could be economical profitable. Such an analysis could focus on copper losses regarding; the reserve base vs. the reserves, the production chain, and waste and recycle. It could also investigate if it is energy and economical beneficial to increase the efficiency of the upstream processes proving an increase of the energy efficiency of crushing and grinding could also be conducted.

Other factors which affect the energy (i.e. electricity and diesel) increase, such as deposit depth and liberation size could provide more accurate estimates for the future. This might be an idea for future studies.

Regarding the inventory, the electricity demand percent distribution between mining and beneficiation is assumed to be equal to the percent distribution the EcoInvent providers (Mischa Classen et al., 2007) assumes. However, Norgate and Haque`s (Norgate and Haque, 2010) LCA study energy result presented quite different numbers. While the EcoInvent assumes a mining- beneficiation electricity percent distribution is 0.15-0.85, Norgate and Haque`s result was a mining-beneficiation energy percent distribution of 0.34-0.66. On the other hand, the largest mining energy demand contributor, loading and haulage (25 %), is powered by diesel which is regarded as an own input in this process model`s inventory.

In the base case the diesel demand per kg Cu in mining output for the hydrometallurgical process mining is remarkably 100 times higher than the diesel demand per kg Cu output for the pyro metallurgical process mining. The difference cannot be due to the ore grade as those are both equal to 0.99 in the base case. Diesel is burned in construction machines in the mining process. Hydrometallurgical mining is identical to pyro metallurgical copper mine operation (Mischa Classen et al., 2007), so the only possible explanation has to be the that the power efficiency in the building machines is extremely less than for the pyro metallurgical mining building machines. The mineral structure of oxide ore is in fact different from the mineral structure of sulphide ore.

There are also huge uncertainties considering different requirements and emissions due to the fact that current databases obtain information from old and few facilities. A more detailed and accurate inventory regarding lower uncertainty would make the LCA results even more robust.

Further studies, emphasizing e.g. local environment, labor or providing most income to the developing areas in the world, would provide more colored results.

Regarding the scenario work, it is based on earlier scenario studies presented in literature. The scenario studies consist of future copper demand and annual in-use stock data. Annual regional copper demand, regional and global recycling input rate, and regional and global ore grades are generated by this study and the scenario work. To achieve those generated parameters, a number of general assumptions were made. Those assumptions are not ideal, but the best guess based on literature and own judgments. The scenario model method of this study has the potential to be improved for further work. The following bullet points discuss that.

- The copper flow output from the use-phase is calculated based on the copper demand the same year. In hindsight after the scenario modelling took place, it was understood that this is not the correct way to calculate the copper material outflow. The copper flow depends, in fact, on the amount of copper that was put into use 30 years ago (Harmsen et al., 2013), and is now discarded, and average in-use stock growth (i.e. average over the years the products in the output was a demand). This has definitely resulted into an overestimation of the recycling input rates. Anyway, a future study including this important aspect is essential to improve the validity of the results.
- On the other hand, this study has assumed a global scrap pool since scenario work (i.e. regarding copper demand and in-use stock) available from literature has divided the world copper demand and in-use stock among four regions, not six as ours did. To avoid this assumption in future work, the number of detailed copper demand and in-use stock data must be equal or more than the number of regions considered in future studies.

- Scenario data results regarding annual increase of EOL collection & EOL recovery rates were not available in literature, and the rate of increase should be discussed in detail in further studies *before* conducting a scenario analysis including this parameter.
- Regarding the ore grade, current study has considered the global averaged ore grades 0.85 and 0.87 for the year 2030. Norgate`s work presented the expected average ore grade 0.7 in 2030. Our global study considers “a best case” where we globally mine ore having the largest ore grades at all time.

The scenario parameters generated by this study:
<u>Ore grade:</u> The demand for primary resources is much larger for the A Scenario than the B Scenarios. Assuming that the ore mined first has the highest ore grade available, should logically mean a faster ore grade decline for the A Scenario. The ore grade decline rate is in fact slightly higher for the B Scenarios between 2020 and 2030, while it is lower compared to the A1 Scenario between 2030 - 2050. The amount of ore resources (MT copper ore) having a high ore grade is to a huge extent less than the amount of ore resources having a lower ore grade. The ore grades of the ore reservoirs will therefore vary to a greater extent in the first years than later. A lower decline of the ore grade for the A Scenario the first years considered in the scenario analyses, which is not directly logical, reflects the huge sensitivity of the ore grade the first years by the primary copper demand. In fact, for the A1 Scenario, the year 2019 the same ore grade as the B1 and B2 Scenario for 2020. However, the ore grades modelled for the B1 and B2 Scenarios differ rarely, and if they do; the difference is small. This will influence a small variation among the B Scenarios concerning direct energy demand. The difference between the A1 Scenario and the B Scenarios underlines the future problem of declining ore grade as literature has already been discussing for years.

<u>Recycling input rate:</u> The recycling input rate depends on scrap available and the EOL recycling rate. Scrap available depends on stock size and lifetime. In Scenario B1 and B2 recycling input rate is expected to increase to 77 %. (Harmsen et al., 2013) claim that a higher recycling rate than 70 % is very unlikely due to technological challenges. The author of current work disagrees to some point. As mentioned earlier in the thesis, it is the interplay of stock growth and the lifetime that determines scrap generation that determines the overall potential for recycling.

However, regarding the in-use stock growth, the gathered data (Gerst, 2009) were from the years 2015, 2025 and 2050. The time interval 2025-2050 had a larger in-use stock growth than the time interval 2015-2025. This generated a leap from 2025 to 2026. Since the copper outflow of the use-phase is dependent on the in-use stock growth, the copper flow output of the use-phase in 2026 compared to 2025 is quite low. The copper outflow from the use-phase will however increase towards 2050, but approaching the same values as in 2025 takes according to our model 10-15 years. The leap generates, in fact, an unnatural decrease in RIR around 2026. The RIR in 2050 is actually lower than the RIR in 2025 for the A1 Scenario. This could be explained from stock dynamics explained in detail in section 2. However, the way we have utilized the in-use stock growth data from the literature without adjusting them considerably are discussible. A smooth transition of outflow is not the solution, since the result would exclude the importance of in-use stock growth. On the other hand, by including various in-use stock growths annually (and not period for period) and smooth the in-use stock growth transition from 2025 to 2026 might be a subject for a next study.

5. Concluding Remarks

This master`s thesis has discussed two problems of modern society; shortage of copper resources and an increase of electricity use and global warming potential (GWP) from copper production in the future.

Unlike most studies regarding environmental impacts from copper production, this study is; comprehensive considering that it includes a dynamic life cycle and is forward-looking regarding a number of factors which have high relevance for the result. The methodology of life cycle analysis (LCA) is utilized together with scenario building, and scenario and sensitivity analysis. The scenario and sensitivity parameters utilized in the analyses are based on the scenario building, which has in hindsight shown to have been conducted with errors. This should be taken into consideration when reading the results for electricity use and GWP for a certain year. The results are on the other hand correct if one sees them in relation to the scenario and sensitivity parameters generated by the modelling. The central results of this master thesis follow:

1) *Copper depletion time:*
   Expected depletion of known copper resources in the near future will put pressure on the modern society, depending on how much we produce, and consume of copper. To extend copper depletion time beyond 2050 requires action. A medium in-use stock growth and high end-of-life collection and recovery rate increase could be mentioned as initiatives.
2) *Direct electricity intensity of primary copper production:*
   Direct energy intensity of primary copper production will increase in the future since a declining ore grade is expected. With an ore grade of 0.41, the estimated electricity intensity is 7.1 kWh/ kg refined copper. The increase compared to today is not as crucial as expected by others (200-700 %), but remarkably high for mining and beneficiation (i.e. 66 %). The rate of environmentally cruciality, due to an increase of the demand in electricity, will increase in the future as the electricity-ore grade relation is not linear, but negatively exponential.
3) *GWP-intensity of primary production and the copper production (including secondary production):*
   Three factors, which have high relevance for the results, were investigated: ore grade, energy mix and recycling input rate (RIR). While GWP-intensity (i.e. GWP/kg copper) of *primary production* is dependent of the first two, the GWP-intensity of *copper production* is dependent of all three. The GWP-intensity is expected to increase in the future since a declining ore grade is expected. We could expect an increase of primary production GWP-intensity from 5.2/5.4 (two different scenarios, year 2020) to 7.6/8.9 kg CO_2-eq./kg refined copper (two different scenarios, year 2050), an increase of 46/71 % (primary production). There are on the other hand possibilities to moderate the expected increase or in some cases decrease the GWP-intensity of primary copper production to 5.1/8.3 CO_2-eq./kg refined copper, by focusing on greener energy. Higher recycling input rate (caused by medium in-use stock growth, high lifetime increase and high EOL collection and recovery rate increase) will on the other hand moderate or in some cases decrease the GWP-intensity of copper production.

   Regarding copper criticality (Graedel et al., 2012, Nassar et al., 2012, Gordon et al., 2005, Hertwich et al., 2014) in relation with GWP-intensity, greener energy mix will alone *decrease* the GWP-intensity, and so does a higher rate of RIR. But, the renewable electricity industry are often more copper-intensive than conventional, which will increase the in-use stock growth of copper. The results confirm the existing literature e.g. Hertwich et al`s work (Hertwich et al., 2014).
4) *GWP from copper production:* The total generated GWP from copper production is dependent of a) the GWP-intensity and b) the copper demand. Overall greener energy mix and increased RIR (caused by medium in-use stock growth, high lifetime increase and high EOL collection and recovery rate increase) could moderate an likely GWP increase of 290 MT CO_2-eq. (demand sensitivity parameter

for 2050) or 390 MT CO_2-eq. (demand, ore grade and stripping ratio parameter values for 2050). The rate of *moderation* could be in the order of magnitude 100-120/200-2020 MT CO_2-eq. (less than MT 290/390 CO_2-eq.). Extended producer- and consumer responsibility aiming to decrease the copper demand is essential to moderate or decrease the annual GWP caused by the copper production. The less the copper demand increase is, the less the GWP increase is. However, actions aiming to increase the recycling efficiency and making the energy mix less GWP-intensive will be almost equally effective, or in some cases more effective.

Globally, society has a goal to reduce the annual generated GWP. This study has observed that the GWP-intensity of copper production and annual generated GWP caused by copper production is expected to increase. That increase should be compensated in other industries if society`s goal is to be reached. A solution might be to use copper “more wisely”- like an investment. Trying to reduce the generated GWP caused by other industries, e.g. the electricity industry might be a place to start. A reduction in generated GWP caused by the electricity industry is solved by investing in e.g. wind mill parks. On the other hand, the renewable electricity industry demands more copper per kWh produced than the conventional electricity industry, so if we should invest in *less* emission intensive electricity in the future, an increased RIR is important to extent copper depletion time.

The fact that copper will be more CO_2-intensive, and emissions will rise, contrary to what is needed to curb global warming are very policy relevant. New updated information and interesting observations concerning the environmental aspect of copper production are constantly published. Feeding policy makers with the most recent research, and introducing them to precautionary actions to avoid future issues – would probably change the way policy makers think regarding the copper cycle, copper production and how we use it today. For example, introducing qualitative and quantitative sectorial targets, and introducing emission trading where the emissions are addressed to the consumer instead of the producer, might change the way policy makers think. This might be crucial to reach society`s global goal of reducing the annually GWP.

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Appendix A: Primary Copper Production – process description in detail

(Ayres et al., 2002, Mischa Classen et al., 2007).

The pyro metallurgical process route is divided into five main stages; mining, beneficiation, pretreatment, reduction and refining.

Mining takes place at a copper deposit, which is a host rock that contains copper ore. To this date, porphyry copper deposits are the largest source of copper ore. The copper ore is mined either underground or by open pit. The percent of Cu in the host rock and the percentage of Cu in copper ore (the ore grade) are two different parameters, and should not be mixed. The first is important considering diesel demand, explosives demand and overburden disposed in the mining process, and the last is important considering tailings disposed in the beneficiation process. Both is important considering energy demand in the mining and beneficiation process.

In the mining stage the operations drilling, blasting, and loading and haulage takes place. In the drilling process a cylindrical hole is made by a tool for the purpose of exploration, blasting preparation, or tunneling. In the blasting process copper ore are liberated from the host rock and the size of the ore is reduced. The host rock without copper ore is called overburden, and is disposed. The loading and hauling process transports the copper ore to the site where beneficiation takes place. The copper ore flow into beneficiation is a mineral body comprising metal bearing particles, unwanted minerals and gangue which is the worthless material that surrounds and is closely mixed with the wanted mineral.

Beneficiation includes the operations crushing and grinding, and separation. Crushing reduce the size of the material into coarse particles, and grinding reduce the size of the material into fine particles. A “liberation size” has to be obtained to be able to separate the metal bearing particles from the gangue. The separation process separates valuable substances from undesired substances (unwanted minerals and gangue) by gravity concentration and flotation. The valuable product out of this process is named copper concentrate.

Pretreatment includes the operations drying, and roasting which is an oxidation operation. Oxidation of the concentrate is necessary in the reduction process to be able to separate the high-grade copper sulphide matte from the slag which is the unwanted by-product from the smelting process. The process is elaborated later.

The reduction process comprises the operations smelting and converting, and produces the product named blister copper. Blister copper is then refined by three operations; fire refining, electrolytic refining and remolding of cathodes. Copper cathodes are the final product having a Cu% of 99.96%.

While some operation stages is self-explanatory by the process name, some needs to be explained and elaborated to better understand the process inventory. The beneficiation separation process (a), the pretreatment process roasting (b), reduction (both smelting and converting) (c) and fire refining is empasized to be explained in a greater detail.

a) *After crushing and grinding, the ore is gravity concentrated. This process separates the metal-bearing particles from the unwanted minerals. The following operation is called flotation which separates the gangue/tailings from the sulphidic minerals. To neutralise the flow, lime is added. The flotation process might be divided into four stages, and several organic chemicals is demanded. 1) Collectors (xanthate or aerofloat) is added to increase the natural hydrophobicity of the surface of the already hydrophobic mineral surface. This is carried out to increase the* *separability of the hydrophopic (concentrate) and hydrophilic (tailings) particles. 2) Oxygen rich air is supplied to the liquid collecting the hydrophipic particles by bubbles going upwards forming froth on the surface of the flotation cell. 3) Frothers (e.g. Methyl isobutyl carbinol) are added to help form a stable froth. 4) The mineral laden froth is separated from the flotation cell. The concentration is further cleaned and the tailings are treated by scavenging.*

b) *In the roasting step part of the iron is oxidized and sulphur dioxide is driven off. The oxidation process is necessary to produce two phases with the help of a siliceous flux in the smelting process.*

c) *In the smelting process the roasting product is melted with a siliceous flux. The flux combines with the oxidized iron and two immiscible phases is produced; liquid silicate slag and a solution of molten sulphides containing the wanted minerals.*

In the converting process air + oxygen are added, and more sulphur is driven off as sulphur dioxide. The remaining iron is oxidized and fluxed. The silicate slag product is removed. The copper valuable product is a high-grade copper sulphide matte having a purity of 98 %.

$$
\begin{aligned}
&2\mathrm{CuFeS_2} + 4\mathrm{O_2} = \mathrm{Cu_2S} + 2\mathrm{FeO} + 3\mathrm{SO_2}\\
&\mathrm{FeS_2} + \frac{5}{2}\mathrm{O_2} = \mathrm{FeO} + 2\mathrm{SO_2}\\
&\mathrm{FeO} + \mathrm{SiO_2} = \mathrm{FeO.SiO_2}\\
&\mathrm{Cu_2S} + \mathrm{O_2} = 2\mathrm{Cu} + \mathrm{SO_2}
\end{aligned}
$$

$$
\begin{aligned}
&\mathrm{Cu_2S} = \mathrm{matte}\\
&\mathrm{SiO_2} = \mathrm{flux}\\
&\mathrm{FeO.SiO_2} = \mathrm{slag}
\end{aligned}
$$

d) *Fire refining remolds the copper matte. Natural gas is blown through the copper to remove any remaining sulfur and oxygen as sulphur dioxide. Impure copper as anodes is the copper valuable product from this process.*

The hydrometallurgical process route is divided into three main stages, mining, “pretreatment-leaching-solvent extraction” and refining. Mining is identical to pyro metallurgical mining. The following pretreatment process, which includes grinding and separation, is not that common in the hydrometallurgical process route but is included nevertheless. While leaching is a recovering stage (extracting minerals from solid producing leach liquor containing soluble salts), solvent extraction is a solution cleaning stage (where precipitation of impurities and filtration or selective enrichment of copper takes place). Refining comprises the operations electro winning and remolding of cathodes.

Leaching and solvent extraction is elaborated to better understand the process inventory.

In the leaching process stage the ore is reacted with dilute sulfuric acid to mobilise the contained metals. The time required for this process is measured in years. The products are a low-grade leach liquid (which is soluble salts in a aqueous media) and solid waste. Large amounts of sulphure dioxide is emitted and considerable amounts of sulphuric acid and leaching agents emit into water and air (Ayres et al., 2002).

The solvent extraction process comprises the steps "selective extraction of copper from the aqueous leach solution into an organic phase", where a solvent chemical reacts with and binds the copper in the solvent, and "the re-extraction or stripping of the copper into dilute sulphuric acid", to produce a copper sulphate solution (an ionic copper flow in an aqua phase) which is more suitable for electro winning. (Bartos, 2003, Ayres et al., 2002)

The solvent extraction process comprises the steps "selective extraction of copper from the aqueous leach solution into an organic phase", where a solvent chemical reacts with and binds the copper in the solvent, and "the re-extraction or stripping of the copper into dilute sulphuric acid", to produce a copper sulphate solution (i.e. an ionic copper flow in an aqua phase) which is more suitable for electro winning.

Appendix B: Calculation principles

Scaling

Section 2.7.1 presents the concept behind scaling. Here we demonstrate the concept by an example from the global inventory.

Steel input to beneficiation =
$$2.7\mathrm{E}-02\frac{\mathrm{kg}}{\mathrm{kg,copper\_concentrate}}\cdot 3.2\frac{\mathrm{kg,copper\_concentrate}}{\mathrm{kgCu}}=8.7\,\mathrm{E}-2\,\mathrm{kg/\,kgCu}$$

Electricity

Section 2.7.1 presents the concept behind energy calculation. Here we demonstrate the concept by an example from the global inventory (two significant numbers shown).

Electricity input to mining
and beneficiation =
$$16\cdot 1.0^{-0.6}GJ\,/\,tCu\cdot 0.3((kWh\cdot tCu)/(GJ\cdot kgCu))=4.4kWh/kgCu$$

The ratio between mining and beneficiation electricity demand is 0,146-0,855. The results are per kg Cu out of the beneficiation process.

Electricity input to beneficiation =
$$4.4kWh/kgCu\cdot 0.855=3.8kWh/kgCu$$

Electricity input to mining =
$$4.4kWh/kgCu\cdot 0.146=0.6kWh/kgCu$$

Overburden & Tailings

Section 2.7.1 presents the concept behind overburden & tailings calculations. Here we demonstrate the concept by an example from the global inventory.

Overburden =
$$\frac{1}{0.36}-\frac{1}{0.99}=177kg\,/\,kgCu$$

Tailings = $$\frac{1}{0.84}\cdot\frac{1}{0.99}-3.15=118kg/kgCu$$

Diesel & Explosives

Section 2.7.1 presents the concept behind diesel & explosives calculations. Here we demonstrate the concept by an example from the global inventory.

Diesel = $$\frac{1}{0.84}\cdot\frac{1}{0.99}-3.15=118kg/kgCu$$

Explosives = $$\frac{1}{0.84}\cdot\frac{1}{0.99}-3.15=118kg/kgCu$$

Appendix C: Regional ore deposit overview

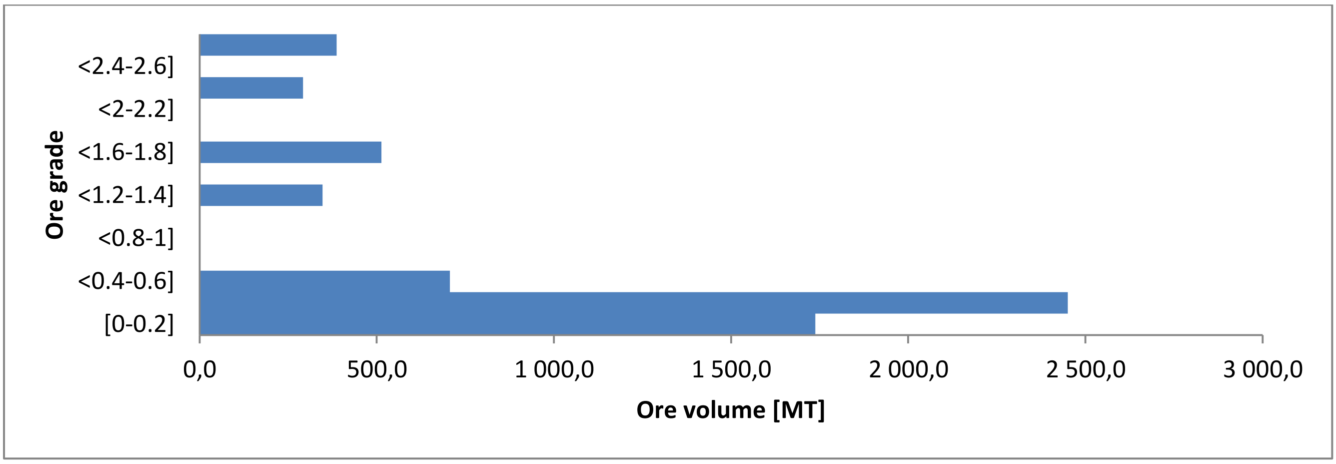


Figure C1: Europe

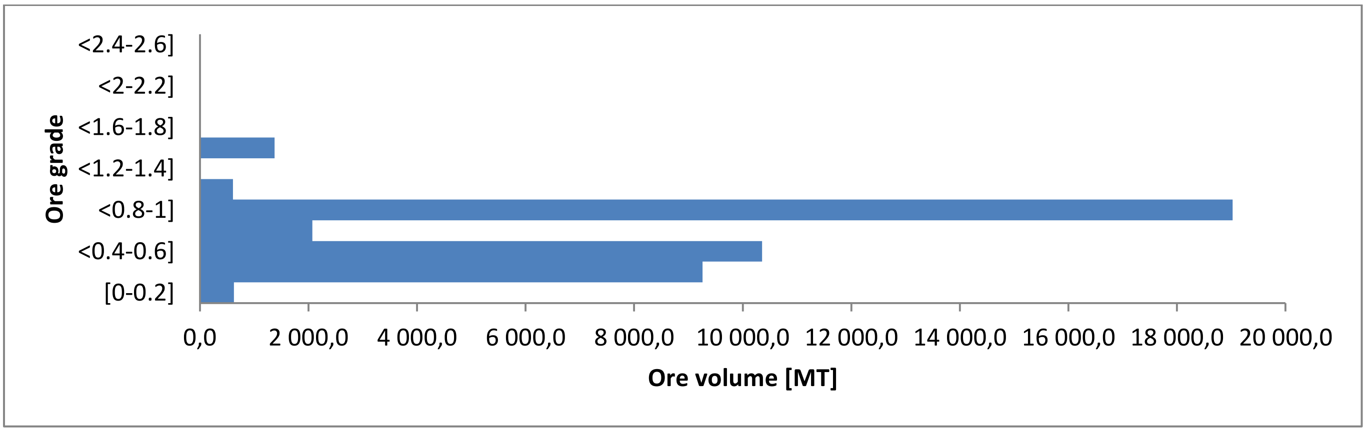


Figure C2: Asia

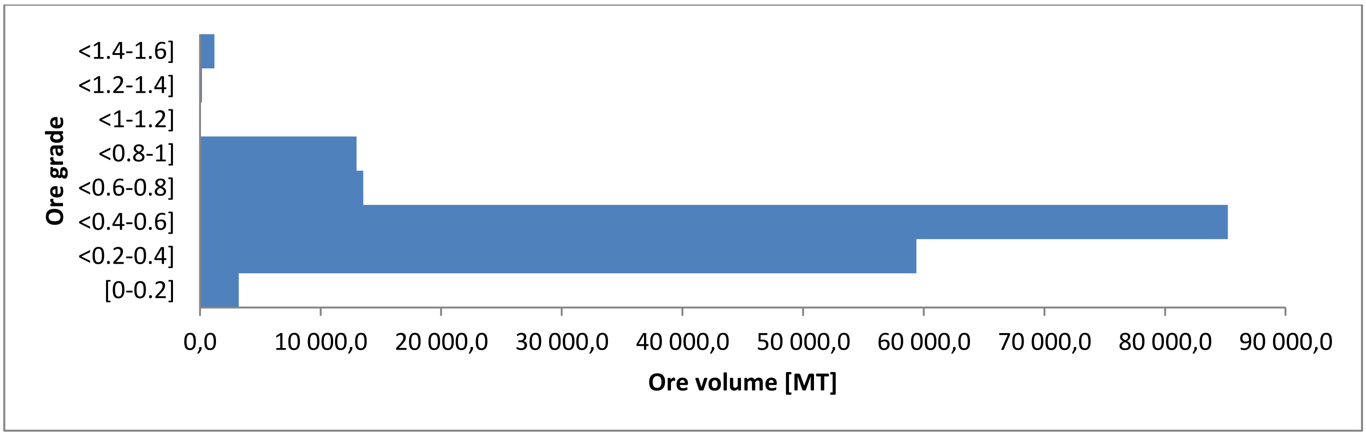


Figure C3: Latin America

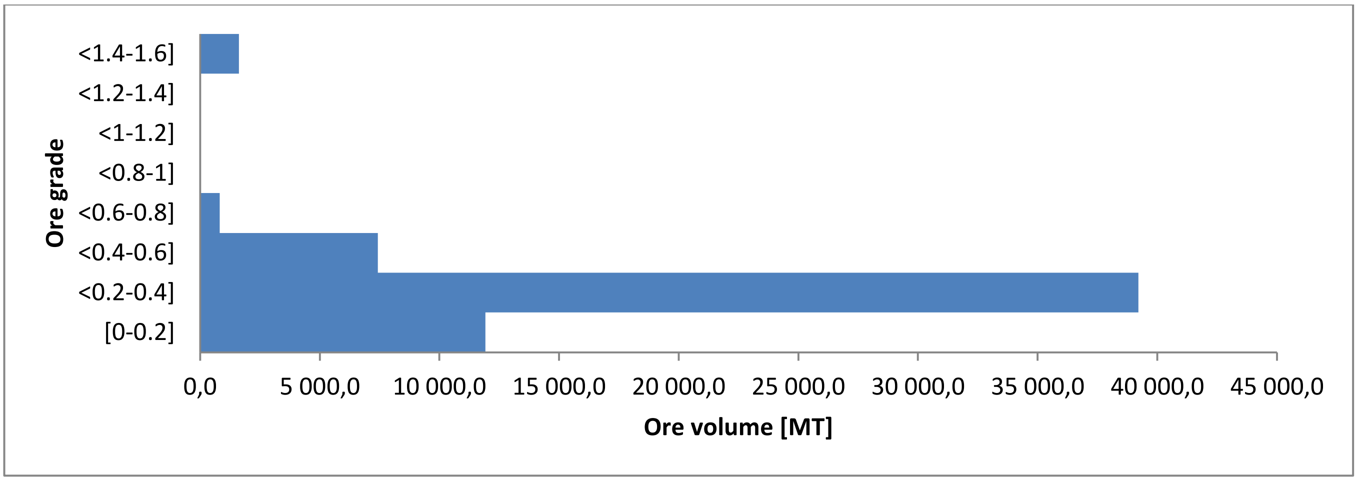


Figure C4: North America

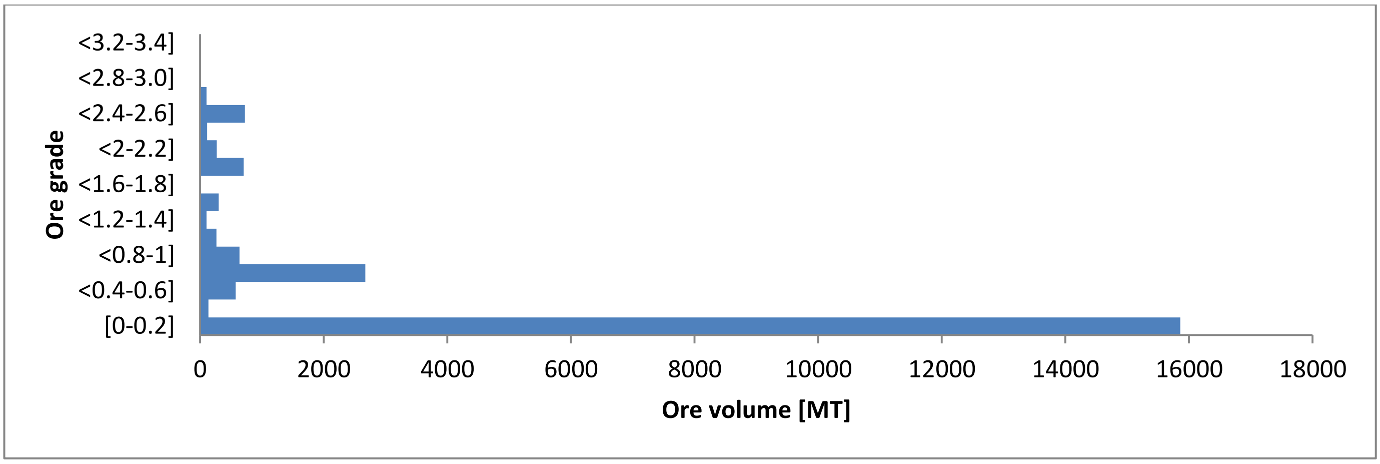


Figure C5: Africa

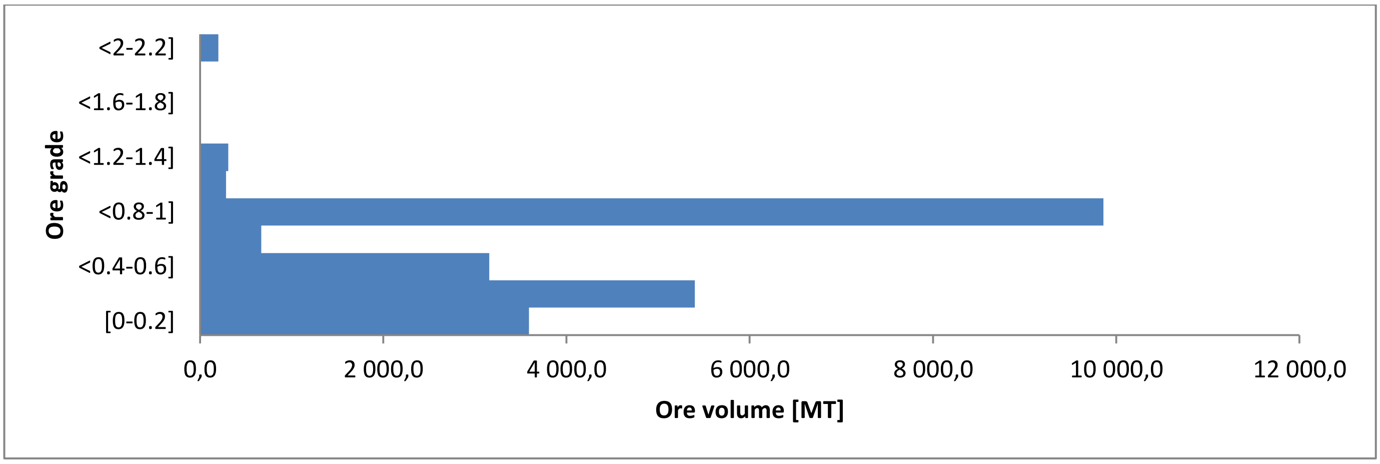


Figure C6: Oceania

Appendix D: Detailed flow chart

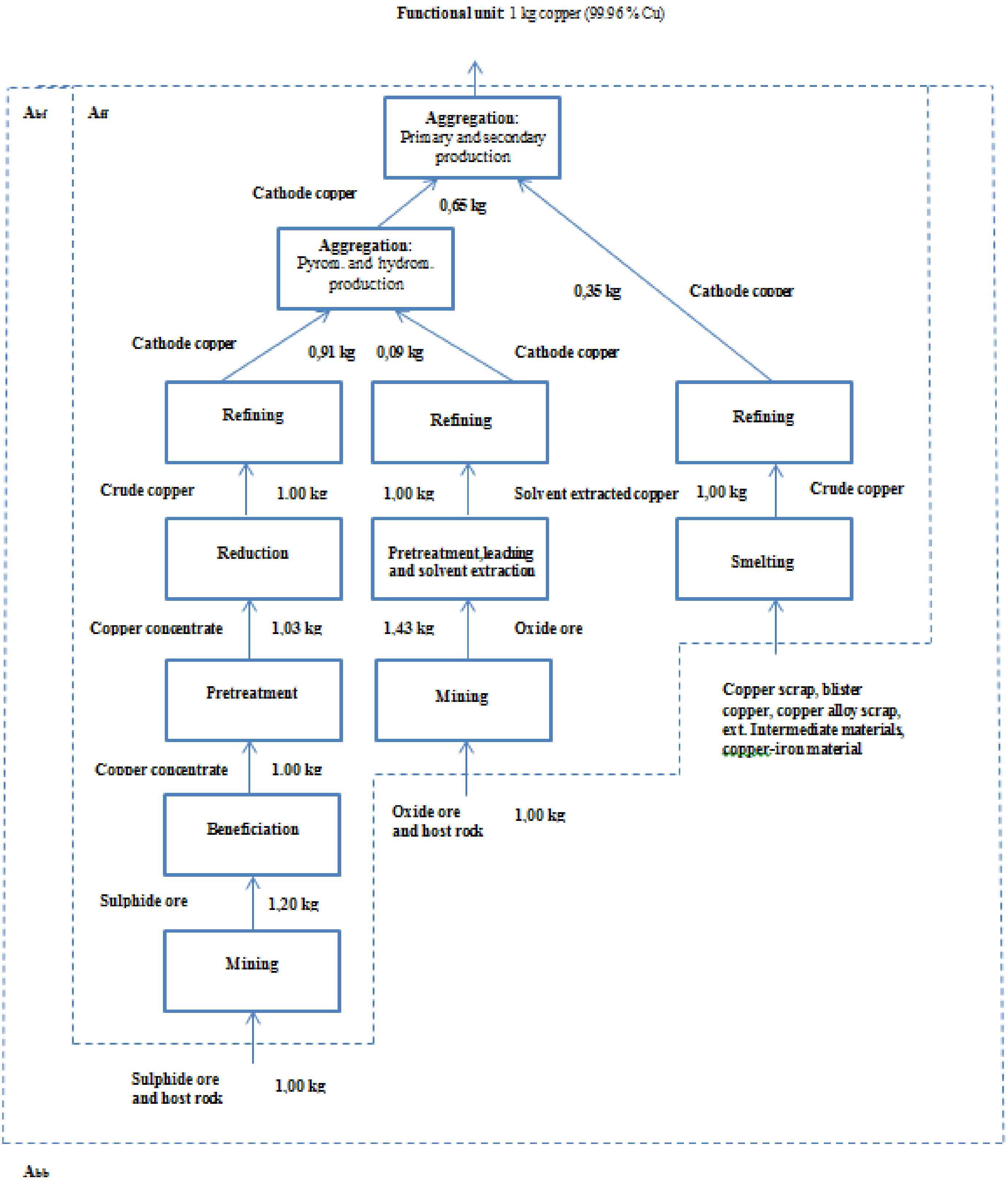


Figure D1: Detailed LCA process model

Appendix E: Overview of region- and scenario names utilized from the literature

The variables utilized by the scenario analyses were; a) averaged annually energy mix, b) annually copper final demand, c) annually recycling input rate and b) annually ore grade and stripping ratio of mined ore.

a) The former and future energy mix`s for six world regions and the global average (United Nations Environmental Programme, 2014) is based on baseline and bluemap scenarios. The different energy mixes is elaborated in appendix I.

Table E1: Energy mix, regions

Regions and scenarios considered in Master Thesis		UNEP region- and scenario name
Europe	A1	OECD-Europe, Baseline
	B1	OECD-Europe, Blue Map
	B2	OECD-Europe, Blue Map
North America	A1	OECD-North America, Baseline
	B1	OECD-North America, Blue Map
	B2	OECD-North America, Blue Map
Oceania	A1	OECD-Pacific, Baseline
	B1	OECD-Pacific, Blue Map
	B2	OECD-Pacific, Blue Map
Latin America	A1	Latin America, Baseline
	B1	Latin America, Blue Map
	B2	Latin America, Blue Map
Africa	A1	Africa, Baseline
	B1	Africa, Blue Map
	B2	Africa, Blue Map
Asia	A1	Economies in Transition, Baseline
	B1	Economies in Transition, Blue Map
	B2	Economies in Transition, Blue Map

Table E2: Energy mix, global

		UNEP scenario name
Global	A1	Global, Baseline
	B1	Global, Blue Map
	B2	Global, Blue Map

b) The future demand in copper for four regions (Ayres et al., 2002) is based on the SRES framework. The global demand is the sum of the four regions.

Table E3: Copper demand, regions

Regions and scenarios considered in Master Thesis		Scenario name in Ayres et al.`s work (Ayres et al., 2002)
REF	A1	ConSc1
	B1	ConSc2
	B2	ConSc2
ASIA	A1	ConSc1
	B1	ConSc2
	B2	ConSc2
OECD90	A1	ConSc2
	B1	ConSc1
	B2	ConSc1
ALM	A1	ConSc1
	B1	ConSc2
	B2	ConSc2

Where:

- REF: All countries undergoing economic reform, grouping together the East European countries and the Newly Independent states of the former Soviet Union;
- ASIA: All developing countries in Asia;
- OECD90: This group includes all the countries belonging to the Organization for Economic Cooperation and Development (OECD) as of 1990
- ALM: The rest of the world including all developing countries in Africa, Latin America, and the Middle East.

c) The quantification process of recycling input rate and ore grade & stripping ratio was based on a) ore reservoir data (Mudd et al., 2012), b) future final copper demands (Ayres et al., 2002) and copper in use-stocks conducted by earlier scenario analyses (Gerst, 2009) c) the scenario storylines of this master thesis and d) mailing correspondence with Dr. Sharif Jahanshahi. The global in-use stock is the sum of the four regions.

Table E4: In-stock use, regions

Regions and scenarios considered in Master Thesis		Scenario name in Gerst`s work (Gerst, 2009)
REF	A1	A1 Dev
	B1	B1 Dev
	B2	B2 Dev
ASIA	A1	A1 Dev
	B1	B1 Dev
	B2	B2 Dev
OECD90	A1	A1 Ind
	B1	B1 Ind
	B2	B2 Ind
ASIA	A1	A1 Dev
	B1	B1 Dev
	B2	B2 Dev

Appendix F: Inventory, base case, global

The requirements for primary and secondary production are presented here, while the region specific emissions is presented in appendix H (where Africa represent the assumed global average (Mischa Classen et al., 2007)).

Primary copper production

Table F1: Inventory, primary copper production

Copper ore mined	Stage	Inventory				Uncertainty	Reference
		Item	Modul name in EcoInvent	Value	Units		
Sulphide ore	Mining	Conveyor Belt	conveyor belt, at plant/ RER/ m	1,0E-05	m/kg Cu in ore	3,3[a]	EcoInvent
		Electricity	electricity, hard coal, at power plant/ UCTE/ kWh	2,5E-01	kWh/kg Cu in ore	0.71[b]	Northey et al.
			electricity, natural gas, at power plant/ UCTE/ kWh	2,0E-01			
			electricity, oil, at power plant/ UCTE/ kWh	7,8E-02			
			electricity, nuclear, at power plant/ UCTE/ kWh	6,5E-02			
			electricity, hydropower, at power plant/ CZ/ kWh	1,6E-01			
			electricity, at wind power plant/ RER/ kWh	2,8E-02			
		Overburden	disposal, non-sulfidic overburden, off-site/ GLO/ kg	1,8E+02	kg/kg Cu in ore	NN	Section 2.7
		Mine Infrastructure (underground)	non-ferrous metal mine, underground/ GLO/ unit	5,9E-10	unit/kg Cu in ore	3,3[a]	EcoInvent
		Blasting	blasting/ RER/ kg	1,4E-01	kg/kg Cu in ore	NN/1[a]	Section 2.7/ EcoInvent
		Mine infrastructure (open-pit)	non-ferrous metal mine, surface/ GLO/ unit	1,4E-09	unit/kg Cu in ore	3,3[a]	EcoInvent
		Diesel	diesel, burned in building machine/ GLO/ MJ	1,1E-02	MJ/kg Cu in ore	NN/1[a]	Section 2.7/ EcoInvent
	Benefi ciation	Chemical, inorganic	chemicals inorganic, at plant/ GLO/ kg	8,7E-02	kg/kg Cu in ore	2,0[a]	EcoInvent
		Aluminum hydroxide factory	aluminum hydroxide, plant/ RER/ unit	9,5E-10	unit/kg Cu in ore	3,0[a]	EcoInvent
		Sulphidic tailing	disposal, sulfidic tailings, off-site/ GLO/ kg	1,2E+02	kg/kg Cu in copper concentrate	NN	Section 2.7
		Steel	chromium steel 18/8, at plant/ RER/ kg	8,4E-02	kg/kg Cu in copper concentrate	1,2[a]	EcoInvent
		Lime	limestone, milled, packed, at plant/ CH/ kg	1,8E-01	kg/kg Cu in copper concentrate	1[a]	EcoInvent
		Electricity	electricity, hard coal, at power plant/ UCTE/ kWh	1,2E+00	kWh/kg Cu in copper concentrate	0.71[b]	Northey et al.
			electricity, natural gas, at power plant/ UCTE/ kWh	1,0E+00			
			electricity, oil, at power plant/ UCTE/ kWh	3,8E-01			
			electricity, nuclear, at power plant/ UCTE/ kWh	3,2E-01			
			electricity, hydropower, at power plant/ CZ/ kWh	7,9E-01			

		electricity, at wind power plant/ RER/ kWh	1,4E-01			
	Chemical, organic	chemicals organic, at plant/ GLO/ kg	2,6E-02	kg/kg Cu in copper concentrate	2,0[a]	EcoInvent
	Sodium cyanide	sodium cyanide, at plant/ RER/ kg	4,0E-03	kg/kg Cu in copper concentrate	2,0[a]	EcoInvent
Pretreatment	Electricity	electricity, hard coal, at power plant/ UCTE/ kWh	1,9E-02	kWh/kg Cu in copper concentrate	1[a]	EcoInvent
		electricity, natural gas, at power plant/ UCTE/ kWh	1,6E-02			
		electricity, oil, at power plant/ UCTE/ kWh	6,0E-03			
		electricity, nuclear, at power plant/ UCTE/ kWh	5,0E-03			
		electricity, hydropower, at power plant/ CZ/ kWh	1,2E-02			
		electricity, at wind power plant/ RER/ kWh	2,2E-03			
	Heat	natural gas, burned in industrial furnace >100kW/ RER/ MJ	1,3E+00	MJ/kg Cu in copper concentrate	3,0[a]	EcoInvent
	Non-ferrous metal smelter	non-ferrous metal smelter/ GLO/ unit	9,9E-12	unit/kg Cu in copper concentrate	1,4[a]	EcoInvent
	Lime, packed	limestone, milled, packed, at plant/ CH/ kg	2,3E-01	kg/kg Cu in copper concentrate	1[a]	EcoInvent
Reduction	Heat, other than natural gas	heavy fuel oil, burned in industrial furnace 1MW, non-modulating/ RER/ MJ	5,7E+00	MJ/kg Cu in crude copper	1[a]	EcoInvent
	Oxygen	oxygen, liquid, at plant/ RER/ kg	2,6E-01	kg/kg Cu in crude copper	1[a]	EcoInvent
	Wastewater, upolluted	treatment, sewage, unpolluted, to wastewater treatment, class 3/ CH/ m3	4,4E-03	m3/kg Cu in crude copper	1[a]	EcoInvent
	Electricity	electricity, hard coal, at power plant/ UCTE/ kWh	4,5E-02	kWh/kg Cu in crude copper	1[a]	EcoInvent
		electricity, natural gas, at power plant/ UCTE/ kWh	3,6E-02			
		electricity, oil, at power plant/ UCTE/ kWh	1,4E-02			
		electricity, nuclear, at power plant/ UCTE/ kWh	1,2E-02			
		electricity, hydropower, at power plant/ CZ/ kWh	2,9E-02			
		electricity, at wind power plant/ RER/ kWh	5,1E-03			
	Heat, natural gas	natural gas, burned in industrial furnace >100kW/ RER/ MJ	4,4E-03	MJ/kg Cu in crude copper	1,4[a]	EcoInvent
	Silica sand	silica sand, at plant/ DE/ kg	7,5E-01	kg/kg Cu in crude copper	1[a]	EcoInvent
	Nickel smelter slag	disposal, nickel smelter slag, 0% water, to residual material landfill/ CH/ kg	1,1E+00	kg/kg Cu in crude copper	1,9[a]	EcoInvent
	Anode	anode, aluminium electrolysis/ RER/ kg	9,1E-04		1[a]	EcoInvent
Refining	Electricity	electricity, hard coal, at power plant/ UCTE/ kWh	9,4E-02	kg/kg Cu in	1[a]	EcoInvent
		electricity, natural gas, at power plant/ UCTE/ kWh	7,6E-02			

			electricity, oil, at power plant/ UCTE/ kWh	2,9E-02	crude copper kWh/kg Copper		
			electricity, nuclear, at power plant/ UCTE/ kWh	2,4E-02			
			electricity, hydropower, at power plant/ CZ/ kWh	6,0E-02			
			electricity, at wind power plant/ RER/ kWh	1,1E-02			
		Heat, natural gas	natural gas, burned in industrial furnace >100kW/ RER/ MJ	3,1E+00	MJ/kg Copper	1[a]	EcoInvent
Oxide ore	Mining	Overburden	disposal, sulfidic tailings, off-site/ GLO/ kg	2,8E+02	kg/kg Cu in ore	NN	Section 2.7
		Electricty	electricity, hard coal, at power plant/ UCTE/ kWh	2,8E-01	kWh/kg Cu in ore	1,5[a]	EcoInvent
			electricity, natural gas, at power plant/ UCTE/ kWh	2,3E-01			
			electricity, oil, at power plant/ UCTE/ kWh	8,6E-02			
			electricity, nuclear, at power plant/ UCTE/ kWh	7,2E-02			
			electricity, hydropower, at power plant/ CZ/ kWh	1,8E-01			
			electricity, at wind power plant/ RER/ kWh	3,1E-02			
		Blasting	blasting/ RER/ kg	4,0E-10	kg/kg Cu in ore	1,2[a]	EcoInvent
		Diesel	diesel, burned in building machine/ GLO/ MJ	1,2E+01	MJ/kg Cu in ore	1,2[a]	EcoInvent
		Mine infrastructure, open-pit	non-ferrous metal mine, surface/ GLO/ unit	2,0E-08	unit/kg Cu in ore	3,0[a]	EcoInvent
		Conveyor belt	conveyor belt, at plant/ RER/ m	3,0E-05	m/kg Cu in ore	1,5[a]	EcoInvent
	Pretreatment, leaching and Solvent-Extraction	Electricity	electricity, hard coal, at power plant/ UCTE/ kWh	9,5E-01	kWh/kg Cu in crude copper	1, 5[a]	EcoInvent
			electricity, natural gas, at power plant/ UCTE/ kWh	7,7E-01			
			electricity, oil, at power plant/ UCTE/ kWh	2,9E-01			
			electricity, nuclear, at power plant/ UCTE/ kWh	2,5E-01			
			electricity, hydropower, at power plant/ CZ/ kWh	6,1E-01			
			electricity, at wind power plant/ RER/ kWh	1,1E-01			
		Organics	chemical plant, organics/ RER/ unit	4,0E-10	unit/kg Cu in crude copper	3,0[a]	EcoInvent
		Ammonia	ammonia, liquid, at regional storehouse/ RER/ kg	1,7E-03	kg/kg Cu in crude copper	1[a]	EcoInvent
		Steel	chromium steel 18/8, at plant/ RER/ kg	1,9E-01	kg/kg Cu in crude copper	NN	EcoInvent
	Refining	Electricity	electricity, hard coal, at power plant/ UCTE/ kWh	1,6E+00	kWh/kg Copper	1,5[a]	EcoInvent
			electricity, natural gas, at power plant/ UCTE/ kWh	1,3E+00			
			electricity, oil, at power plant/ UCTE/ kWh	4,9E-01			
			electricity, nuclear, at power plant/ UCTE/ kWh	4,1E-01			
			electricity, hydropower, at power plant/ CZ/ kWh	1,0E+00			
			electricity, at wind power	1,8E-01			

		plant/ RER/ kWh				

[a] = standard deviation

[b] = correlation coefficient

Secondary copper production

Table F2: Inventory, secondary production

Stage	Inventory				Uncertainty	Reference
	Item	Modul name in EcoInvent	Value	Units		
Smelting	Copper scrap, copper alloy scrap, ext.intermediate materials and copper-iron material	iron scrap, at plant/ RER/ kg	1,38E+00	kg/kg Cu in crude copper	2,26 [a]	EcoInvent
	Blister copper	copper, blister-copper, at primary smelter/ RER/ kg	1,20E-01	kg/kg Cu in crude copper	1,13 [a]	EcoInvent
	Limestone	limestone, milled, packed, at plant/ CH/ kg	7,78E-02	kg/kg Cu in crude copper	1,13 [a]	EcoInvent
	Silica	silica sand, at plant/ DE/ kg	6,58E-02	kg/kg Cu in crude copper	1,13 [a]	EcoInvent
	Coke and coal	hard coal, burned in industrial furnace 1-10MW/ RER/ MJ	6,86E+00	MJ/kg Cu in crude copper	1,60 [a]	EcoInvent
	Fuel	heavy fuel oil, burned in industrial furnace 1MW, non-modulating/ RER/ MJ	2,72E+00	MJ/kg Cu in crude copper	1,13 [a]	EcoInvent
	Infrastructure	non-ferrous metal smelter/ GLO/ unit	1,01E-11	unit/kg Cu in crude copper	3,07 [a]	EcoInvent
	Effluents	treatment, sewage, unpolluted, to wastewater treatment, class 3/ CH/ m3	1,05E-03	m3/kg Cu in crude copper	1,13 [a]	EcoInvent
	Zinc Oxide	zinc oxide, at plant/ RER/ kg	-5,38E-02	kg/kg Cu in crude copper	-	EcoInvent
	Lead	lead, primary, at plant/ GLO/ kg	-1,11E-02	kg/kg Cu in crude copper	-	EcoInvent
	Tin	tin, at regional storage/ RER/ kg	-1,11E-02	kg/kg Cu in crude copper	-	EcoInvent
Refining	Electricity	electricity, hard coal, at power plant/ UCTE/ kWh	3,5E-01	kWh/kg copper	1,13	EcoInvent
		electricity, natural gas, at power plant/ UCTE/ kWh	2,9E-01			
		electricity, oil, at power plant/ UCTE/ kWh	1,1E-01			
		electricity, nuclear, at power plant/ UCTE/ kWh	9,1E-02			
		electricity, hydropower, at power plant/ CZ/ kWh	2,3E-01			
		electricity, at wind power plant/ RER/ kWh	4,0E-02			
	Anode slime	disposal, nickel smelter slag, 0% water, to residual material landfill/ CH/ kg	5,68E-03	kg/kg copper	1,13	EcoInvent

[a] = standard deviation

[b] = correlation coefficient

Appendix G: Specific Assumptions

The specific assumptions is made based on the report by the EcoInvent providers (Mischa Classen et al., 2007) and obtained knowledge on copper production. PMA is an abbreviation of process model assumption.

Table G1: Specific Assumptions

Copper ore deposit: 90-95 % of the copper deposits is in the form of sulphide minerals
Copper deposit and ore: There are 0.99 wt-% Cu in ores, the input of bot the pyro- and hydrometallurgical process route. There are 0.36 wt-% Cu in the deposit in ground
Copper deposit: There are 8,2E-3 wt-% Mo in the deposit in ground. The molybdenum concentrate is simplified to be the only byproduct addressed with a negative sign. Molybdenite concentrate is only extracted in beneficiation.
Copper deposit: The minerals in sulphide ores is simplified to be only chalcopyrite (CuFeS2) with a fraction of molybdenum (Mo)
Copper mining: Only copper as a main product is accounted for
Copper mining: The input into hydrometallurgical mining is 100 % oxide ore.
Copper mining: 70 % of all mining is done in open pits
Copper mining: 83.5 % yield of Cu in mining and beneficiation
Overburden: No overburden refilled
Tailings: No tailings develop additionally to the mining for the hydrometallurgical process route, meaning the 70 % yield of Cu in pretreatment, leaching and solvent extraction is addressed to mining. All losses of Cu in beneficiation are due to the byproduct of Copper Sulphate
Dross: All dross is handled by internal recovery
Pretreatment, pyro metallurgical process route: No Cu- and copper concentrate losses in the process pretreatment in the pyro metallurgical process route
Pretreatment, pyro metallurgical process route: Pretreatment is necessary, but there are no material losses in this process.
Smelting: The smelting process is only a part of the reduction process
Reduction: Output flow of the reduction process contains 98 wt-% Cu.
Refining: The only Cu-containing outflow of refining, except from Copper Anodes is slag
Refined copper: There are 99.96 wt-% Cu in refined copper.
Hydrometallurgical chemical: All sulfuric acid needed is generated by own processes and 100 % of it is recycled.
Leaching: All leaching residues are recycled, meaning no Cu lost in the leaching process.
Solvent extraction: Output flow of solvent extraction has 98 wt-% Cu
Hydrometallurgical processes: Output flow of pretreatment, leaching and solvent extraction contains only dissolved minerals
Secondary: Refining consists of traditional electrolysis tank house and electrolysis purification. The purification process does not address any other demands than extra electricity for stirring.
Secondary: The by-products Lead-Tin alloys, Zinc oxides, Nickel sulphate and Copper sulphate is burden-free
Secondary: Secondary copper used in smelters and refineries is composed of 100 % old scrap
Secondary: 36 % of copper in old scrap comes from pure copper production. The rest comes from alloy products
Secondary: The Cu wt-% of the inflow of process 2 is 95 %, while the Cu wt-% of the outflow of process 2 is 99.96 %
Secondary: All slag is internal used in building
Secondary: Blast furnace, Converters and Anode furnace is aggregated into a process called smelting
Final demand share: Europe (21%), Africa (1%), Asia (63%), Latin America (3%), North America (11%) and Oceania (1%).

Appendix H: Compilation of Region specific Emission Factors

Table H1: Emission factors, Africa

Process	Emission	Unit	Amount/kg Cu out of the	Compartment	Reference

			process		
Mining, pyro	Transformation, to mineral extraction site	m2	1,97E-04	natural resource	EcoInvent
	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	kg	1,12E+00	natural resource	EcoInvent
	Transformation, from unspecified	m2	1,97E-04	natural resource	EcoInvent
	Occupation, mineral extraction site	m2*year	5,89E-03	natural resource	EcoInvent
	Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	kg	2,47E-02	natural resource	EcoInvent
Beneficiation, pyro	Copper	kg	2,60E-06	air	EcoInvent
	Cadmium, ion	kg	5,08E-08	water	EcoInvent
	Arsenic, ion	kg	4,75E-07	water	EcoInvent
	Selenium	kg	2,60E-09	air	EcoInvent
	Water	m3	8,05E-02	air	EcoInvent
	TOC, Total Organic Carbon	kg	6,56E-04	water	EcoInvent
	Iron, ion	kg	4,68E-05	water	EcoInvent
	Arsenic	kg	7,81E-08	air	EcoInvent
	Antimony	kg	1,04E-08	air	EcoInvent
	Zinc, ion	kg	1,22E-05	water	EcoInvent
	COD, Chemical Oxygen Demand	kg	1,68E-03	water	EcoInvent
	Particulates, > 10 um	kg	2,56E-03	air	EcoInvent
	Chromium, ion	kg	8,80E-08	water	EcoInvent
	Nickel, ion	kg	3,91E-06	water	EcoInvent
	Cadmium	m3	5,73E-09	air	EcoInvent
	Water, river	kg	1,61E-01	natural resource	EcoInvent
	Aluminium	kg	1,39E-05	water	EcoInvent
	Particulates, > 2.5 um, and < 10um	kg	2,30E-02	air	EcoInvent
	Particulates, < 2.5 um	kg	2,65E-02	air	EcoInvent
	Beryllium	kg	1,35E-07	air	EcoInvent
	Fluorine	kg	4,95E-05	air	EcoInvent
	Calcium, ion	kg	1,10E-01	water	EcoInvent
	Carbon disulfide	kg	1,13E-02	air	EcoInvent
	Zinc	kg	9,89E-06	air	EcoInvent
	Cobalt	kg	1,26E-07	water	EcoInvent
	Cobalt	kg	1,29E-06	air	EcoInvent
	BOD5, Biological Oxygen Demand	kg	1,68E-03	water	EcoInvent
	Nickel	kg	4,16E-06	air	EcoInvent
	Lead	kg	4,50E-07	water	EcoInvent
	Mercury	kg	6,06E-09	water	EcoInvent
	Dissolved solids	kg	8,31E-04	water	EcoInvent
	Boron	kg	5,20E-07	air	EcoInvent
	Carbon dioxide, fossil	kg	7,97E-02	air	EcoInvent

	Nitrogen, organic bound	kg	3,66E-03	water	EcoInvent
	Manganese	kg	6,14E-05	air	EcoInvent
	Water	m3	8,05E-02	water	EcoInvent
	Cyanide	kg	4,38E-04	water	EcoInvent
	Mercury	kg	3,23E-09	air	EcoInvent
	DOC, Dissolved Organic Carbon	kg	6,56E-04	water	EcoInvent
	Sulfate	kg	3,79E-01	water	EcoInvent
	Manganese	kg	3,97E-06	water	EcoInvent
	Chromium	kg	5,20E-06	air	EcoInvent
	Copper, ion	kg	1,27E-06	water	EcoInvent
	Lead	kg	9,04E-07	air	EcoInvent
Pretreatment, pyro	-	-	-	-	-
Reduction, pyro	Cadmium, ion	kg	1,20E-08	air	EcoInvent
	Chromium, ion	kg	1,26E-07	water	EcoInvent
	Tin, ion	kg	1,26E-07	water	EcoInvent
	Copper, ion	kg	2,32E-07	air	EcoInvent
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	1,81E-12	air	EcoInvent
	Zinc, ion	kg	3,74E-07	water	EcoInvent
	Arsenic, ion	kg	8,25E-08	water	EcoInvent
	Zinc	kg	6,79E-04	air	EcoInvent
	Carbon dioxide, fossil	kg	9,96E-02	air	EcoInvent
	Arsenic	kg	9,06E-04	water	EcoInvent
	Particulates, > 10 um	kg	9,21E-05	water	EcoInvent
	Cadmium	kg	3,17E-04	air	EcoInvent
	Particulates, < 2.5 um	kg	4,60E-07	water	EcoInvent
	Vanadium	kg	6,79E-06	air	EcoInvent
	Lead	kg	7,05E-08	water	EcoInvent
	Carbon monoxide, fossil	kg	2,72E-05	air	EcoInvent
	Particulates, > 2.5 um, and < 10um	kg	2,76E-04	air	EcoInvent
	Chromium	kg	9,06E-07	air	EcoInvent
	Water, river	m3	4,41E-03	water	EcoInvent
	Lead	kg	2,26E-03	air	EcoInvent
	Water	m3	6,62E-04	air	EcoInvent
	Tin	kg	1,13E-04	water	EcoInvent
	Mercury	kg	1,26E-09	air	EcoInvent
	Nickel	kg	1,77E-03	water	EcoInvent
	Water	m3	3,75E-03	air	EcoInvent
	Mercury	kg	1,81E-06	water	EcoInvent
	Copper	kg	2,49E-03	water	EcoInvent
	NMVOC, non-methane volatile organic compounds, unspecified origin	kg	1,36E-05	water	EcoInvent
	Manganese	kg	2,72E-04	air	EcoInvent
	Sulfur dioxide	kg	4,15E-01	air	EcoInvent

	Selenium	kg	9,06E-05	air	EcoInvent
	Nickel, ion	kg	9,38E-08	air	EcoInvent
	Antimony	kg	1,13E-04	air	EcoInvent
Refining, pyro	-	-	-	-	-
Mining, hydro	Occupation, mineral extraction site	m2*year	2,07E-02	land	EcoInvent
	Transformation, to mineral extraction site	m2	6,89E-04	land	EcoInvent
	Transformation, from unspecified	m2	6,89E-04	land	EcoInvent
	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	kg	2,04E+00	in ground	EcoInvent
Pretreatment, leaching and extraction, hydro	Water	m3	2,55E-02	unspecified	EcoInvent
	Water, river	m3	1,70E-01	water	EcoInvent
	Water	m3	1,45E-01	unspecified	EcoInvent
Refining, hydro					EcoInvent
Secondary Production: Smelting	PM<2,5	Kg	2,96E-04	air	EcoInvent
	PM2.5-10	Kg	9,86E-03	air	EcoInvent
	PM>10	Kg	9,86E-03	air	EcoInvent
	SO2 to air	Kg	3,15E-01	air	EcoInvent
	NOx to air	Kg	1,05E-01	air	EcoInvent
	CO to air	Kg	2,10E-01	air	EcoInvent
	Arsenic to air	Kg	2,10E-01	air	EcoInvent
	Antimony to air	Kg	3,15E-04	air	EcoInvent
	Cadmium to air	Kg	3,15E-04	air	EcoInvent
	Copper to air	Kg	8,92E-03	air	EcoInvent
	Lead to air	Kg	9,45E-03	air	EcoInvent
	Nickel to air	Kg	1,05E-04	air	EcoInvent
	Zinc to air	Kg	3,94E-02	air	EcoInvent
	TCDD	Kg	5,26E-11	air	EcoInvent
	Waste heat	Kg	4,18E+00	air	EcoInvent
Secondary Production: Refining	-	-	-	-	-

Table H2: Emission factors, North America

Process	Emission	Unit	Amount/kg Cu out of the process	Compartment	Reference
Mining, pyro	Transformation, to mineral extraction site	m2	3,06E-04	natural resource	EcoInvent
	Copper, 0.59% in sulfide, Cu 0.22% and Mo 8.2E-3% in crude ore, in ground	kg	1,04E+00	natural resource	EcoInvent
	Transformation, from unspecified	m2	3,06E-04	natural resource	EcoInvent
	Occupation, mineral extraction site	m2*year	9,21E-03	natural resource	EcoInvent

	Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	kg	2,33E-02	natural resource	EcoInvent
Beneficiation, pyro	Water, river	m3	1,81E-01	natural resource	EcoInvent
	Water	m3	9,03E-02	water	EcoInvent
	Copper, ion	kg	1,43E-06	water	EcoInvent
	Mercury	kg	6,80E-09	water	EcoInvent
	Water	m3	9,03E-02	air	EcoInvent
	Cadmium, ion	kg	5,70E-08	water	EcoInvent
	Zinc	kg	1,54E-05	air	EcoInvent
	Antimony	kg	1,62E-08	air	EcoInvent
	Cadmium	kg	8,94E-09	air	EcoInvent
	Manganese	kg	4,46E-06	water	EcoInvent
	Manganese	kg	7,72E-05	air	EcoInvent
	Nickel, ion	kg	4,40E-06	water	EcoInvent
	Iron, ion	kg	5,26E-05	water	EcoInvent
	Sulfate	kg	4,25E-01	water	EcoInvent
	Arsenic, ion	kg	5,32E-07	water	EcoInvent
	Cobalt	kg	1,62E-06	air	EcoInvent
	TOC, Total Organic Carbon	kg	7,37E-04	water	EcoInvent
	Carbon dioxide, fossil	kg	9,33E-02	air	EcoInvent
	Particulates, < 2.5 um	kg	4,13E-02	air	EcoInvent
	Aluminium	kg	1,56E-05	water	EcoInvent
	Nickel	kg	6,50E-06	air	EcoInvent
	Calcium, ion	kg	1,24E-01	water	EcoInvent
	Dissolved solids	kg	9,33E-04	water	EcoInvent
	Copper	kg	4,07E-06	air	EcoInvent
	Cobalt	kg	1,41E-07	water	EcoInvent
	Fluorine	kg	7,72E-05	air	EcoInvent
	BOD5, Biological Oxygen Demand	kg	1,88E-03	water	EcoInvent
	Arsenic	kg	1,22E-07	air	EcoInvent
	Zinc, ion	kg	1,37E-05	water	EcoInvent
	Chromium, ion	kg	9,89E-08	water	EcoInvent
	Particulates, > 2.5 um, and < 10um	kg	3,59E-02	air	EcoInvent
	Mercury	kg	4,07E-09	air	EcoInvent
	Lead	kg	5,05E-07	water	EcoInvent
	Boron	kg	8,11E-07	air	EcoInvent
	Beryllium	kg	2,11E-07	air	EcoInvent
	DOC, Dissolved Organic Carbon	kg	7,37E-04	water	EcoInvent
	COD, Chemical Oxygen Demand	kg	1,88E-03	water	EcoInvent
	Nitrogen, organic bound	kg	4,10E-03	water	EcoInvent
	Chromium	kg	8,11E-06	air	EcoInvent
	Selenium	kg	4,07E-09	air	EcoInvent
	Particulates, > 10 um	kg	3,98E-03	air	EcoInvent
	Lead	kg	1,14E-06	air	EcoInvent
	Carbon disulfide	kg	1,76E-02	air	EcoInvent
	Cyanide	kg	6,86E-04	water	EcoInvent

Pretreatment, pyro	Water	M3	5,33E-01	water	EcoInvent
Reduction, pyro	Water	m3	3,53E-03	water	EcoInvent
	Copper, ion	kg	2,19E-07	water	EcoInvent
	Particulates, > 2.5 um, and < 10um	kg	2,51E-04	air	EcoInvent
	Arsenic	kg	2,68E-05	air	EcoInvent
	Lead	kg	1,24E-04	air	EcoInvent
	Copper	kg	2,06E-04	air	EcoInvent
	Zinc, ion	kg	3,52E-07	water	EcoInvent
	Mercury	kg	1,19E-09	water	EcoInvent
	NMVOC, non-methane volatile organic compounds, unspecified origin	kg	1,24E-05	air	EcoInvent
	Particulates, > 10 um	kg	8,38E-05	air	EcoInvent
	Carbon monoxide, fossil	kg	2,47E-05	air	EcoInvent
	Cadmium, ion	kg	1,13E-08	water	EcoInvent
	Tin, ion	kg	1,19E-07	water	EcoInvent
	Mercury	kg	8,24E-08	air	EcoInvent
	Selenium	kg	4,53E-06	air	EcoInvent
	Vanadium	kg	3,09E-07	air	EcoInvent
	Chromium, ion	kg	1,19E-07	water	EcoInvent
	Chromium	kg	4,12E-08	air	EcoInvent
	Water	m3	6,23E-04	air	EcoInvent
	Lead	kg	6,64E-08	water	EcoInvent
	Arsenic, ion	kg	7,77E-08	water	EcoInvent
	Sulfur dioxide	kg	3,27E-01	air	EcoInvent
	Water, river	m3	4,15E-03	natural resource	EcoInvent
	Nickel, ion	kg	8,83E-08	water	EcoInvent
	Antimony	kg	4,53E-06	air	EcoInvent
	Particulates, < 2.5 um	kg	4,19E-07	air	EcoInvent EcoInvent
	Tin	kg	5,15E-06	air	EcoInvent
	Cadmium	kg	5,36E-06	air	EcoInvent
	Manganese	kg	1,24E-05	air	EcoInvent
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	1,65E-12	air	EcoInvent
	Zinc	kg	1,24E-04	air	EcoInvent
	Carbon dioxide, fossil	kg	9,07E-02	air	EcoInvent
	Nickel	kg	4,53E-05	air	EcoInvent
Refining, pyro	-	-	-	-	-
Mining, hydro	Occupation, mineral extraction site	m2*year	2,07E-02	land	EcoInvent
	Transformation, to mineral extraction site	m2	6,89E-04	land	EcoInvent
	Transformation, from unspecified	m2	6,89E-04	land	EcoInvent
	Copper, 0.99% in sulfide, Cu 0.36%	kg	2,04E+00	in ground	EcoInvent

	and Mo 8.2E-3% in crude ore, in ground				
Pretreatment, leaching and extraction, hydro	Water	m3	2,55E-02	unspecified	EcoInvent
	Water, river	m3	1,70E-01	water	EcoInvent
	Water	m3	1,45E-01	unspecified	EcoInvent
Refining, hydro	-	-	-	-	-
Secondary Production: Smelting	PM<2,5	Kg	2,96E-04	air	EcoInvent
	PM2.5-10	Kg	9,86E-03	air	EcoInvent
	PM>10	Kg	9,86E-03	air	EcoInvent
	SO2 to air	Kg	3,15E-01	air	EcoInvent
	NOx to air	Kg	1,05E-01	air	EcoInvent
	CO to air	Kg	2,10E-01	air	EcoInvent
	Arsenic to air	Kg	2,10E-01	air	EcoInvent
	Antimony to air	Kg	3,15E-04	air	EcoInvent
	Cadmium to air	Kg	3,15E-04	air	EcoInvent
	Copper to air	Kg	8,92E-03	air	EcoInvent
	Lead to air	Kg	9,45E-03	air	EcoInvent
	Nickel to air	Kg	1,05E-04	air	EcoInvent
	Zinc to air	Kg	3,94E-02	air	EcoInvent
	TCDD	Kg	5,26E-11	air	EcoInvent
	Waste heat	Kg	4,18E+00	air	EcoInvent
Secondary Production: Refining	-	-	-	-	-

Table H3: Emission factors, Latin America

Process	Emission	Unit	Amount/kg Cu out of the process	Compartment	Reference
Mining, pyro	Transformation, to mineral extraction site	m2	1,52E-04	natural resource	EcoInvent
	Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	kg	1,03E+00	natural resource	EcoInvent
	Transformation, from unspecified	m2	1,52E-04	natural resource	EcoInvent
	Occupation, mineral extraction site	m2*year	4,56E-03	natural resource	EcoInvent
	Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	kg	2,05E-02	natural resource	EcoInvent
Beneficiation, pyro	COD, Chemical Oxygen Demand	kg	7,55E-04	water	EcoInvent
	Chromium, ion	kg	3,96E-08	water	EcoInvent
	Water	m3	3,63E-02	air	EcoInvent
	Aluminum	kg	6,26E-06	water	EcoInvent
	Mercury	kg	2,72E-09	water	EcoInvent
	Nitrogen, organic bound	kg	1,65E-03	water	EcoInvent
	Water	m3	3,63E-02	water	EcoInvent
	Zinc, ion	kg	5,50E-06	water	EcoInvent
	Cobalt	kg	5,66E-08	water	EcoInvent
	Carbon dioxide,	kg	5,11E-02	air	EcoInvent

	fossil				
	Cadmium	kg	4,43E-09	air	EcoInvent
	Dissolved solids	kg	3,75E-04	water	EcoInvent
	Calcium, ion	kg	4,98E-02	water	EcoInvent
	Iron, ion	kg	2,11E-05	water	EcoInvent
	Copper, ion	kg	5,74E-07	water	EcoInvent
	Sulfate	kg	1,71E-01	water	EcoInvent
	Particulates, < 2.5 um	kg	2,04E-02	air	EcoInvent
	Nickel, ion	kg	1,77E-06	water	EcoInvent
	DOC, Dissolved Organic Carbon	kg	2,96E-04	water	EcoInvent
	Nickel	kg	3,22E-06	air	EcoInvent
	Cadmium, ion	kg	2,29E-08	water	EcoInvent
	Cyanide	kg	3,38E-04	water	EcoInvent
	TOC, Total Organic Carbon	kg	2,96E-04	water	EcoInvent
	Mercury	kg	2,01E-09	air	EcoInvent
	Boron	kg	4,01E-07	air	EcoInvent
	Cobalt	kg	8,04E-07	air	EcoInvent
	Carbon disulfide	kg	8,72E-03	air	EcoInvent
	Copper	kg	2,01E-06	air	EcoInvent
	Water, river	m3	7,26E-02	air	EcoInvent
	Manganese	kg	3,83E-05	water	EcoInvent
	BOD5, Biological Oxygen Demand	kg	7,55E-04	air	EcoInvent
	Fluorine	kg	3,83E-05	water	EcoInvent
	Arsenic, ion	kg	2,14E-07	natural resource	EcoInvent
	Antimony	kg	8,04E-09	air	EcoInvent
	Beryllium	kg	1,05E-07	air	EcoInvent
	Lead	kg	2,03E-07	water	EcoInvent
	Lead	kg	5,63E-07	air	EcoInvent
	Zinc	kg	7,62E-06	air	EcoInvent
	Particulates, > 10 um	kg	1,98E-03	air	EcoInvent
	Selenium	kg	2,01E-09	air	EcoInvent
	Particulates, > 2.5 um, and < 10um	kg	1,78E-02	air	EcoInvent
	Chromium	kg	4,01E-06	air	EcoInvent
	Arsenic	kg	6,03E-08	air	EcoInvent
	Manganese	kg	1,79E-06	water	EcoInvent
Pretreatment, pyro	water	m3	4,28E-01	water	EcoInvent
Reduction, pyro	Vanadium	kg	6,18E-06	air	EcoInvent
	Copper, ion	kg	1,93E-07	water	EcoInvent
	Selenium	kg	8,24E-05	air	EcoInvent
	Chromium, ion	kg	1,05E-07	water	EcoInvent
	Tin, ion	kg	1,05E-07	water	EcoInvent
	Zinc	kg	6,18E-04	air	EcoInvent
	Water	m3	5,51E-04	air	EcoInvent
	Chromium	kg	8,24E-07	air	EcoInvent
	Mercury	kg	1,05E-09	water	EcoInvent
	Arsenic, ion	kg	6,86E-08	water	EcoInvent
	Water, river	m3	3,67E-03	natural resource	EcoInvent
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	1,65E-12	air	EcoInvent

	Mercury	kg	1,65E-06	air	EcoInvent
	Copper	kg	2,27E-03	air	EcoInvent
	Nickel	kg	1,61E-03	air	EcoInvent
	Antimony	kg	1,03E-04	air	EcoInvent
	Tin	kg	1,03E-04	air	EcoInvent
	Lead	kg	2,06E-03	air	EcoInvent
	Carbon monoxide, fossil	kg	2,47E-05	air	EcoInvent
	Lead	kg	5,86E-08	water	EcoInvent
	Manganese	kg	2,47E-04	air	EcoInvent
	Arsenic	kg	8,24E-04	air	EcoInvent
	Water	m3	3,12E-03	water	EcoInvent
	Zinc, ion	kg	3,11E-07	water	EcoInvent
	Cadmium	kg	2,88E-04	air	EcoInvent
	Sulfur dioxide	kg	3,27E-01	air	EcoInvent
	Nickel, ion	kg	7,80E-08	water	EcoInvent
	Particulates, > 2.5 um, and < 10um	kg	2,51E-04	air	EcoInvent
	Cadmium, ion	kg	1,00E-08	water	EcoInvent
	Carbon dioxide, fossil	kg	9,07E-02	air	EcoInvent
Refining, pyro	-	-	-	-	-
Mining, hydro	Occupation, mineral extraction site	m2*year	2,07E-02	land	EcoInvent
	Transformation, to mineral extraction site	m2	6,89E-04	land	EcoInvent
	Transformation, from unspecified	m2	6,89E-04	land	EcoInvent
	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	kg	2,04E+00	in ground	EcoInvent
Pretreatment, leaching and extraction, hydro	Water	m3	2,55E-02	unspecified	EcoInvent
	Water, river	m3	1,70E-01	water	EcoInvent
	Water	m3	1,45E-01	unspecified	EcoInvent
Refining, hydro	-	-	-	-	-
Secondary Production: Smelting	PM<2,5	Kg	2,96E-04	air	EcoInvent
	PM2.5-10	Kg	9,86E-03	air	EcoInvent
	PM>10	Kg	9,86E-03	air	EcoInvent
	SO2 to air	Kg	3,15E-01	air	EcoInvent
	NOx to air	Kg	1,05E-01	air	EcoInvent
	CO to air	Kg	2,10E-01	air	EcoInvent
	Arsenic to air	Kg	2,10E-01	air	EcoInvent
	Antimony to air	Kg	3,15E-04	air	EcoInvent
	Cadmium to air	Kg	3,15E-04	air	EcoInvent
	Copper to air	Kg	8,92E-03	air	EcoInvent
	Lead to air	Kg	9,45E-03	air	EcoInvent
	Nickel to air	Kg	1,05E-04	air	EcoInvent
	Zinc to air	Kg	3,94E-02	air	EcoInvent
	TCDD	Kg	5,26E-11	air	EcoInvent
	Waste heat	Kg	4,18E+00	air	EcoInvent
Secondary Production: Refining	-	-	-	-	-

Table H4: Emission factors, Asia

Process	Emission	Unit	Amount/kg Cu out of the process	Compartment	Reference
Mining, pyro	Transformation, to mineral extraction site	m2	4,43E-04	natural resource	EcoInvent
	Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore, in ground	kg	1,33E+00	natural resource	EcoInvent
	Transformation, from unspecified	m2	4,43E-04	natural resource	EcoInvent
	Occupation, mineral extraction site	m2*year	1,33E-02	natural resource	EcoInvent
	Molybdenum, 0.016% in sulfide, Mo 8.2E-3% and Cu 0.27% in crude ore, in ground	kg	3,18E-02	natural resource	EcoInvent
Beneficiation, pyro	Cobalt	kg	2,66E-07	water	EcoInvent
	Carbon disulfide	kg	2,55E-02	air	EcoInvent
	Arsenic	kg	1,76E-07	air	EcoInvent
	Lead	kg	9,54E-07	water	EcoInvent
	Mercury	kg	5,85E-09	air	EcoInvent
	Nickel	kg	9,38E-06	air	EcoInvent
	Antimony	kg	2,35E-08	air	EcoInvent
	Aluminum	kg	2,94E-05	water	EcoInvent
	TOC, Total Organic Carbon	kg	1,39E-03	water	EcoInvent
	Nitrogen, organic bound	kg	7,75E-03	water	EcoInvent
	Mercury	kg	1,28E-08	water	EcoInvent
	Water	m3	1,71E-01	water	EcoInvent
	Cadmium	kg	1,29E-08	air	EcoInvent
	Zinc, ion	kg	2,59E-05	water	EcoInvent
	Nickel, ion	kg	8,28E-06	water	EcoInvent
	Sulfate	kg	8,04E-01	water	EcoInvent
	Arsenic, ion	kg	1,01E-06	water	EcoInvent
	Chromium	kg	1,17E-05	air	EcoInvent
	Water, river	m3	3,41E-01	natural resource	EcoInvent
	Copper, ion	kg	2,70E-06	water	EcoInvent
	Particulates, < 2.5 um	kg	5,97E-02	air	EcoInvent
	Selenium	kg	5,85E-09	air	EcoInvent
	Calcium, ion	kg	2,34E-01	water	EcoInvent
	Iron, ion	kg	9,91E-05	water	EcoInvent
	Carbon dioxide, fossil	kg	1,48E-01	air	EcoInvent
	Cyanide	kg	9,91E-04	water	EcoInvent
	BOD5, Biological Oxygen Demand	kg	3,55E-03	water	EcoInvent
	Copper	kg	5,85E-06	air	EcoInvent
	Cobalt	kg	2,35E-06	air	EcoInvent
	Fluorine	kg	1,11E-04	air	EcoInvent
	Particulates, > 10 um	kg	5,77E-03	air	EcoInvent
	Water	m3	1,71E-01	air	EcoInvent

	Lead	kg	1,64E-06	air	EcoInvent
	Cadmium, ion	kg	1,08E-07	water	EcoInvent
	Manganese	kg	1,11E-04	air	EcoInvent
	Particulates, > 2.5 um, and < 10um	kg	5,20E-02	air	EcoInvent
	COD, Chemical Oxygen Demand	kg	3,55E-03	water	EcoInvent
	Beryllium	kg	3,05E-07	air	EcoInvent
	Zinc	kg	2,23E-05	air	EcoInvent
	Boron	kg	1,17E-06	air	EcoInvent
	Dissolved solids	kg	1,76E-03	water	EcoInvent
	Chromium, ion	kg	1,86E-07	water	EcoInvent
	DOC, Dissolved Organic Carbon	kg	1,39E-03	water	EcoInvent
	Manganese	kg	8,40E-06	water	EcoInvent
Pretreatment, pyro	water	m3	8,87E-01	water	EcoInvent
Reduction, pyro	Mercury	kg	2,00E-06	air	EcoInvent
	Manganese	kg	3,00E-04	air	EcoInvent
	Sulfur dioxide	kg	5,77E-01	air	EcoInvent
	Carbon monoxide, fossil	kg	3,00E-05	air	EcoInvent
	Particulates, < 2.5 um	kg	5,08E-07	air	EcoInvent
	Selenium	kg	1,00E-04	air	EcoInvent
	Antimony	kg	1,25E-04	air	EcoInvent
	Cadmium	kg	3,50E-04	air	EcoInvent
	Chromium	kg	1,00E-06	air	EcoInvent
	Copper	kg	2,75E-03	air	EcoInvent
	Carbon dioxide, fossil	kg	1,10E-01	air	EcoInvent
	Vanadium	kg	7,50E-06	air	EcoInvent
	Water	m3	4,83E-03	water	EcoInvent
	Lead	kg	9,08E-08	air	EcoInvent
	Particulates, > 10 um	kg	1,02E-04	air	EcoInvent
	Tin	kg	1,25E-04	air	EcoInvent
	Nickel	kg	1,95E-03	air	EcoInvent
	Lead	kg	2,50E-03	air	EcoInvent
	Cadmium, ion	kg	1,55E-08	water	EcoInvent
	Zinc, ion	kg	4,82E-07	water	EcoInvent
	Arsenic, ion	kg	1,06E-07	water	EcoInvent
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	2,00E-12	air	EcoInvent
	Chromium, ion	kg	1,62E-07	water	EcoInvent
	Particulates, > 2.5 um, and < 10um	kg	3,04E-04	air	EcoInvent
	Tin, ion	kg	1,62E-07	water	EcoInvent
	Nickel, ion	kg	1,21E-07	water	EcoInvent
	NMVOC, non-methane volatile organic compounds, unspecified origin	kg	1,50E-05	air	EcoInvent
	Water, river	m3	5,68E-03	water	EcoInvent

	Mercury	kg	1,62E-09	air	EcoInvent
	Water	m3	8,52E-04	water	EcoInvent
	Arsenic	kg	1,00E-03	air	EcoInvent
	Copper, ion	kg	2,99E-07	water	EcoInvent
	Zinc	kg	7,50E-04	air	EcoInvent
Refining, pyro	-	-	-	-	-
Mining, hydro	Occupation, mineral extraction site	m2*year	2,07E-02	land	EcoInvent
	Transformation, to mineral extraction site	m2	6,89E-04	land	EcoInvent
	Transformation, from unspecified	m2	6,89E-04	land	EcoInvent
	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	kg	2,04E+00	in ground	EcoInvent
Pretreatment, leaching and extraction, hydro	Water	m3	2,55E-02	unspecified	EcoInvent
	Water, river	m3	1,70E-01	water	EcoInvent
	Water	m3	1,45E-01	unspecified	EcoInvent
Refining, hydro	-	-	-	-	-
Secondary Production: Smelting	PM<2,5	Kg	2,96E-04	air	EcoInvent
	PM2.5-10	Kg	9,86E-03	air	EcoInvent
	PM>10	Kg	9,86E-03	air	EcoInvent
	SO2 to air	Kg	3,15E-01	air	EcoInvent
	NOx to air	Kg	1,05E-01	air	EcoInvent
	CO to air	Kg	2,10E-01	air	EcoInvent
	Arsenic to air	Kg	2,10E-01	air	EcoInvent
	Antimony to air	Kg	3,15E-04	air	EcoInvent
	Cadmium to air	Kg	3,15E-04	air	EcoInvent
	Copper to air	Kg	8,92E-03	air	EcoInvent
	Lead to air	Kg	9,45E-03	air	EcoInvent
	Nickel to air	Kg	1,05E-04	air	EcoInvent
	Zinc to air	Kg	3,94E-02	air	EcoInvent
	TCDD	Kg	5,26E-11	air	EcoInvent
	Waste heat	Kg	4,18E+00	air	EcoInvent
Secondary Production: Refining	-	-	-	-	-

Table H5: Emission factors, Oceania

Process	Emission	Unit	Amount/kg Cu out of the process	Compartment	Reference
Mining, pyro	Transformation, to mineral extraction site	m2	1,61E-04	natural resource	EcoInvent
	Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	kg	1,32E+00	natural resource	EcoInvent
	Transformation, from unspecified	m2	1,61E-04	natural resource	EcoInvent
	Occupation,				

	mineral extraction site	m2*year	4,83E-03	natural resource	EcoInvent
	Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	kg	2,70E-02	natural resource	EcoInvent
Beneficiation, pyro	Chromium, ion	kg	6,25E-08	water	EcoInvent
	Arsenic, ion	kg	3,37E-07	water	EcoInvent
	Cyanide	kg	3,00E-04	air	EcoInvent
	Chromium	kg	3,57E-06	air	EcoInvent
	Dissolved solids	kg	5,90E-04	air	EcoInvent
	Mercury	kg	1,78E-09	air	EcoInvent
	Calcium, ion	kg	7,83E-02	water	EcoInvent
	Manganese	kg	3,40E-05	air	EcoInvent
	Cadmium, ion	kg	3,63E-08	water	EcoInvent
	Water	m3	5,72E-02	air	EcoInvent
	Sulfate	kg	2,70E-01	air	EcoInvent
	TOC, Total Organic Carbon	kg	4,67E-04	air	EcoInvent
	Copper	kg	1,78E-06	air	EcoInvent
	Iron, ion	kg	3,31E-05	water	EcoInvent
	Antimony	kg	7,11E-09	air	EcoInvent
	Carbon disulfide	kg	7,75E-03	air	EcoInvent
	Beryllium	kg	9,27E-08	air	EcoInvent
	Particulates, < 2.5 um	kg	1,81E-02	air	EcoInvent
	Carbon dioxide, fossil	kg	4,29E-02	air	EcoInvent
	Zinc	kg	6,77E-06	air	EcoInvent
	Fluorine	kg	3,40E-05	air	EcoInvent
	Lead	kg	3,20E-07	air	EcoInvent
	Water, river	m3	1,14E-01	water	EcoInvent
	Arsenic	kg	5,36E-08	air	EcoInvent
	Mercury	kg	4,32E-09	air	EcoInvent
	Nickel, ion	kg	2,78E-06	water	EcoInvent
	Aluminium	kg	9,88E-06	air	EcoInvent
	Zinc, ion	kg	8,67E-06	water	EcoInvent
	Lead	kg	4,98E-07	air	EcoInvent
	Cadmium	kg	3,92E-09	air	EcoInvent
	Particulates, > 10 um	kg	1,75E-03	air	EcoInvent
	COD, Chemical Oxygen Demand	kg	1,19E-03	air	EcoInvent
	BOD5, Biological Oxygen Demand	kg	1,19E-03	air	EcoInvent
	Boron	kg	3,57E-07	air	EcoInvent
	Nitrogen, organic bound	kg	2,60E-03	air	EcoInvent
	DOC, Dissolved Organic Carbon	kg	4,67E-04	air	EcoInvent
	Water	kg	5,72E-02	air	EcoInvent
	Cobalt	kg	8,93E-08	air	EcoInvent
	Cobalt	kg	7,11E-07	water	EcoInvent
	Manganese	kg	2,82E-06	air	EcoInvent
	Particulates, > 2.5 um, and < 10um	kg	1,58E-02	air	EcoInvent

	Selenium	kg	1,78E-09	air	EcoInvent
	Nickel	kg	2,85E-06	air	EcoInvent
	Copper, ion	kg	9,04E-07	water	EcoInvent
Pretreatment, pyro	water	m3	8,12E-01	water	EcoInvent
Reduction, pyro	Cadmium, ion	kg	1,20E-08	air	EcoInvent
	Chromium, ion	kg	1,26E-07	water	EcoInvent
	Tin, ion	kg	1,26E-07	water	EcoInvent
	Copper, ion	kg	2,32E-07	air	EcoInvent
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	1,81E-12	air	EcoInvent
	Zinc, ion	kg	3,74E-07	water	EcoInvent
	Arsenic, ion	kg	8,25E-08	water	EcoInvent
	Zinc	kg	6,79E-04	air	EcoInvent
	Carbon dioxide, fossil	kg	9,96E-02	air	EcoInvent
	Arsenic	kg	9,06E-04	water	EcoInvent
	Particulates, > 10 um	kg	9,21E-05	water	EcoInvent
	Cadmium	kg	3,17E-04	air	EcoInvent
	Particulates, < 2.5 um	kg	4,60E-07	water	EcoInvent
	Vanadium	kg	6,79E-06	air	EcoInvent
	Lead	kg	7,05E-08	natural resource	EcoInvent
	Carbon monoxide, fossil	kg	2,72E-05	water	EcoInvent
	Particulates, > 2.5 um, and < 10um	kg	2,76E-04	air	EcoInvent
	Chromium	kg	9,06E-07	air	EcoInvent
	Water, river	m3	4,41E-03	natural resource	EcoInvent
	Lead	kg	2,26E-03	air	EcoInvent
	Water	m3	6,62E-04	water	EcoInvent
	Tin	kg	1,13E-04	air	EcoInvent
	Mercury	kg	1,26E-09	air	EcoInvent
	Nickel	kg	1,77E-03	water	EcoInvent
	Water	m3	3,75E-03	air	EcoInvent
	Mercury	kg	1,81E-06	water	EcoInvent
	Copper	kg	2,49E-03	air	EcoInvent
	NMVOC, non-methane volatile organic compounds, unspecified origin	kg	1,36E-05	water	EcoInvent
	Manganese	kg	2,72E-04	water	EcoInvent
	Sulfur dioxide	kg	4,15E-01	water	EcoInvent
	Selenium	kg	9,06E-05	air	EcoInvent
	Nickel, ion	kg	9,38E-08	air	EcoInvent
	Antimony	kg	1,13E-04	natural resource	EcoInvent
Refining, pyro	-	-	-	-	-
Mining, hydro	Occupation, mineral extraction site	m2*year	2,07E-02	land	EcoInvent
	Transformation, to mineral extraction site	m2	6,89E-04	land	EcoInvent

	Transformation, from unspecified Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	m2 kg	6,89E-04 2,04E+00	land in ground	EcoInvent EcoInvent
Pretreatment, leaching and extraction, hydro	Water Water, river Water	m3 m3 m3	2,55E-02 1,70E-01 1,45E-01	unspecified water unspecified	EcoInvent EcoInvent EcoInvent
Refining, hydro	-	-	-	-	-
Secondary Production: Smelting	PM<2,5 PM2.5-10 PM>10 SO2 to air NOx to air CO to air Arsenic to air Antimony to air Cadmium to air Copper to air Lead to air Nickel to air Zinc to air TCDD Waste heat	Kg Kg Kg Kg Kg Kg Kg Kg Kg Kg Kg Kg Kg Kg Kg	2,96E-04 9,86E-03 9,86E-03 3,15E-01 1,05E-01 2,10E-01 2,10E-01 3,15E-04 3,15E-04 8,92E-03 9,45E-03 1,05E-04 3,94E-02 5,26E-11 4,18E+00	air air air air air air air air air air air air air air air	EcoInvent EcoInvent EcoInvent EcoInvent EcoInvent EcoInvent EcoInvent EcoInvent EcoInvent EcoInvent EcoInvent EcoInvent EcoInvent EcoInvent EcoInvent
Secondary Production: Refining	-	-	-	-	-

Table H6: Emission factors, Europe

Process	Emission	Unit	Amount/kg Cu out of the process	Compartment	Reference
Mining, pyro	Transformation, to mineral extraction site Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground Transformation, from unspecified Occupation, mineral extraction site Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	m2 kg m2 m2*year kg	1,06E-04 1,34E+00 1,06E-04 3,19E-03 3,89E-02	natural resource natural resource natural resource natural resource natural resource	EcoInvent EcoInvent EcoInvent EcoInvent EcoInvent
Beneficiation, pyro	Selenium Aluminium Cobalt Nitrogen, organic	kg kg kg kg	1,17E-09 3,20E-06 4,68E-07 8,40E-04	air water air water	EcoInvent EcoInvent EcoInvent EcoInvent

	bound				
	Chromium, ion	kg	2,02E-08	water	EcoInvent
	Arsenic	kg	3,52E-08	air	EcoInvent
	Fluorine	kg	2,23E-05	air	EcoInvent
	Manganese	kg	2,23E-05	air	EcoInvent
	TOC, Total Organic Carbon	kg	1,51E-04	water	EcoInvent
	Manganese	kg	9,11E-07	water	EcoInvent
	Particulates, < 2.5 um	kg	1,19E-02	air	EcoInvent
	Water, river	m3	3,70E-02	natural resource	EcoInvent
	Cadmium	kg	2,58E-09	air	EcoInvent
	BOD5, Biological Oxygen Demand	kg	3,85E-04	water	EcoInvent
	Chromium	kg	2,35E-06	air	EcoInvent
	DOC, Dissolved Organic Carbon	kg	1,51E-04	water	EcoInvent
	Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground				
	Particulates, > 2.5 um, and < 10um	kg	1,04E-02	air	EcoInvent
	Antimony	kg	4,68E-09	air	EcoInvent
	Beryllium	kg	6,09E-08	air	EcoInvent
	Boron	kg	2,35E-07	air	EcoInvent
	COD, Chemical Oxygen Demand	kg	3,85E-04	water	EcoInvent
	Cyanide	kg	1,98E-04	water	EcoInvent
	Nickel	kg	1,88E-06	air	EcoInvent
	Sulfate	kg	8,74E-02	water	EcoInvent
	Copper, ion	kg	2,93E-07	water	EcoInvent
	Arsenic, ion	kg	1,09E-07	water	EcoInvent
	Mercury	kg	1,40E-09	water	EcoInvent
	Lead	kg	1,04E-07	water	EcoInvent
	Lead	kg	3,28E-07	air	EcoInvent
	Nickel, ion	kg	9,03E-07	water	EcoInvent
	Cobalt	kg	2,89E-08	water	EcoInvent
	Carbon disulfide	kg	5,09E-03	air	EcoInvent
	Mercury	kg	1,17E-09	air	EcoInvent
	Zinc	kg	4,47E-06	air	EcoInvent
	Copper	kg	1,17E-06	air	EcoInvent
	Particulates, > 10 um	kg	1,16E-03	air	EcoInvent
	Iron, ion	kg	1,08E-05	water	EcoInvent
	Water	kg	1,85E-02	air	EcoInvent
	Carbon dioxide, fossil	m3	2,99E-02	air	EcoInvent
	Water	kg	1,85E-02	water	EcoInvent
	Zinc, ion	kg	2,81E-06	water	EcoInvent
	Calcium, ion	kg	2,54E-02	water	EcoInvent
	Cadmium, ion	kg	1,17E-08	water	EcoInvent
	Dissolved solids	kg	1,91E-04	water	EcoInvent
Pretreatment, pyro	water	m3	4,05E-01	water	EcoInvent
Reduction, pyro	Tin	kg	6,25E-06	air	EcoInvent

	Particulates, > 10 um	kg	1,02E-04	air	EcoInvent
	Water	m3	4,93E-03	water	EcoInvent
	Antimony	kg	5,50E-06	air	EcoInvent
	Zinc	kg	1,50E-04	air	EcoInvent
	Water	m3	8,70E-04	air	EcoInvent
	Vanadium	kg	3,75E-07	air	EcoInvent
	Arsenic, ion	kg	1,08E-07	water	EcoInvent
	Cadmium	kg	6,50E-06	air	EcoInvent
	Chromium, ion	kg	1,66E-07	water	EcoInvent
	Particulates, < 2.5 um	kg	5,08E-07	air	EcoInvent
	Nickel, ion	kg	1,23E-07	water	EcoInvent
	Chromium	kg	5,00E-08	air	EcoInvent
	NMVOC, non-methane volatile organic compounds, unspecified origin	kg	1,50E-05	air	EcoInvent
	Tin, ion	kg	1,66E-07	water	EcoInvent
	Sulfuric acid	kg	0,00E+00	air	EcoInvent
	Nickel	kg	5,50E-05	air	EcoInvent
	Copper, ion	kg	3,05E-07	water	EcoInvent
	Cadmium, ion	kg	1,58E-08	water	EcoInvent
	Manganese	kg	1,50E-05	air	EcoInvent
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	2,00E-12	air	EcoInvent
	Lead	kg	9,26E-08	water	EcoInvent
	Lead	kg	1,50E-04	air	EcoInvent
	Zinc, ion	kg	4,91E-07	water	EcoInvent
	Copper	kg	2,50E-04	air	EcoInvent
	Carbon dioxide, fossil	kg	1,10E-01	air	EcoInvent
	Mercury	kg	1,00E-07	air	EcoInvent
	Particulates, > 2.5 um, and < 10um	kg	3,04E-04	air	EcoInvent
	Mercury	kg	1,66E-09	water	EcoInvent
	Sulfur dioxide	kg	3,57E-02	air	EcoInvent
	Carbon monoxide, fossil	kg	3,00E-05	air	EcoInvent
	Arsenic	kg	3,25E-05	air	EcoInvent
	Water, river	m3	5,80E-03	natural resource	EcoInvent
	Selenium	kg	5,50E-06	air	EcoInvent
Refining, pyro		-	-	-	-
Mining, hydro	Occupation, mineral extraction site	m2*year	2,07E-02	land	EcoInvent
	Transformation, to mineral extraction site	m2	6,89E-04	land	EcoInvent
	Transformation, from unspecified	m2	6,89E-04	land	EcoInvent
	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in	kg	2,04E+00	in ground	EcoInvent

	crude ore, in ground				
Pretreatment, leaching and extraction, hydro	Water Water, river Water	m3 m3 m3	2,55E-02 1,70E-01 1,45E-01	unspecified water unspecified	EcoInvent EcoInvent EcoInvent
Refining, hydro	-	-	-	-	-
Secondary Production: Smelting	PM<2,5	Kg	2,96E-04	air	EcoInvent
	PM2.5-10	Kg	9,86E-03	air	EcoInvent
	PM>10	Kg	9,86E-03	air	EcoInvent
	SO2 to air	Kg	3,15E-01	air	EcoInvent
	NOx to air	Kg	1,05E-01	air	EcoInvent
	CO to air	Kg	2,10E-01	air	EcoInvent
	Arsenic to air	Kg	2,10E-01	air	EcoInvent
	Antimony to air	Kg	3,15E-04	air	EcoInvent
	Cadmium to air	Kg	3,15E-04	air	EcoInvent
	Copper to air	Kg	8,92E-03	air	EcoInvent
	Lead to air	Kg	9,45E-03	air	EcoInvent
	Nickel to air	Kg	1,05E-04	air	EcoInvent
	Zinc to air	Kg	3,94E-02	air	EcoInvent
	TCDD	Kg	5,26E-11	air	EcoInvent
	Waste heat	Kg	4,18E+00	air	EcoInvent
Secondary Production: Refining	-	-	-	-	-

Appendix I: Other information in tabular format

Table I1: Energy mix, Europe

		A1	B1	B2
2020	Coal	18 %	18 %	18 %
	Gas	22 %	16 %	16 %
	Oil	4.7 %	2.0 %	2.0 %
	Nuclear	11 %	27 %	27 %
	Hydro	21 %	16 %	16 %
	Wind++	23 %	20 %	20 %
2025	Coal	16 %	14 %	14 %
	Gas	22 %	14 %	14 %
	Oil	3.4 %	1.6 %	1.6 %
	Nuclear	9.9 %	28 %	28 %
	Hydro	20 %	17 %	17 %
	Wind++	28 %	25 %	25 %

Table I2: Energy mix, Africa

		A1	B1	B2
2020	Coal	13 %	16 %	16 %
	Gas	50 %	34 %	34 %
	Oil	19 %	18 %	18 %
	Nuclear	0.7 %	2,2 %	2.2 %
	Hydro	11 %	12 %	12 %
	Wind++	5.1 %	18 %	18 %
2025	Coal	13 %	14 %	14 %
	Gas	52 %	30 %	30 %
	Oil	16 %	15 %	15 %
	Nuclear	0.8 %	2,7 %	2.7 %
	Hydro	12 %	13 %	13 %
	Wind++	6.8 %	25 %	25 %

Table I3: Energy mix, Asia

		A1	B1	B2
2020	Coal	25 %	18 %	18 %
	Gas	35 %	32 %	32 %
	Oil	4.7 %	1.8 %	1.8 %
	Nuclear	10 %	20 %	20 %
	Hydro	23 %	19 %	19 %
	Wind++	2.9 %	9 %	9.3 %
2025	Coal	24 %	16 %	16 %
	Gas	35 %	30 %	30 %
	Oil	3.6 %	1.4 %	1.4 %
	Nuclear	10 %	20 %	20 %
	Hydro	23 %	20 %	20 %
	Wind++	3.9 %	13 %	13 %

Table I4: Energy mix, Latin America

		A1	B1	B2
2020	Coal	4.7 %	3.0 %	3.0 %
	Gas	22 %	7.7 %	7.7 %
	Oil	11 %	8.2 %	8.2 %
	Nuclear	1.5 %	4.1 %	4.1 %
	Hydro	55 %	68 %	68 %
	Wind++	5.7 %	9.1 %	9.1 %
2025	Coal	5.4 %	2.8 %	2.8 %
	Gas	24 %	5.8 %	5.8 %
	Oil	9.4 %	6.5 %	6.5 %
	Nuclear	1.5 %	5.0 %	5.0 %
	Hydro	53 %	68 %	68 %
	Wind++	6.8 %	11 %	11 %

Table I5: Energy mix, North America

		A1	B1	B2
2020	Coal	27 %	26 %	26 %
	Gas	34 %	17 %	17 %
	Oil	6.7%	1.6 %	1.6 %
	Nuclear	8.9 %	22 %	22 %
	Hydro	13 %	14 %	14 %
	Wind++	9.9 %	20 %	20 %
2025	Coal	26 %	19 %	19 %
	Gas	34 %	16 %	16 %
	Oil	6.2 %	1.2 %	1.2 %
	Nuclear	8.7 %	24 %	24 %
	Hydro	13 %	14 %	14 %
	Wind++	13 %	26 %	26 %

Table I6: Energy mix, Oceania

		A1	B1	B2
2020	Coal	22 %	25 %	25 %
	Gas	28 %	16 %	16 %
	Oil	10 %	6,5 %	6,5 %
	Nuclear	17 %	36 %	36 %
	Hydro	15 %	6,7 %	6,7 %
	Wind++	7,8 %	10 %	10 %
2025	Coal	21 %	20 %	20 %
	Gas	29 %	13 %	13 %
	Oil	8.0 %	5,2 %	5,2 %
	Nuclear	18 %	41 %	41 %
	Hydro	15 %	6,8 %	6,8 %
	Wind++	9,5 %	14 %	14 %

Three significant digits are utilized in tables I7 - I10 to present the increase better since the increase would show as 0 for some regions if we have utilized only two digits.

Table I7: Final demands [MT]

	Europe			Africa			Asia			Latin America			North America			Oceania		
	A1	B1	B2	A1	B1	B2	A1	B1	B2	A1	B1	B2	A1	B1	B2	A1	B1	B2
2020	6.58	6.56	6.56	0.38	0.38	0.38	19.5	19.4	19.4	1.01	1.00	1.00	3.39	3.38	3.38	0.25	0.25	0,.25
2025	7.52	7.64	7.64	0.43	0.44	0.44	22.2	22.6	22.6	1.15	1.17	1.17	3.87	3.94	3.94	0.29	0.29	0.29

Table I8: Ore grade

	Europe			Africa			Asia			Latin America			North America			Oceania		
	A1	B1	B2	A1	B1	B2	A1	B1	B2	A1	B1	B2	A1	B1	B2	A1	B1	B2
2020	1.78	2.40	2.40	3.36	3.36	3.36	0.87	1.04	1.08	1.46	1.46	1.46	1.47	1.47	1.47	2.01	2.01	2.01
2025	0.11	0.74	1.04	3.36	3.36	3.36	0.85	0.85	0.85	1.46	1.46	1.46	0.64	1.47	1.47	2.01	2.01	2.01

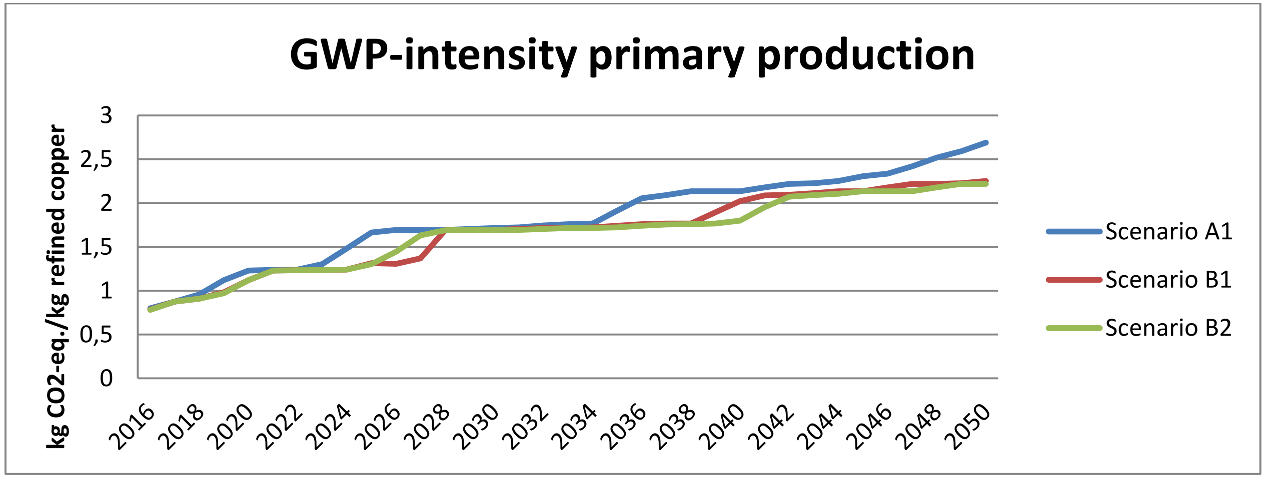
Table I9: Stripping ratio

	Europe			Africa			Asia			Latin America			North America			Oceania		
	A1	B1	B2	A1	B1	B2	A1	B1	B2	A1	B1	B2	A1	B1	B2	A1	B1	B2
2020	0.22	0.21	0.21	1.97	1.86	1.86	1.04	0.98	0.98	2.28	2.15	2.15	1.89	1.79	1.79	0.85	0.80	0.80
2025	0.24	0.22	0.22	2.18	1.95	1.95	1.15	1.03	1.03	2.52	2.26	2.26	2.09	1.88	1.88	0.94	0.84	0.84

Table I10: Recycling input rate

	Europe			Africa			Asia			Latin America			North America			Oceania		
	A1	B1	B2	A1	B1	B2	A1	B1	B2	A1	B1	B2	A1	B1	B2	A1	B1	B2
2020	36.4 %	48.4 %	50.4 %	36.4 %	48.4 %	50.4 %	36.4 %	48.4 %	50.4 %	36.4 %	48.4 %	50.4 %	36.4 %	48.4 %	50.4 %	36.4 %	48.4 %	50.4 %
2025	39.0 %	51.6 %	53.3 %	39.0 %	51.6 %	53.3 %	39.0 %	51.6 %	53.3 %	39.0 %	51.6 %	53.3 %	39.0 %	51.6 %	53.3 %	39.0 %	51.6 %	53.3 %

Table I11: GWP-intensity mining and beneficiation, primary production (Northey et al., 2012)



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