Life Cycle Impact Assessment of Mineral resources: Potential paths forward and some dead-ends

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What I will say...

- Geological depletion is not seen as meaningful - it is so remote (or even physically impossible!) that it is of little policy or market relevance
- Economic availability or supply risk is of more general concern and it should be evaluated parallel to LCA - not within it
- Availability is not an intrinsic property of a metal or mineral - the objective of ongoing assessment method development must be more clearly thought out
- Declining ore grades are neither a sign of depletion, nor an indicator of availability
- The mineral resources Area of Protection (AoP) might be better addressed within LCSA
What can we learn from the current use of LCA of mineral resources?

• The most commonly used method for abiotic resource depletion (ARD) is Guinee & Heijungs (1995) or derivatives thereof.

• For current methods assessing LCIA of mineral resources there is, however, no globally agreed upon method, or even problem statement.

• Mining, Minerals and Sustainable Development Project (MMSD), final report *Breaking New Ground* published in 2002 describes the fine balance required by sustainable development through the management of five types of capital: natural, manufactured, human, social and financial.

• In its current standardized form (ISO 14040: 2006), LCA focuses on only a portion of the factors defined and regarded as crucial in MMSD.

• Two views: *Fixed stock paradigm* (there exists a finite quantity of a given resource or “crustal abundance”) - pessimistic. *Opportunity cost paradigm* – optimistic (economic question driven by market demand): Tilton (2002)
The dead-end...
and why we need to re-define the path forward...

The fixed stock paradigm
Cu-production and reserves reported by USGS in annual commodity reports 1995-2010

NO FIXED STOCK!

- Blue: Year 1
- Purple: Year 2 est.
- Green: Reserves
- Brown: Reserve base

Years: 94/95, 95/96, 96/97, 97/98, 98/99, 99/00, 00/01, 01/02, 02/03, 03/04, 04/05, 05/06, 06/07, 07/08, 08/09
Aitik Cu-Au mine, Sweden

NO FIXED STOCK!
“In the **fixed stock** view, natural resources are to be preserved; it is assumed that use leads to some form of penalty or reduction in value/availability”

“In the **opportunity cost** view, natural resources are treated more like flows that need to be managed to best meet human demands”

**BUT…**

Measuring resource **availability** to humans requires a different, and much more complex, set of variables than does **depletion** of natural stocks
LCA practitioners do not use the traditional definitions utilized by leading geological institutions. If LCA is to be understood and supported by mining companies and their stakeholders, the CRIRSCO definitions of terms should be adopted.

**Crustal Content** represents the total amount of an element in a given layer of the earth’s crust.

**Extractable Global Resource** is the amount of crustal content that will ultimately prove extractable by humans.

**Mineral Resource** (CRISCO 2013) is a concentration or occurrence of solid material of economic interest in or on the Earth’s crust in such form, grade or quality and quantity that there are reasonable prospects for eventual economic extraction.

**Mineral Reserve** (CRIRSCO 2013) is the economically mineable part of a measured and/or indicated mineral resource.

**Resource Depletion** is the process of physically reducing the global amount of a specific resource.

**Resource Availability** is an economic term that refers to the accessibility, presence or readiness of a resource for human use.
Crustal content – the “real” fixed stock

<table>
<thead>
<tr>
<th>Element</th>
<th>Content average crust (g/t)</th>
<th>Tonnes upper km total land</th>
<th>Tonnes upper km EU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>820000</td>
<td>3.30 x 10^16</td>
<td>9.79 x 10^14</td>
</tr>
<tr>
<td>Fe</td>
<td>630000</td>
<td>2.53 x 10^16</td>
<td>7.52 x 10^14</td>
</tr>
<tr>
<td>Mn</td>
<td>1100</td>
<td>4.43 x 10^14</td>
<td>1.31 x 10^13</td>
</tr>
<tr>
<td>Mg</td>
<td>290000</td>
<td>1.17 x 10^16</td>
<td>3.40 x 10^14</td>
</tr>
<tr>
<td>P</td>
<td>1000</td>
<td>6.62 x 10^14</td>
<td>1.19 x 10^13</td>
</tr>
<tr>
<td>Li</td>
<td>24</td>
<td>6.66 x 10^12</td>
<td>2.87 x 10^11</td>
</tr>
<tr>
<td>V</td>
<td>97</td>
<td>3.90 x 10^13</td>
<td>1.16 x 10^12</td>
</tr>
<tr>
<td>Cr</td>
<td>92</td>
<td>3.70 x 10^13</td>
<td>1.10 x 10^12</td>
</tr>
<tr>
<td>Co</td>
<td>17.3</td>
<td>6.96 x 10^12</td>
<td>2.07 x 10^11</td>
</tr>
<tr>
<td>Ni</td>
<td>47</td>
<td>1.90 x 10^13</td>
<td>5.61 x 10^11</td>
</tr>
<tr>
<td>Cu</td>
<td>28</td>
<td>1.13 x 10^13</td>
<td>3.34 x 10^11</td>
</tr>
<tr>
<td>Zn</td>
<td>67</td>
<td>2.70 x 10^13</td>
<td>8.00 x 10^11</td>
</tr>
<tr>
<td>Ga</td>
<td>17.5</td>
<td>7.04 x 10^12</td>
<td>2.09 x 10^11</td>
</tr>
<tr>
<td>Ge</td>
<td>1.4</td>
<td>5.63 x 10^11</td>
<td>1.67 x 10^10</td>
</tr>
<tr>
<td>Mo</td>
<td>1.1</td>
<td>4.43 x 10^11</td>
<td>1.31 x 10^10</td>
</tr>
<tr>
<td>Pd</td>
<td>0.00052</td>
<td>2.09 x 10^9</td>
<td>6.20 x 10^6</td>
</tr>
<tr>
<td>Ag</td>
<td>0.053</td>
<td>2.13 x 10^10</td>
<td>6.33 x 10^8</td>
</tr>
<tr>
<td>In</td>
<td>0.056</td>
<td>2.25 x 10^10</td>
<td>6.69 x 10^8</td>
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<tr>
<td>Sn</td>
<td>2.1</td>
<td>8.45 x 10^11</td>
<td>2.50 x 10^10</td>
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<td>Ce</td>
<td>63</td>
<td>2.53 x 10^13</td>
<td>7.52 x 10^11</td>
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<td>Pr</td>
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<td>Nd</td>
<td>27</td>
<td>1.00 x 10^13</td>
<td>3.22 x 10^11</td>
</tr>
<tr>
<td>Sm</td>
<td>4.7</td>
<td>1.88 x 10^12</td>
<td>5.61 x 10^10</td>
</tr>
</tbody>
</table>

1) Main elements from “WebElements” and trace elements from Rudnick & Gao 2004
2) Total land area 149 000 000 km² (Wikipedia)
3) EU32 area 4 422 773 km² (EU statistics)
4) Density continental crust 2.7 t/m³, weight 2.7 x 10^10 t/km³

“Crustal content is a stable, comprehensive dataset, with which a physical estimate of resource depletion for abiotic resources – if desired and/or useful - could be estimated”

Source: Springer (Accepted 2015) JLCA-D-15-00156

Geological scarcity

<table>
<thead>
<tr>
<th>Element</th>
<th>2008 production rate</th>
<th>2050 production rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>338 880</td>
<td>97 923</td>
</tr>
<tr>
<td>Cu</td>
<td>21 711</td>
<td>6 274</td>
</tr>
<tr>
<td>Au</td>
<td>7 926</td>
<td>2 290</td>
</tr>
</tbody>
</table>

1) Top 1 000m continental crust
2) No recycling, 100% extraction
“While crustal content estimates have not changed significantly over time, mineral resource and reserve data is subject to significant variation over time. This makes it unsuitable for use in LCIA.”

\[
\text{Abiotic depletion} = \sum_i ADP_i \times m_i \quad \text{(Oers et al. 2002)}
\]

**Alternative 1**

\[
ADP_i = \frac{DR_i / (R_i)^2}{DR_{ref} / (R_{ref})^2}
\]

- \(ADP_i\): Abiotic Depletion Potential of resource (dimensionless);
- \(m_i\): quantity of resource i extracted (kg);
- \(R_i\): assumed stock (crustal content/reserve base/mineral reserves) of resource (kg);
- \(DR_i\): extraction rate of resource (kg \cdot yr\(^{-1}\))
- \(R_{ref}\): assumed stock of the reference resource, antimony (kg)
- \(DR_{ref}\): extraction rate of the reference resource, \(R_{ref}\) (kg \cdot yr\(^{-1}\))

**Alternative 2** (without the extraction rate)

\[
ADP_i = \frac{1}{(R_i)^2}
\]

Result highly sensitive to the size of the assumed stock, and therefore, variability in that stock over time

Stock physical; crustal content

Stock economic; reserve base/mineral reserve

Meaningful estimates of Extractable Global Resources (physical stock) are not possible at this time by geological experts. Thus they are not possible for generalists developing an LCIA model!

**What’s in the denominator matters for decision-makers using LCA!**
Economic stock

Economic data change annually in response to demand, exploration and supply cycles, politics and socio-economic trends.

The iron ore reserve base has fluctuated over recent years – together with market demand - as a result of frequent reviews of the estimate. Meanwhile, the USGS estimate of total world resources has remained unchanged.

Copper reserve base has continually increased over the same period as a result of frequent reviews of the estimate.

The indium reserve base has consistently been under reported, and the USGS stopped reporting it after 2007.

Source: Springer (Accepted 2015) JLCA-D-15-00156
What’s in the denominator matters for decision-makers using LCA!

- The impact of changing reserve data on characterization factors (CF) is significant, and influence the outcome of decision-making in comparative LCA!
- Depending on your preferred choice of methods you get different results also very much depending on incomplete knowledge of abundance of metals
- Therefore it is not working as a tool for decision making!

Source: Springer (Accepted 2015) JLCA-D-15-00156
The opportunity cost approach: *prices* and availability

- Price changes with demand in economic cycles
- The distance between the GNP line and the capacity of production provides a measure of the availability of the metal on the market
- Market demand and perceptions of this short-term availability determine metal prices and directly affect reported mineral reserves
- Raw-material prices are directly impacted by less predictable socio-economic movements, which do not lend themselves well to characterization in LCA
- Therefore the contention that observed short-term raw-material price trends are evidence of resource depletion cannot be relied upon

Source: Springer (Accepted 2015) JLCA-D-15-00156
The opportunity cost approach: *grades* and availability

- Ore grade declines seen today have been more a result of technological developments than a driver for them.
- Therefore assumption that declining ore grades are indicative of resource depletion is wrong!

Source: Springer (Accepted 2015) JLCA-D-15-00156
The Area of Protection (AoP) concept intended to capture the impact of reducing the amount of natural resources in the environment on long-term environmental sustainability

<table>
<thead>
<tr>
<th>Method</th>
<th>Intended Area of Protection</th>
<th>Actual Area of Protection</th>
<th>Data Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADP (Gumee and Heijungs 1995)</td>
<td>Depletion of Non-renewable resources</td>
<td>Long term depletion of (Primary) Abiotic Resources</td>
<td>Average Crustal Concentration Volume of the Continental Crust Production</td>
</tr>
<tr>
<td>ADP (Van Oers et al. 2002 Alternatives 1 &amp; 2)</td>
<td>Depletion of non-renewable resources</td>
<td>Medium-term availability of resources</td>
<td>Mineral resources Mineral reserves</td>
</tr>
<tr>
<td>EDIP (Hauschild and Wenzel 1998)</td>
<td>Depletion of non-renewable resources</td>
<td>Short-term availability of resources per person</td>
<td>Mineral reserves</td>
</tr>
<tr>
<td>Exergy (Finnveden &amp; Ostlund 1997, Dewulf et al. 2007)</td>
<td>Environmental &amp; socioeconomic efficiency of resource use</td>
<td>“Natural” stocks and flows of exergy</td>
<td>Exergy co-efficients</td>
</tr>
<tr>
<td>IMPACT 2002 (Jolliet et al 2003) &amp; EI99 (Goedkoop and Spriensma 2001)</td>
<td>Depletion of non-renewable resources</td>
<td>Medium-term availability of resources in current fleet of mines</td>
<td>Processed ore-grades</td>
</tr>
<tr>
<td>ReCiPe (Goedkoop et al 2009)</td>
<td>Damage to resource availability - “additional net present costs that society has to pay as a result of an extraction”</td>
<td>Medium-term availability of resources in current fleet of mines</td>
<td>Processed ore-grades and fuel prices</td>
</tr>
<tr>
<td>AADP (Schneider et al. 2011)</td>
<td>Depletion of non-renewable resources</td>
<td>Medium-term availability of resources</td>
<td>Mineral resources Anthropogenic stocks</td>
</tr>
<tr>
<td>AADP (Schneider et al. 2015)</td>
<td>Depletion of non-renewable resources</td>
<td>Medium-long term availability of resources</td>
<td>Ultimately extractable reserve estimations Anthropogenic stocks</td>
</tr>
</tbody>
</table>

“Meaningful LCIA requires an unambiguous AoP, a valid mechanism to link the studied product system to impacts on the AoP and a representative data-set”

- Change of paradigm – from the fixed stock paradigm to the opportunity cost paradigm in CML Handbook
- The ILCD project of the European Commission JRC has endorsed the use of the reserve base as denominator
- Therefore we are now using a denominator that introduces greater uncertainty than before into the original equation

Source: Springer (Accepted 2015) JLCA-D-15-00156
Towards an opportunity cost approach

**Short-term availability**

Schneider et al. (2014) Economic Scarcity Potential (ESP) moves the concept of AoP away from its traditional “protection” view, which is step in a more useful direction for assessing the short-term availability (economic scarcity) of resources since it incorporates reserves, recycling, country and company concentration of mining activity, economic stability, demand growth, trade barriers, and companion metal fraction.

**Long-term availability**

Other methods than ESP must be sought for the 30+ year timeframe, such as the “Cumulative Availability Curve” (CAC) of Tilton (2003), to explore the long run availability of minerals and the threat of resource depletion.

The CAC attempts to capture how much of a mineral is economically available over all time at various prices and new technology can be relied upon to keep up with demand as higher prices and costs will trigger the need for innovative alternatives.

An ESP type approach highlights supply risk associated with a particular material, a CAC can assist in understanding the plausible longer term availability.
“Fixed stock that equals crustal content (incl. stock in anthropogenic use) is the only measure for estimating mineral depletion that fit within the logical construct of Life Cycle Assessment as it is currently standardized by ISO 14040 series of standards. Nothing else is fixed stock. However, opportunity cost measures such as mineral resources and reserves, prices and production costs are more applicable in the context of understanding mineral demand and availability”

• The LCA practitioners and the minerals industries must understand a common language
• The industry standard for reporting (CRIRSCO 2013) should take precedence
• Methods that use ore grade as a key variable - such as IMPACT2002, Eco-Indicator99 and ReCiPe - for calculating resource impacts should be avoided
Potential paths forward... and integrating opportunity cost into life cycle sustainability assessment (LCSA)

A simple way to determine what tool is most appropriate in the case of LCSA is by considering the time frame in which one desires to understand the impacts of a product system or risks to the product system.

Source: Springer (Accepted 2015) JLCA-D-15-00156
Conclusions

• No uniform globally accepted set of characterization models and factors for *resource depletion* in LCIA...
  • therefore LCIA must be refined before fit for decision-making tool

• *Resource depletion* does not belong at all in LCA – an inherently environmental tool cannot do justice to a problem that is socio-political and economic in nature

• Availability of resources is an issue of more general concern and driven by demand, politics, markets and technology

• AoP in LCA is to date so poor that it has only triggered controversy, misunderstandings, hence, the added value of its inclusion in LCA so far has been minimal and ...
  • therefore economic factors must be investigated separately – but in parallel – via forecasting tools designed to give us a “window in” to the future of mineral availability

• The five forms of capital that are critical in the context of future resource availability are- natural, manufactured, human, social and financial capital ...
  • and they must all be part of a Life Cycle Sustainability Assessment (LCSA)