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Guiding European Policy toward a low-carbon economy. Modelling sustainable Energy system Development under Environmental And Socioeconomic constraints

Annex 4: Task 2.2.c.2. Exergy extraction curves considering non-renewable resources and raw materials

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**Authors:** Abel Ortego, Alicia Valero, Guiomar Calvo

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Introduction

It is common knowledge that this century is characterized by a global increase of material extraction at worldwide level. Demand of the main metals that modern society needs to produce the goods has increased dramatically over the past decades, thereby increasing the extraction to meet this demand. Between 1998 and 2014, world material extraction of the main commodities increased by a factor of 1.7 (Kippenberger, 2001; USGS, 2015), a very significant number if we compare it to the 8 factor increase observed by Krausmann et al. (2009) from 1900 to 2005. For instance, in the past 10 years approximately one quarter of the total historic mine production of copper was produced, showing that global copper production has doubled every 25 years since data started to being recorded (Meinert et al., 2016). Combined with the global population growth, which is projected to increase to 11.2 billion by 2100 (United Nations, 2015), the concern about the availability of raw materials is on the rise.

To meet the ongoing increases in demands for metals makes the mining industry one of the most energy-intensive industrial sectors. According to the International Energy Agency, between 8 and 10% of the world total energy consumption is dedicated to the extraction of materials that the society demands, and that number does not take into account metallurgical processes, transport and other mining related activities (International Energy Agency, 2016).

Whilst some studies show that the ore grade in the mines, meaning the concentration of the minerals in the mines, is decreasing over time (Mudd, 2014, 2012, 2007; Northey et al., 2014) other studies state that the declining ore grades must neither be interpreted as a sign of depletion nor as an indicator of resource availability (Drielsma et al., 2016, 2015). As the changes in ore grade can be attributed to other factors such as innovation and improvements in extractive technologies, extending the life of older mines over finding new ones, among others (West, 2011), as well as the fact that for most metals, as ore grades decline, the deposit size grows faster than the decline in ore grade – meaning greater contained metals (e.g. copper – Mudd et al, 2013; nickel – Mudd and Jowitt, 2014; uranium – Mudd, 2014; zinc - Swart and Dewulf, 2013). A deeper quantitative analysis is crucial to better understand the relationship between the ore grade changes and the energy intensity in mines.

Once the analysis of the evolution of the ore grade over time is carried out in current mining facilities, another important factor to take into account is to assess the consequences on the future availability of natural resources. There are multiple approaches to assess this factor and
measure its depletion degree and the most used ones will be discussed in later sections. But first, a review of the main terms used regarding mineral resources and mineral availability will be carried out.

**Mineral availability**

The scarcity of minerals is generally controlled by two terms, supply and demand. Usually supply refers to the amount of raw materials that is made available to the industry and depends mainly on the extraction of minerals from the Earth and the secondary supply coming from recycling. The extraction is limited by the amount of minerals present in the crust, by the total resources, the reserve base and the reserves, as shown in Figure 1. Classification of mineral reserves and resources (from USGS).

![Classification of mineral reserves and resources](image)

*Figure 1. Classification of mineral reserves and resources (from USGS).*

Resources or total resources is the best estimate of the total availability of each commodity in the crust in such form and amount that economic extraction is currently or potentially feasible. The reserve base, also called extractable global resource, is that part of an identified resource that meets specific physical and chemical criteria (ore grade, quality, depth, etc). Finally, reserves are defined as the part of the reserve base that can be economically extracted in a determined time. Therefore, as the technology and commodities prices change, the reserves vary as well. If new production technologies are developed, unattainable resources can be reachable or profitable. In this classification, the reserve base is probably the most reasonable approximation of the quantity of a resource that can be produced over time.
The reserve and resource estimations usually come from inventories of mining companies as well as from national geological services, and they are limited by many factors, such as price of the commodities, lack of exploration, geologic limitations and demand. As the type information and the data reported can substantially vary, there are several initiatives that are trying to unify the reports, developing a standard which includes useful information about exploration results, mineral resources and reserves for investors and professional advisers. First developed in 2006, and later published in 2008, the “Pan-European Standard for Reporting of Exploration Results, Mineral Resources and Reserves”, known as the PERC Reporting Standard, had this as main purpose (PERC Reporting Standard, 2013). Other attempts have been made in Australia, being the JORC Code the first published in 1989 (JORC Code, 2012), followed, among others, by CIM in Canada (CIM, 2010). The first international standard was published in 2006 by CRIRSCO using the standards that existed in previous models (CRIRSCO, 2013). Even if all the definitions of reserves and resources are similar in all the reporting templates, CRIRSCO has harmonized the codes into a common international reporting standard.

Currently, one of the most used sources for reserve, reserve base and resource information is the United States Geological Service, as it compiles information from mines and deposits from all over the world and for all the mineral commodities. Yet, the information is sometimes incomplete or inaccurate, and as 2009, the reserve base estimations are no longer provided. Table 1 shows the reserves and resources information for the commodities selected in this study. Different sources have been compared and the best and more accurate data have been used for the following steps of the process (Emsley, 2001; Frenzel et al., 2016, 2014; Sverdrup and Ragnarsdottir, 2014; USGS, 2015). As reserves and resources information concerning rare earth elements (REE) is not always reported disaggregated by element, the resources information that has been used are the estimations from Haque et al. (2014), that analyzed the percentage of rare earths in various ore deposits and the known resources of rare earth containing ores.

Table 1. Reserves and resources information for each commodity.

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Reserves (tonnes)</th>
<th>Resources (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>28,000,000,000</td>
<td>75,000,000,000</td>
</tr>
<tr>
<td>Antimony</td>
<td>2,000,000</td>
<td>4,300,000</td>
</tr>
<tr>
<td>Arsenic</td>
<td>1,080,000</td>
<td>11,000,000</td>
</tr>
<tr>
<td>Barite</td>
<td>350,000,000</td>
<td>2,000,000,000</td>
</tr>
<tr>
<td>Beryllium</td>
<td>NA</td>
<td>400,000</td>
</tr>
<tr>
<td>Cadmium</td>
<td>500,000</td>
<td>6,000,000</td>
</tr>
<tr>
<td>Chromium</td>
<td>480,000,000</td>
<td>12,000,000,000</td>
</tr>
<tr>
<td>Commodity</td>
<td>Reserves (tonnes)</td>
<td>Resources (tonnes)</td>
</tr>
<tr>
<td>---------------------------</td>
<td>------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Cobalt</td>
<td>7,200,000</td>
<td>145,000,000</td>
</tr>
<tr>
<td>Copper</td>
<td>720,000,000</td>
<td>2,100,000,000</td>
</tr>
<tr>
<td>Fluorspar</td>
<td>240,000,000</td>
<td>5,300,000,000</td>
</tr>
<tr>
<td>Gallium</td>
<td>5,200</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Germanium</td>
<td>12,500</td>
<td>440,000</td>
</tr>
<tr>
<td>Gold</td>
<td>55,000</td>
<td>135,000</td>
</tr>
<tr>
<td>Graphite</td>
<td>230,000,000</td>
<td>800,000,000</td>
</tr>
<tr>
<td>Indium</td>
<td>11,000</td>
<td>47,100</td>
</tr>
<tr>
<td>Iron ore</td>
<td>160,000,000,000</td>
<td>800,000,000,000</td>
</tr>
<tr>
<td>Lead</td>
<td>87,000,000</td>
<td>2,000,000,000</td>
</tr>
<tr>
<td>Lithium</td>
<td>13,500,000</td>
<td>39,500,000</td>
</tr>
<tr>
<td>Magnesium</td>
<td>2,400,000,000</td>
<td>12,000,000,000</td>
</tr>
<tr>
<td>Manganese</td>
<td>570,000,000</td>
<td>1,030,000,000</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>11,000,000</td>
<td>14,000,000</td>
</tr>
<tr>
<td>Nickel (sulphides)</td>
<td>32,400,000</td>
<td>52,000,000</td>
</tr>
<tr>
<td>Nickel (laterites)</td>
<td>48,600,000</td>
<td>78,000,000</td>
</tr>
<tr>
<td>Niobium</td>
<td>4,300,000</td>
<td>-</td>
</tr>
<tr>
<td>PGM</td>
<td>66,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Phosphate rock</td>
<td>67,000,000,000</td>
<td>300,000,000,000</td>
</tr>
<tr>
<td>REE</td>
<td>-</td>
<td>99,591,835</td>
</tr>
<tr>
<td>Silver</td>
<td>530,000</td>
<td>1,308,000</td>
</tr>
<tr>
<td>Tantalum</td>
<td>58,500</td>
<td>100,000</td>
</tr>
<tr>
<td>Tellurium</td>
<td>11,080</td>
<td>25,000</td>
</tr>
<tr>
<td>Tin</td>
<td>4,800,000</td>
<td>76,200,000</td>
</tr>
<tr>
<td>Titanium (ilmenite)</td>
<td>740,000,000</td>
<td>1,840,000,000</td>
</tr>
<tr>
<td>Titanium (rutile)</td>
<td>54,000,000</td>
<td>160,000,000</td>
</tr>
<tr>
<td>Tungsten</td>
<td>3,300,000</td>
<td>-</td>
</tr>
<tr>
<td>Vanadium</td>
<td>15,000,000</td>
<td>63,000,000</td>
</tr>
<tr>
<td>Zinc</td>
<td>230,000,000</td>
<td>1,900,000,000</td>
</tr>
</tbody>
</table>

Logically, both reserves and resources are dynamic data. They may be reduced as ore is mined, as the extraction feasibility diminishes or increase as additional deposits are discovered or are more thoroughly explored, as innovation in mining and processing can change an uneconomic deposit into a reserve. Therefore these data must be taken as a first approach that can change over time.
Energy use in the mining industry

As stated before, the mining industry consumes between 8 and 10% of the world total energy therefore, it is fundamental to have a previous knowledge of the mining processes where the energy is used. Many mining companies have started to report annually their sustainability performance along with their financial results. Focusing on impacts on the environment both from and material and social point of view. These reports vary substantially from one company to another but they can be used as an approach to have real information on their performance. Using the reported data it is possible to analyze links between different factors, such as energy consumption, ore grade, mineral production, greenhouse gas emissions, solid wastes among others.

A preliminary analysis of several mines and companies has been accomplished to select the ones that provide both consistent and disaggregated information related to energy use on a site by site basis, leading to a total of 38 mines chosen for subsequent analyses. Data has been sourced from numerous companies’ reports, including financial, annual, quarterly and sustainable reports. Using the information available, the following data has been compiled when possible for each year and for each individual mine:

- Ore milled
- Contained mineral or metal production
- Average ore grade
- Electricity and diesel use
- Waste rock

The quality and consistency of the reports varied significantly between companies and even between different years in the same company. Some of the companies, but still a little portion of the total, have already adopted the Global Reporting Initiative (GRI) protocol, a coalition of the United Nations, industry, government and civil society groups (GRI, 2006). The aim of this initiative is to provide guidelines to achieve uniform and consistent reports on sustainability performance for different sectors, including mining and metals (GRI, 2011). The main drawback is that these reports only require general data regarding different social, economic and environmental aspects. For instance, a company that has several mines in operation can provide only aggregated data for the energy consumed within all the owned mines, fulfilling the requirements of the GRI but at the
same time making the data of little value to analyze with respect to ore grades, project configuration and other key factors which are known to affect energy intensity. Hence, the extent of quality of data can vary considerably, discrepancies and between different reports have been corrected when possible, but due to the specific mines chosen and the consistency of their reporting, there is expected to be only a minor degree of uncertainty in the data collected herein.

The main data and results for the selected mines, with information of the main metal extracted, mine type and process can be found in Table 2. Each mine site has been categorized based on the metals extracted and the major mining and extraction methods used, separating between underground (UG), open cut (OC) and OC+UG mines. The main methods differentiated in the mining process are mine (M), concentration (C), smelting (S), refining (R) and leaching (L).

**Table 2. Average energy intensity use for selected mines.** Mine type: OC—open cut; UG—underground. Process: M—Mine, C—Concentrator, S—Smelter, R—Refinery, L—Leaching. For kWh/t ore and L diesel/t rock the average number is provided as well as the standard deviation, the number in brackets represents the number of data points for each mine.

<table>
<thead>
<tr>
<th>Mine</th>
<th>Company</th>
<th>Main Metals</th>
<th>Mine Type</th>
<th>Mine Process</th>
<th>2013 Production of Main Metal (t)</th>
<th>Average kWh/t Ore</th>
<th>Average L Diesel/t Rock</th>
<th>Period Reported</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granny Smith</td>
<td>Goldfields</td>
<td>Au</td>
<td>UG + OC</td>
<td>MCL</td>
<td>12,533 (kg)</td>
<td>3.1 ± 1.1 (14)</td>
<td>1.1 ± 0.6 (6)</td>
<td>1991–2009</td>
</tr>
<tr>
<td>Agnew</td>
<td>Goldfields</td>
<td>Au</td>
<td>UG + OC</td>
<td>MCL</td>
<td>6718 (kg)</td>
<td>3.1 ± 1.1 (14)</td>
<td>0.6 ± 0.4 (5)</td>
<td>1991–2009</td>
</tr>
<tr>
<td>St Ives</td>
<td>Goldfields</td>
<td>Au</td>
<td>UG + OC</td>
<td>MCL</td>
<td>7185 (kg)</td>
<td>1.9 ± 1.1 (18)</td>
<td>1.9 ± 1.1 (18)</td>
<td>1989–2013</td>
</tr>
<tr>
<td>Darlot</td>
<td>Au</td>
<td>Au</td>
<td>UG</td>
<td>MCL</td>
<td>2482 (kg)</td>
<td>1.9 ± 1.1 (18)</td>
<td>1.9 ± 1.1 (18)</td>
<td>1989–2013</td>
</tr>
<tr>
<td>Cadia Valley</td>
<td>Newcrest Mining</td>
<td>Cu-Au</td>
<td>OC + UG</td>
<td>MS</td>
<td>56,971 (kg)</td>
<td>5.3 ± 1.2 (6)</td>
<td>5.3 ± 1.2 (6)</td>
<td>1993–2007</td>
</tr>
<tr>
<td>Ernest Henry</td>
<td>Glencore</td>
<td>Cu-Au</td>
<td>OC</td>
<td>MC</td>
<td>35,562 (kg)</td>
<td>4.9 ± 1.0 (7)</td>
<td>4.9 ± 1.0 (7)</td>
<td>1998–2007</td>
</tr>
<tr>
<td>Mount Isa (Cu)</td>
<td>Glencore</td>
<td>Cu-Ag</td>
<td>MC</td>
<td>MCL</td>
<td>142,705 (kg)</td>
<td>81 ± 34 (6)</td>
<td>81 ± 34 (6)</td>
<td>2005–2012</td>
</tr>
<tr>
<td>Osborne</td>
<td>Barrick</td>
<td>Cu-Au</td>
<td>OC + UG</td>
<td>MC</td>
<td>141,270 (kg)</td>
<td>41 ± 23 (6)</td>
<td>41 ± 23 (6)</td>
<td>2004–2009</td>
</tr>
<tr>
<td>Prominent Hill</td>
<td>OZ Minerals</td>
<td>Cu-Ag</td>
<td>OC</td>
<td>MC</td>
<td>73,362 (kg)</td>
<td>64 ± 25 (6)</td>
<td>64 ± 25 (6)</td>
<td>2009–2014</td>
</tr>
<tr>
<td>Olympic Dam</td>
<td>BHP Billiton</td>
<td>Cu-U-Ag-Au</td>
<td>OC + UG</td>
<td>MCSR</td>
<td>166,200 (kg)</td>
<td>107 ± 23 (17)</td>
<td>107 ± 23 (17)</td>
<td>1991–2014</td>
</tr>
<tr>
<td>Cannington</td>
<td>BHP Billiton</td>
<td>Pb-Ag</td>
<td>UG</td>
<td>MC</td>
<td>210,815 (kg)</td>
<td>130 ± 13</td>
<td>130 ± 13</td>
<td>2005–2009</td>
</tr>
<tr>
<td>McArthur River</td>
<td>Glencore</td>
<td>Zn-Pb-Ag</td>
<td>OC + UG</td>
<td>MC</td>
<td>203,300 (kg)</td>
<td>60 ± 5 (5)</td>
<td>60 ± 5 (5)</td>
<td>2006–2010</td>
</tr>
<tr>
<td>Century</td>
<td>MMG</td>
<td>Zn-Pb-Ag</td>
<td>OC</td>
<td>MC</td>
<td>488,233 (kg)</td>
<td>120 ± 35 (7)</td>
<td>120 ± 35 (7)</td>
<td>2009–2014</td>
</tr>
<tr>
<td>Golden Grove</td>
<td>MMG</td>
<td>Zn-Cu-Ag</td>
<td>UG</td>
<td>MC</td>
<td>23,619 (kg)</td>
<td>55 ± 7 (7)</td>
<td>55 ± 7 (7)</td>
<td>2009–2014</td>
</tr>
<tr>
<td>Rosebery</td>
<td>MMG</td>
<td>Zn-Pb-Cu-Ag</td>
<td>UG</td>
<td>MC</td>
<td>88,369 (kg)</td>
<td>62 ± 12 (7)</td>
<td>62 ± 12 (7)</td>
<td>2009–2014</td>
</tr>
</tbody>
</table>

**Chile**

<table>
<thead>
<tr>
<th>Mine</th>
<th>Company</th>
<th>Main Metals</th>
<th>Mine Type</th>
<th>Mine Process</th>
<th>2013 Production of Main Metal (t)</th>
<th>Average kWh/t Ore</th>
<th>Average L Diesel/t Rock</th>
<th>Period Reported</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mantos Blancos</td>
<td>AngloAmerican</td>
<td>Cu</td>
<td>OC</td>
<td>MCSR</td>
<td>54,600 (kg)</td>
<td>15 ± 3 (10)</td>
<td>15 ± 3 (10)</td>
<td>2002–2014</td>
</tr>
<tr>
<td>El Soldado</td>
<td>AngloAmerican</td>
<td>Cu</td>
<td>OC + UG</td>
<td>MCSR</td>
<td>51,500 (kg)</td>
<td>28 ± 7 (11)</td>
<td>28 ± 7 (11)</td>
<td>2002–2014</td>
</tr>
<tr>
<td>Mantoverde</td>
<td>AngloAmerican</td>
<td>Cu</td>
<td>OC</td>
<td>MC</td>
<td>56,800 (kg)</td>
<td>12 ± 2 (11)</td>
<td>12 ± 2 (11)</td>
<td>2002–2014</td>
</tr>
<tr>
<td>El Tesoro</td>
<td>Antofagasta</td>
<td>Cu</td>
<td>OC</td>
<td>MCL</td>
<td>102,600 (kg)</td>
<td>31 ± 7 (7)</td>
<td>31 ± 7 (7)</td>
<td>2007–2014</td>
</tr>
<tr>
<td>Michilla</td>
<td>Antofagasta</td>
<td>Cu</td>
<td>OC + UG</td>
<td>MCL</td>
<td>38,300 (kg)</td>
<td>34 ± 2 (5)</td>
<td>34 ± 2 (5)</td>
<td>2007–2014</td>
</tr>
<tr>
<td>Escondida</td>
<td>BHP Billiton</td>
<td>Cu</td>
<td>OC</td>
<td>MCL</td>
<td>1,193,660 (kg)</td>
<td>31 ± 13 (12)</td>
<td>31 ± 13 (12)</td>
<td>2004–2011</td>
</tr>
<tr>
<td>Radomiro Tomic</td>
<td>CODELCO</td>
<td>Cu</td>
<td>OC</td>
<td>MCL</td>
<td>379,589 (kg)</td>
<td>13 ± 3 (13)</td>
<td>13 ± 3 (13)</td>
<td>2011–2013</td>
</tr>
<tr>
<td>Collahuasi</td>
<td>AngloAmerican and</td>
<td>Cu-Mo</td>
<td>OC</td>
<td>MCL</td>
<td>444,509 (kg)</td>
<td>20 ± 1 (10)</td>
<td>20 ± 1 (10)</td>
<td>2002–2014</td>
</tr>
<tr>
<td>Los Pelambres</td>
<td>AngloAmerican</td>
<td>Cu-Mo</td>
<td>OC</td>
<td>MCL</td>
<td>405,300 (kg)</td>
<td>27 ± 10 (8)</td>
<td>27 ± 10 (8)</td>
<td>2003–2014</td>
</tr>
<tr>
<td>Chuquicamata</td>
<td>Codileco</td>
<td>Cu-Mo</td>
<td>OC</td>
<td>MCSR</td>
<td>339,012 (kg)</td>
<td>46 ± 1 (3)</td>
<td>46 ± 1 (3)</td>
<td>2008–2010</td>
</tr>
<tr>
<td>Los Broncos</td>
<td>AngloAmerican</td>
<td>Cu-Mo</td>
<td>OC</td>
<td>MCL</td>
<td>416,300 (kg)</td>
<td>20 ± 8 (11)</td>
<td>20 ± 8 (11)</td>
<td>2002–2014</td>
</tr>
<tr>
<td>División Andina</td>
<td>CODELCO</td>
<td>Cu-Mo-Ag</td>
<td>OC + UG</td>
<td>MC</td>
<td>236,715 (kg)</td>
<td>25 ± 3 (12)</td>
<td>25 ± 3 (12)</td>
<td>2003–2011</td>
</tr>
</tbody>
</table>
Mine only to an underground mine only, the energy use being higher in the latter case. The open

There is an exception with the Granny Smith mine, as in 2007 the mine changed from an open cut mine only to an underground mine only, the energy use being higher in the latter case. The open

The electricity intensity use, kWh/t ore as a function of the ore grade, for all the commodities is represented in Figure 2. In the left diagram, there are two series of data sets, as the copper mines usually have lower average ore grades than the lead-zinc mines. There seems to be a link between the amount of electricity used per tonne of ore mined in open cut and underground mines, as the latter increases when the ore grade decreases. In the case of mines that have both open cut and underground facilities, represented in grey in the figure, the data are quite clustered in the lower part of the diagram, and this decreasing tendency is not clear. However, this could be easily explained by the way each mine reports their data as data from underground and open cut mines are reported together and both have very different electricity requirements. Usually, underground mines are more intensive in electricity because of mine depth and ventilation (Northey et al., 2013). Still, open cut mines have electricity demand and it has not been possible to assess the percentages that correspond to each facility in these sets of data. Regarding electricity use and type of process configuration, the dependency is not very clear when analyzing the data but there are many other factors that could be influencing this, from each individual process to the equipment used.

As for electricity intensity use in gold mines (right diagram), only information related to a selected group of Australian gold mines is represented with the average ore grade measured in grams per tonne. Data seem quite dispersed when observing only the ore grade variations but the electricity requirements remains approximately within the same levels, between 25 and 150 kWh/t ore. There is an exception with the Granny Smith mine, as in 2007 the mine changed from an open cut mine only to an underground mine only, the energy use being higher in the latter case. The open
cut mine had requirements of 116 kWh/t ore while the underground mine has requirements of 414 kWh/t ore as average, almost four times higher.

![Figure 2. Electricity use (in kWh per tonne of ore) as a function of ore grade; each data point represents a year of production of a mine site. Code= 1: copper ore mines (both underground and open cut facilities, in grey); 2: copper mines; 3: zinc mines.](image)

Another factor that can be analyzed is the influence of the mining process and configuration in the electricity use per tonne of ore mined. Mines that extract lead and zinc usually have a MC configuration (mine + concentrator). The majority of copper mines have also MC configurations, very few have a smelter and even fewer have MCSR, while a modest minority include also a HLSX/EW circuit. There is only one mine that has a ML configuration (mine + leaching), *Sepon* (Laos), and as this mining process is quite particular the data regarding electricity use are very different. Regarding gold mines, they all have a MCL configuration (mine + concentrator + leaching).

Diesel intensity use, in liters of diesel per tonne of rock mined, is represented in Figure 3 as a function of the ore grade. Usually diesel is used in mines for transport and machinery and sometimes for electricity production. In the case of diesel used for transport there are two main distinctions, diesel used for transport inside the mine and diesel used for transport outside the mine, although the reports rarely differentiate between each different use in the mine. This could become significantly relevant in the case of older mines, as trucks have to go deeper and further.
Figure 3. Diesel intensity (in L diesel/t rock) as a function of ore grade for each metal (in %) by mine type, each data point represents a year of production of a mine site. Code= 1: copper mines; 2: zinc mines.

In this case, the information of copper, lead, zinc and nickel mines is represented distinguishing between open cut, underground mixed mines (mines that have both open cut and underground facilities). As the mining reports vary considerably regarding this issue, it has not been possible to obtain as many values as for electricity intensity use, but it can still be used to have an overall picture of the diesel consumption in these mines.

Concerning the ore grade and the diesel consumption, it seems that the ore grade has a certain influence on the diesel consumption, although there is not a clear relationship between these two factors in the case of the selected period and mines. Again there is a cluster of data corresponding to the copper mixed mines in the lower part of the diagram, represented in grey, but this could be explained by the way each mine reports the information on diesel use.

Figure 4 shows the trends of total energy consumption as a function of the ore grade, along with the concentration energy (in GJ/t), for the different mines and commodities (4a: copper, 4b: zinc, 4c: gold). New data of the gold mines as well as data from previous works (Domínguez and Valero, 2013) are represented in Figure 4c. It can be observed that the general trend is that the energy consumption is increasing when the ore grade decreases. Using this information, the average total energy consumption to extract each commodity can be calculated, being 28.2 GJ/t, 11.03 GJ/t and 145,888 GJ/t for copper, zinc and gold respectively.
Figure 4. Energy requirements (in GJ/t) for copper (a), zinc (b) and gold(c) production as a function of the ore grade.

The above observed trends are a reflection of the Second Law of Thermodynamics behavior which states that any activity performed implies the destruction of resources – degradation might be controlled and slowed down but it cannot be avoided in the long run (Valero and Valero, 2014). When the ore grade decreases in the mine, the energy required for metal extraction increases. For this reason mines with higher ore grades are exploited first, leaving the remainder for the future, hoping that technological improvements will offset those costs. But even if technology improves, the exponential character of the Second Law that can be observed in the figure, clearly shows that when the ore grade approaches crustal abundance, the energy needed is exponentially higher. Thus, technology can improve extraction but cannot reduce the minimum energy required for the mining process as the minerals become dispersed.

Ore grade and energy consumption

One straightforward information that can be obtained with the data of average ore grade reported by the mining companies is the variation of ore grade over time. In the case of the gold mines analyzed the average ore grade is 5.26 g/t. In the case of the zinc and lead-zinc mines analyzed, the average zinc ore grade is 9.6% and the average lead ore grade is 3.4%. These mines produced more than 1 million ton in 2009, which corresponded approximately to 16% of the total zinc world production that same year (USGS, 2010).

A more exhaustive analysis has been carried out in the case of copper mines as there is more reliable and representative information available (Figure 5). A total of 25 copper mines have been included in the analysis from different countries. According to Cox & Singer (1992), the average copper ore grade in the mine (x_m) is 1.67% around 1990 and in the case of the 25 copper mines
analyzed, the average ore grade is 1.48%. These selected mines produced more than 5 million tons in 2009, which corresponded to 32% of the total world production that same year (USGS, 2010).

Figure 5. Evolution of copper ore grade for selected mines over the years. For explicative purposes, the combined weighted average ore grade has been represented as well.

In general, a decrease of ore grades can be discerned, whether the mine has a high initial copper ore grade, such as Neves-Corvo (Portugal) or Mount Isa (Australia), or a lower copper ore grade, such as Aguablanca (Spain), Telfer (Australia) or El Tesoro (Chile). For example, El Soldado copper mine (Chile) had an average oxide ore grade in 2003 of 1.7% and in 2012 the average ore grade was only 0.46%. As an average, the combined weighted decrease of the copper ore grade in all the mines analyzed was approximately 25% from 2003 to 2013.

Another interesting conclusion that can be drawn observing the data compiled for this study, is that the total copper produced in mines with higher ore grades, such as Sepon (Laos), Osborne (Australia) or Mount Isa (Australia), is much lower when compared to low ore grade mines, such as Bingham Canyon (United States), Chuquicamata or Escondida (Chile).

Besides, the total energy consumption as a function of the total mineral produced has been analyzed for selected Chilean copper mines to observe the relationship between declining ore grades, energy and production over the years (Figure 6).
It remains clear that the total energy consumed in the copper mining projects included in this study as well as the tonnes of copper produced increases over time. In the case of total energy consumption, there is a 46% increase from 2003 to 2013. Additionally, there is a 30% increase of copper produced. Although there is a relationship between increases in production with energy consumption, in this case the first factor increases more acutely than the latter. This general increase is distinctly linked to the exponential extraction that can be observed at global level, as more energy is needed to produce the minerals to meet society demands. Additionally, the decrease in ore grades observed before for those same mines also entails an increase in energy consumption, as more gangue mineral has to be removed from the ore to produce the same amount of concentrate. In the specific case of the mines analyzed, it has not been possible to compile enough information on waste rock and tailings so the information is representative enough. But for instance, in the case of copper, there is a clear tendency between decrease of ore grade and increase in waste rock (Mudd, 2009b). Therefore the three factors analyzed, energy consumption, ore grade and production, are closely linked and strongly influence each other.

Methods to assess the future availability of natural resources

Once we have information about the current evolution of ore grade over time for different commodities, it is important to assess the future availability of natural resources to identify possible bottlenecks and constraints. One of the simplest approaches is the reserves-to-production ratio, R/P or RPR ratio. This ratio represents the number of years of which the current level of production can be sustained by the available reserves, dividing the proved reserves by the production data of a specific year. It has been used to forecast the future availability of a resource.
but it is a very simplistic interpretation. Even if these studies usually focus on fossil fuels (Bartlett, 2006, 2000), this methodology can be also applied to non-fuel minerals. Using long-term projection for selected minerals, the years to exhaustion using 1979 and 2000 production levels were predicted using reserves information (Leontief et al., 1983; Sohn, 2006). Of the eight minerals analyzed, only copper, mercury and tin showed potential medium-term prospects for reserve exhaustion. Additionally, other recent studies have predicted the time to depletion of scarce minerals and their relationship with sustainability (Harmsen et al., 2013; Henckens et al., 2014). Yet, the R/P ratio is a static value, as it assumes that the production is constant over time and this tendency has been clearly proved wrong over the years, and it can only be regarded as an early warning indicator (Scholz and Wellmer, 2013). New discoveries, changes in production rate or technology or even changes in the economic situation or environmental or governmental restrictions can produce significant variations in this R/P ratio in a short period of time (Feygin and Satkin, 2004).

An alternative option to better predict the mineral behavior is through the so-called Hubbert peak model. In the case of fossil fuels, the Hubbert peak model has been extensively used to evaluate fossil fuel peak production and depletion (Hubbert, 1962, 1956). Peak oil can be defined as the maximum rate of production of oil in any area under consideration. Contrarily to the R/P ratio, it is a dynamic model in terms of production and usually generates bell-shaped curves of production, taking into account current production and estimates in the future based on the amount of reserves available. Some prominent studies have also used this model to predict the evolution of crude oil extraction at planetary level (Campbell, 2003; Campbell and Laherrère, 1998; Deffeyes, 2001). According to these estimations, the maximum production peak is located approximately in the first decade of the 21st century, being the most critical factor the increase of price while demand declines and not the depletion itself (Campbell and Laherrère, 1998). More recent studies also show that the peak of conventional oil has already been reached (Capellán-Pérez et al., 2014; Chapman, 2014; Murray and King, 2012). A different assessment method that can generate multiple scenarios is the regression analysis and this has been applied by Elshkaki et al. (2016) to the case of copper. Using historical demand, per capita GDP, level of urbanization and time as explanatory variables, four scenarios were generated from 2010 to 2050 and compared to the reserves and resources available, observing that the copper demand exceeded projected mineral resources by mid-century.

Nevertheless, these approaches assume that the Earth is finite, that demand eventually will exhaust the available supply, and that the commodities extracted will end up, in the best case scenario, dispersed. Besides, they only rely on physical measures of availability. With this fixed-
stock paradigm, the results might lead to overly pessimistic or overly optimistic expectations, as it compares the extractable amount (in terms of reserves or resources) with the demand of the society in the future. An alternative method is to use the opportunity-cost paradigm, applied to the long-run availability of copper by Tilton and Lagos (2007). This methodology uses real commodity prices as a measure of what a society has to sacrifice to produce a ton of a mineral to assess the effects of depletion, eliminating physical availability from the equation (Tilton, 2010). As in this approach the commodity prices are the main factor used, it is noteworthy mentioning that they can be affected by other factors than mere geological ones. A more complex approach based on a dynamic model that simulates the market supply, production rates, market prices to make future predictions has also been applied to commodities such as copper, lithium and aluminium among others (Sverdrup, 2016; Sverdrup et al., 2015, 2014). These dynamic models take into account not only the ultimately recoverable reserves but also the ore grade and recycling, providing more complex results. For instance, assuming a business-as-usual scenario, combined with the population growth, the supply of aluminium will decline to 2014 level around 2250 assuming that the ultimately recoverable reserves are between 20-25 billion tons of aluminium (Sverdrup et al., 2015).

Each methodology has different advantages and drawbacks that have been extensively discussed in literature (Crowson, 2011; Giraud, 2012; Graedel et al., 2011; Lusty and Gunn, 2015; Meinert et al., 2016; Prior et al., 2012) and some of them will be later discussed. Still, the Hubbert peak model is a direct approach that can provide an order of magnitude of the depletion degree and give information about possible future trends and limits. Therefore, this methodology will be applied to assess the production trends of mineral commodities using available resources information.

**Theoretical background: the Hubbert peak model**

The “peak oil” concept, developed by M. K. Hubbert (1956), a geoscientist working for Royal Dutch Shell in Texas, is based on empirical information on U.S. oil fields. He found that trends in fossil fuel production almost always followed an identical pattern. All curves, regardless of the fuel's exact specification, started slowly before rising steeply and tending towards an exponential increase over time, until an inflection point was reached, upon which the shape became downward concave, meaning that the production follows a bell-shaped curve of a normal distribution. This model has been applied to other commodities besides fossil fuels, although this approach is not free of controversy. Hence, first a short description of the Hubbert peak methodology will be accomplished, followed by a discussion on the advantages and drawbacks of this approach.
The Hubbert peak model is based on the extraction rate and the total amount of oil available reserves. No finite resource can sustain beyond a brief period an exponential production growth rate. Thus, although production rates tend initially to increase exponentially, physical limits, meaning the total amount of available reserves, prevent their continuing to do so. For any production curve of a fixed amount of finite resources, two points on the curve are known from the beginning, namely those at \( t = 0 \) and at \( t = 1 \). The production rate will be zero when the reference time is zero and the rate will return to zero when the resource is exhausted, after passing through one or several maxima. The second consideration is that the area under the production curve must equal the quantity of the resource available (\( R \)). Therefore, a maximum production peak is produced when the high quality and accessible resources have been depleted and then the production starts to decrease, extracting lower quality and harder to access resources, until the total available resource is exhausted.

In this way, the production curve of a certain resource throughout history takes the ideal form of the bell as shown in Figure 7.

![Figure 7. Hubbert’s bell shape curve of the production cycle of any exhaustible resource (Valero and Valero, 2014).](image)

The model of the curve to be adjusted is given by the following equation:

\[
f(t) = \frac{R}{b_0 \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{t-t_0}{b_0} \right)^2}
\]

Where \( R \) are the reserves or resources of the commodity and where the parameters \( b_0 \) and \( t_0 \) are the unknowns. The function’s maximum is given by parameter \( t_0 \), and it verifies that:

\[
f(t_0) = \frac{R}{b_0 \sqrt{2\pi}}
\]
It must be pointed out that any successful prediction obtained using the model (or its derivatives) depends on many factors, the reliability of the estimated resources being a critical one (Höök et al., 2010). For instance, these curves can be asymmetric with the decline much sharper than the growth when several factors, such as economic, geological, political or technological, come into play, which may result in a deterioration of the quality of fit between the data and the curves.

Besides using the business-as-usual model in the extraction, a much discussed drawback is that it takes the resources data (R) as a constant on the long term, using an “all there is” approach, therefore making an important assumption. The current global estimations are not able to assess the ultimately recoverable resources of any non-fuel mineral and the estimations can change with increasing geological knowledge (Crowson, 2011; Graedel et al., 2011; Lusty and Gunn, 2015). For instance, Meinert et al (2016) suggests that there might be enough copper to meet the future global demand, but states that the rates of exploration, discovery success and mine development will need to increase to cover that demand.

Commonly, the data used in determining the reserve and resources quantities are obtained from exploration by drilling discovered ore bodies. These methods are expensive and are usually done by mining companies, on the basis of expected profitable extraction. Data are compiled by different organizations, but these databases are based on economic values derived from decisions taken by those mining companies that are paying for the exploration process (Gordon et al., 2007). Additionally, the investments in exploration are not distributed equally among the minerals, as mining companies tend to put the focus on more expensive commodities such as metals rather than on industrial or construction minerals. Therefore, there is a clear lack of transparency and uncertainty as the economic assumptions behind them is not known. Additionally, there has been a decline in the last 50 years in major mineral deposits discoveries as the Earth has been already intensively explored (Beaty, 2010). For instance, in the case of copper, the exploration and discovery rates of new sources has not kept pace with the amount of ore extracted that is needed to cover the demand of the society and the losses caused by the disposal of end-of-life products (Gordon et al., 2007).

Still, even having accurate resources estimations, it does not mean that they will ever be exploited. Even if the increase in demand and prices have led to technological innovations that have resulted in the discovery of new or alternative sources of minerals and metals, other limitations come into play. Yet, Giraud (2012) states that an increasing price trend could accelerate the pace of exploration and reduce the time-lag between discovery and production, considerably delaying the maximum production peak.
In the case of commodities who have been demonstrated to have a negative impact in the environment and in human health, such as arsenic, cadmium, asbestos or mercury, there has been a decline in consumption thus making the Hubbert curves for these substances less representative. Other potential constraints related with the environment are the availability of energy sources, water limitations or fluctuations related to climate change. The concentration of a particular mineral or metal that is being mined, the ore grade, can influence considerably the energy use in the mining sector. As mines with lower costs are exploited, the social, economic and environmental costs increase (Prior et al., 2012). As ore grade declines in the mine, so does the quality of the ore, increasing exponentially the amount of energy needed for mining, concentration, smelting and refining processes. Studies carried out in Australia have shown that long-term trends for copper, gold, nickel, lead, silver and zinc ore grades are declining (Mudd, 2014, 2007; Mudd et al., 2013; Mudd and Jowitt, 2014). As a consequence, more energy, water, and capital is needed to extract and process low ore grade mines to obtain the same amount of ore than before, generating then more waste rock.

As the Hubbert model assumes that the consumption pattern follows a symmetrical path, there are other factors that can produce changes in that trend as a result of wars of other political or social events (May et al., 2012). Accordingly, there are possible deviations that can be caused by political instability or constraints on international trade, investment niche, concentration of supply, environment and health factors and even technological factors (Valero and Valero, 2014). For instance, gold is a commodity whose production depends strongly on market speculations, and this same pattern can be observed with other precious metals. Another example is the trade restrictions imposed by China in the case of REE, which caused prices to rise and stimulated exploration in other regions of the world (Wübbeke, 2013). Moreover, the alterations in demand can be very unpredictable as well, as the changes caused by the development of new products that have higher requirements of a certain commodity can produce fluctuations in the extraction pattern.

Substitution and recycling can also have a high impact in the production curve of a mineral, as well as if the mineral is a byproduct, as the extraction decisions might be driven by the host-metal, not following then the typical bell-shaped curves. In the case of indium, a highly critical mineral to manufacture liquid crystal displays and photovoltaic panels, a mineral that is usually extracted as a by-product of zinc and copper slimes, USGS reported a reserve base of 16,000 tonnes while other studies increase this number up to 33,100 tonnes using other assumptions and provide resources estimations of up to 76,900 tonnes (Mudd et al., 2016; USGS, 2007). Still, the production of indium will always be dependent on the zinc production.
Recycling is not considered in the Hubbert peak model, a factor that is fundamental in the case of critical metals, whose production is not very high but whose recycling rates are fundamental for supplying the market. Still, many products contain critical elements mixed in ways that current technology is not able to recycle them separately, limiting the usability of secondary metals and causing a decline in the quality of the metal stocks (Verhoef et al., 2004). Nevertheless, recycling could become more relevant into the next decades when scarcity becomes more acute. Once the peak of a mineral has been reached, the sought for alternative materials and recycling is enhanced so as to reduce production costs. The result is that the curve would be asymmetrical, given that the section right of the peak falls more rapidly than the left climbed.

**Hubbert peak applied to non-fuel minerals**

Generally speaking, the Hubbert Peak Model can be satisfactorily applied to those minerals where the concentration factor is not important, such as liquid and gaseous fossil fuels. However, there have been some prominent studies regarding the application of Hubbert peak model to non-fuel minerals. First, Meadows et al. (1972) applied these exponential-like curves to the production of several commodities. The cycle of copper was analyzed by Roberts and Torrens (1974) and Arndt and Roper (1977) focused their study in 35 minerals both in the United States and at global level. Still, all these studies rely on reserves estimates and consumption rates that were not accurate nor reliable. In the last decades, more studies have been made with better assumptions. For instance, Bardi and Pagani (2008) examined the world production of 57 minerals and found that in 11 cases the production had clearly peak and was already declining, such was the case of mercury, tellurium, cadmium and selenium among others. Glaister and Mudd (2010) used historical production of platinum group metals (PGM) to estimate the maximum peak of production with reserves and reserve plus reserve base, occurring in 2037 and 2049 respectively. Additionally, it has also been applied to the phosphorous cycle, with peak estimations occurring before 2035 (Cordell et al., 2009).

In the case of non-fuel minerals, the bell-shaped curve is better suited if exergy is plotted as a function of time rather than using mass terms (Valero and Valero, 2010). This is because whilst fuel quality remains almost constant with extraction, non-fuel mineral quality degrades as time progresses while mining continues. The maximum production peak is reached when the higher quality resources (commodities with higher concentrations and easier to extract and process) have been extracted and then the production starts to decrease as the lower quality resources are extracted. Therefore exergy is a better unit of measure than mass, as it accounts not only for
quantity but also for ore grades and composition. Moreover, with this approach, the curves can be shown within a few diagrams, as the orders of magnitude are similar.

Using the combined methodology of the Hubbert Peak Model and this exergy approach, the maximum production peaks for selected commodities have been calculated. As there is no accurate nor updated information on the reserve base for each different commodity, resources are going to be used as the reference to calculate the maximum production peaks with the Hubbert peak model as they are less dependent on changes in commodity prices and technology than reserves. In each case, the accumulated production from 1900 to 2015 and the resources for each commodity have been introduced in the calculation system.

First, this model has been applied to the minerals that have the highest production rates of all: aluminium, chromium, copper, iron, manganese and zinc, the so-called, “big six”. Figure 8 shows the Hubbert peaks for each mineral according to the available resources information.

![Figure 8. The Hubbert peak applied to the “big six” resources.](image)

For the remaining commodities, the Hubbert curves are represented considering the available information on resources in Figure 9. Additionally, Table 3 summarizes the list of commodities and their corresponding peak of maximum extraction.
Figure 9. The Hubbert peak applied to selected minerals using available information on resources.

Table 3. Summary of the Hubbert peaks for the selected commodities according to resources information. * In the case of REE, Hubbert peaks have been calculated using extraction and resources information in tonnes (Haque et al., 2014).

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Peak</th>
<th>Commodity</th>
<th>Peak</th>
<th>Commodity</th>
<th>Peak</th>
<th>Commodity*</th>
<th>Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>2084</td>
<td>Germanium</td>
<td>2236</td>
<td>Palladium</td>
<td>2091</td>
<td>Cerium</td>
<td>2092</td>
</tr>
<tr>
<td>Antimony</td>
<td>2012</td>
<td>Gold</td>
<td>2014</td>
<td>Phosphate rock</td>
<td>2187</td>
<td>Dysprosium</td>
<td>2219</td>
</tr>
<tr>
<td>Arsenic</td>
<td>2059</td>
<td>Graphite</td>
<td>2148</td>
<td>Platinum</td>
<td>2112</td>
<td>Erbium</td>
<td>2279</td>
</tr>
<tr>
<td>Barite</td>
<td>2080</td>
<td>Indium</td>
<td>2032</td>
<td>Silver</td>
<td>2022</td>
<td>Europium</td>
<td>2121</td>
</tr>
<tr>
<td>Beryllium</td>
<td>2247</td>
<td>Iron ore</td>
<td>2091</td>
<td>Tantalum</td>
<td>2039</td>
<td>Gadolinium</td>
<td>2162</td>
</tr>
<tr>
<td>Bismuth</td>
<td>2040</td>
<td>Lead</td>
<td>2128</td>
<td>Tellurium</td>
<td>2062</td>
<td>Lanthanum</td>
<td>2110</td>
</tr>
<tr>
<td>Cadmium</td>
<td>2082</td>
<td>Lithium</td>
<td>2037</td>
<td>Tin</td>
<td>2086</td>
<td>Neodymium</td>
<td>2105</td>
</tr>
<tr>
<td>Chromium</td>
<td>2107</td>
<td>Magnesium</td>
<td>2192</td>
<td>Titanium (ilmenite)</td>
<td>2084</td>
<td>Praseodymium</td>
<td>2101</td>
</tr>
<tr>
<td>Cobalt</td>
<td>2142</td>
<td>Manganese</td>
<td>2030</td>
<td>Titanium (rutile)</td>
<td>2082</td>
<td>Samarium</td>
<td>2139</td>
</tr>
<tr>
<td>Copper</td>
<td>2072</td>
<td>Molybdenum</td>
<td>2030</td>
<td>Vanadium</td>
<td>2124</td>
<td>Scandium</td>
<td>2126</td>
</tr>
<tr>
<td>Fluorspar</td>
<td>2153</td>
<td>Nickel (sulphides)</td>
<td>2084</td>
<td>Zinc</td>
<td>2061</td>
<td>Terbium</td>
<td>2171</td>
</tr>
<tr>
<td>Gallium</td>
<td>2068</td>
<td>Nickel (laterites)</td>
<td>2032</td>
<td></td>
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</tr>
</tbody>
</table>
According to these results, using business-as-usual scenarios, in the case of gold, according to the information available, the maximum production peak was in 2014, which goes in line of other recent studies, locating the maximum production peak in 2012 (Sverdrup and Ragnarsdottir, 2014). Additionally, a report carried out by Natural Resource Holdings (NRH) that created a comprehensive database of the world's gold mines and deposits, placed the peak between 2022 and 2025. (NRH Research, 2012). Another mineral commodity that has already reached its maximum production peak is antimony.

Additionally, there are 11 commodities whose maximum production peak is expected in the next 50 years: arsenic, bismuth, indium, lithium, manganese, molybdenum, nickel (from laterites), silver, tantalum, tellurium and zinc. If we extend this period to 100 years, then a total of 28 commodities of the 47 analyzed that could have already reached their maximum production peak. Excluding rare earth elements (REE), only beryllium, cobalt, fluor spar, germanium, graphite, lead, magnesium, phosphate rock and vanadium have resources for more than 100 years. However, the maximum production peak of phosphorous using reserves data plus the cumulative production between 1900 and 2007, was estimated at 2033 (Cordell et al., 2009) while other authors previously stated a peak around 1989 (Déry, 2007). Still, those peaks were calculated using reserves instead of resources and additionally other factors have influenced these values, such as political factors and decreased fertilizer demand.

It is noteworthy mentioning the case of REE, as all their expected maximum production peaks are, except in the case of cerium, between 2101 and 2297, very late when compared to other more common minerals. Indeed, REE are not son rare, as in the crust they are actually more common than antimony or silver. The main problem is that REE usually appear all together concentrated in a mine and not all of them present the same concentrations. Even if the number of identified REE deposits in the world may be over 850, there are few mines in operation, mostly located in China (Haque et al., 2014; Kvar, 2008). For this reason they are often considered as critical minerals in many reports (Angerer et al., 2009; British Geological Survey, 2015; EC, 2010; Resnick Institute, 2011).

**Case Study: Lithium**

Lithium is considered as a critical element by many studies sector (British Geological Survey, 2015; Moss et al., 2011; Resnick Institute, 2011) as a high future demand is expected in electric batteries for the transport sector. Currently, the main use for lithium is for batteries (35%), for mobile phones, computers, cameras and electric vehicles. Still, other uses of lithium oxide (32%) are in
ceramics and special glasses (USGS, 2016). Given the change to a more renewable society, in the following 30 years, a lithium production 10 times larger than the current one is going to be needed so the current fleet of cars can be transformed to electric vehicles (García-Olivares et al., 2012).

There are different deposits where lithium can be found. First pegmatite formations, where lithium bearing minerals are extracted, being Australia one of the largest producers (USGS, 2016). Lithium can also be found in salt lake brines in dry and high altitude regions. Chile is one of the largest lithium brine producers and accounts for almost half of the total world identified resources. The Salar de Atacama, with the greatest lithium and potassium concentrations ever known, started its operation in the late 90’s, changing dramatically the lithium market. During 2015, Chile alone produced 36% of the total lithium mined in the world (USGS, 2016). Another possible source of lithium is sea water, taking into account that the average concentration in the oceans is estimated at 0.17 ppm, as in Oceans the recoverable amount of lithium equivalent, assuming a 50% recovery rate, is estimated at 44,800 million tonnes (Yaksic and Tilton, 2009). However, currently it is not technologically feasible to extract it as huge quantities of water should be processed to produce a significant amount of lithium.

There are many studies that present estimations of world lithium reserves and resources, but these estimations can vary considerable from one study to another. The reports made by the United States Geological Service are used by many authors to provide future projections and assessments of mineral depletion. Still those reports are much aggregated, there are uncertainties in the reported production and for some minerals they present severe gaps. In the case of lithium, the reserves and resources estimations have changed and increased over the years. Since 2000 the estimations of resources have tripled, going from 12.76 million tonnes to almost 40 million tonnes (USGS, 2016, 2001). Other estimations suggest that the world lithium world reserves are between 31 and 71 million tonnes, being 116 million tonnes the maximum resource estimations found in literature (Gruber et al., 2012; Kesler et al., 2012; Mohr et al., 2012; Sverdrup, 2016; Vikström et al., 2013).
In this case study we are going to apply the Hubbert peak model to different lithium resources data to analyze its impact in the maximum production peak (Table 4).

**Table 4. Different estimations of lithium resources.**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Resources (Mt)</th>
<th>Maximum production peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kesler et al. (2012)</td>
<td>31.1</td>
<td>2032</td>
</tr>
<tr>
<td>USGS (2016)</td>
<td>39.5</td>
<td>2037</td>
</tr>
<tr>
<td>Grosjean et al. (2012)</td>
<td>43.6</td>
<td>2038</td>
</tr>
<tr>
<td>Vikström et al. (2013)</td>
<td>65.3</td>
<td>2047</td>
</tr>
<tr>
<td>Mohr et al. (2012)</td>
<td>71.3</td>
<td>2049</td>
</tr>
<tr>
<td>Sverdrup (2016)</td>
<td>116</td>
<td>2060</td>
</tr>
</tbody>
</table>

In Figure 10 the Hubbert peak model has been applied to lithium using different resources estimations, from the most pessimistic to the most optimistic ones. The historical production of lithium from 1900 to 2015 has been represented as well, using data of gross weight production. In all the cases, the lithium that could be extracted from the oceans is not taken into account as the technology needed and the energy consumption is too elevated to be a viable solution in the short-term.

![Figure 10. The Hubbert peak applied to lithium with different resources estimations.](image)

Kesler et al. (2012) assessed the total resources of lithium in brine deposits (21.6 Mt), in pegmatites (3.9 Mt), in hectorite and jaderite deposits (3.4 Mt) and in oilfields and geothermal brines (2 Mt), adding in total 31.1 Mt of lithium resources. With this assessment, the Hubbert
model places the maximum production peak in 2032. Other estimations, around 39-45 Mt (Grosjean et al., 2012; USGS, 2016), delay this peak to the late 2030. The most optimistic resources values, 116 Mt, was used as a possible scenario in a dynamic model assuming that 50% extractability (Sverdrup, 2016). The maximum production peak using the Hubbert theory is in 2060, and even doubling those resource estimations, assuming that there are 232 Mt of lithium, the peak is only delayed to 2078.

Comparing the pessimistic and optimistic resources values, we can see that the maximum production peak is only delayed 46 years while the resources have increased by a factor of nearly 8. Therefore, even if more exploration is undertaken and the resources number increase, the peak is only delayed a few years. If more recycling was undertaken in the future, the total production and availability of lithium could significantly increase. Currently the recycling rate of lithium is almost negligible, being the lithium recycling only <1% (Swain, 2017; UNEP, 2011). In the specific case of batteries, the absolute return flow is very low, as the sales in tonnes in EU in 2007 were 13,181 and the return was 354, being the collection rate approximately 3% (Georgi-Maschler et al., 2012).
Conclusions

The increase in material extraction has reawakened the concerns regarding long-term availability of minerals, as with the expected increase in population the demand for natural resources is expected to continue growing.

The results show that ore grade is gradually decreasing for the selected mines, while production and energy consumption is increasing. This tendency has been proven for the case of copper, as more accurate information was available regarding energy use and ore grade. Additionally, as high ore grade mines are being depleted other mines are put into operation to cover the material demands, consequently slowly decreasing the world reserves and compromising the availability of certain substances for future generations. Therefore, decreasing ore grades is no longer a theoretical issue but a global reality in the case of mines in operation caused by the increasing demand of raw materials. Yet it is important to point out that information regarding ore grade in mines that are still not in operation or not even discovered is unknown. The exploration of new deposits is very influenced by the commodity prices, which have suffered continuous changes over time, and have even begun to decrease in some cases. Even if new mines with higher ore grades could open in the short-term to replace the ones that are exhausted, other factors come into play. Such is the case of the environmental restrictions of different countries where deposits are known to exist, and that avoid to open the mines from starting to extract the minerals as they are not profitable enough under those conditions. Other factors could be related with the availability of energy sources and water limitations. Additionally, development of new technologies and processes could also influence the amount of energy and resources that is needed to produce the goods.

That said, it is a fact that the current pattern of extraction and its increasing energy consumption puts great pressure on the environment, generating larger amounts of waste rock, greenhouse gas emissions, water demands and enhancing social costs. Continuing this trend implies two broad options. One is to open new mines with likely lower ore grades but higher environmental impacts and/or stronger regulatory restrictions. The second one is continuing the exploitation of older mines which permits are already acquired, but with escalating energy and environmental costs.

As mining is still going to be one of the main pillars to cover the world resource requirements, along with recycling, more comprehensive studies should be carried out considering the scarcity of raw materials in the accounting system to improve resource management and promote the sustainable use of natural resources.
Additionally, the available information on mineral resources, being the best estimations based on mining and regional reports that have different degrees of uncertainty, can be used as a first approach to estimate the maximum production peaks of the mineral commodities assuming a business-as-usual trend. For this endeavor, the Hubbert bell-shaped curves have been used, using data on 1900-2015 production and resources estimations.

For the 47 mineral commodities analyzed, 2 have peaked before 2015, 11 have their maximum production peak in the next 50 years and a total of 28 commodities could have reached its maximum production peak before 2115. These values might be affected by several factors, such as the information available on resources or by changes in the future extraction trends. Additionally, several minerals are extracted as a byproduct and their production depends on the production of the main mineral from which they are extracted, such is the case of germanium and indium, which are closely related with the zinc production. Therefore, if the production of zinc changes over time the production of the byproducts can be influenced as well not following the bell-shaped Hubbert curve.

As resources are dynamic data that can change over time, the influence of the availability has been analyzed using lithium as a case study, compiling information on resources from different sources. Using the best case and worst case scenario for resources estimations, the maximum production peak varies from 2032 to 2060, and even by doubling the resources of the best case scenario data, the peak is reached in 2078. Hence, even if the resources estimations change significantly, using the Hubbert methodology, the peak is only delayed a few years. Therefore, the Hubbert model can help determining which minerals are going to be scarcer in the next decades due to exponential extraction and expected increase in demand in certain sectors. It does not mean that after the maximum production peaks have been reached the Earth is going to run out of minerals, but it can be used as a first approach to put focus on those substances and be used as an early warning indicator.

Still, as there are important gaps in the mineral statistics at world level, further studies must be madeconcerting evaluation and characterization of mineral deposits to have better assessments of available mineral resources. Having international standards that can be used by the mining companies is a first approach, but other problems related with exploration and technology development must be solved.
References


Chapman, I., 2014. The end of Peak Oil? Why this topic is still relevant despite recent denials. Energy Policy 64, 93–101. doi:10.1016/j.enpol.2013.05.010


CRIRSCO, 2013. International reporting template for the public reporting of exploration results, mineral resources and mineral reserves.


Geology Reviews 48, 55–69.


Mudd, G.M., Jowitt, S.M., Werner, T.T., 2016. The world’s by-product and critical metal resources
part I: Uncertainties, current reporting practices, implications and grounds for optimism. Ore Geology Reviews. doi:http://dx.doi.org/10.1016/j.oregeorev.2016.05.001


Resources, Conservation and Recycling 103, 139–154. doi:10.1016/j.resconrec.2015.06.008


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