

# Abiotic resource depletion in LCA

**Improving characterisation factors for abiotic resource  
depletion as recommended in the new Dutch LCA  
Handbook**

**25 June 2002**

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'Solium,' verklaarde heer Bommel, 'is eh...wel, het geeft energie, als je begrijpt wat ik bedoel. Eén gram solium geeft genoeg energie voor een jaar. Voor een hele stad. Geweldig, hè?'

'Heel geweldig!' gaf het grijsaardje toe. 'Nou! Is een gram veel?'

'Nee, juist héél weinig,' zei heer Ollie trots. Maar tot zijn verbazing liet zijn toehoorder nu moedeloos het hoofd hangen.

'Dan begrijp ik het niet,' zei hij treurig. 'U hebt zo'n reusachtig denkraam. Wat voor u weinig is, is voor mij veel. Want het bos hier beneden is vermalen; en ik vond het een gróót bos!'<sup>1</sup>

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<sup>1</sup> Uit: Marten Toonder, De bovenbazen, 1974, De Bezige Bij, Amsterdam.

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## Colofon

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# Summary

In this study an inventory has been made of possible options for improving the baseline method to assess depletion of abiotic resources recommended in the new Dutch LCA Handbook (Guinée et al., 2002). The study has identified the following improvement options:

1. Distinction of sub-impact categories under the heading of abiotic resource depletion,
2. Operationalisation of three different sets of characterisation factors based on three different estimations of the assumed extractable reserve,
3. Calculating characterisation factors for configurations.

Potential (future) functions are the reason for the extraction of resources. In this study an attempt is made to describe potential functions and possibilities of substitution of a limited group of 15 resources. Because resources deliver different functions for mankind a distinction of sub-impact categories is necessary. The following distinction in impact categories is suggested:

- I Elements and configurations,
- II Resources for buildings and construction
- III Energy carriers

Sub-impact category I consists of many different elements and configurations with very different potential functions. To aggregate elements and configurations into one sub-impact score a subsequent weighting might be carried out. It is suggested to base the weighting on the present economic value of the function of the element or configuration. These weighting factors, however, are not available yet.

The characterisation factors presented in this report are the results of a function of the yearly extraction of the resource and the reserve of the resource. In the study special attention is given to the estimation of the reserves. The size of the reserves depends on what is considered to be technically and economically feasible. A distinction is made between reserve ultimate (resources in the earth crust), reserve base (resources that have a reasonable potential for becoming economically and technically available) and (economic) reserve (part of the reserve base which could be economically extracted or produced at the time of determination).

At this moment there is insufficient information which reserve is the best available indicator for the assessment of the depletion of abiotic resources. The contribution analysis executed for the different indicators show large differences in the most dominant present extractions of resources that contribute to the problem of depletion. For the assessment of abiotic resource depletion in LCA it therefore is recommended to carry out a sensitivity analysis using the different sets of characterisation factors that are derived in this report. With respect to the guideline on abiotic depletion as stated in the new Dutch Handbook on LCA, we propose to slightly rephrase this into:

Method status	Characterisation method/factor
baseline	based on ultimate reserves and extraction rates
alternative 1	based on <b>reserve bases</b> and extraction rates
alternative 2	based on ultimate or economic reserves only
alternative 3	based on exergy content
additional	–
variant	–

Source: Guinée et al. 2002; Part 2a.

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The changes in the Guinée et al (2002) guidelines on abiotic depletion thus are limited to alternative 1 (see bold text) and to the updated data used for calculating the characterisation factors for the baseline, alternative 1 and alternative 2.; the tables with these updated factors can be found in this report.

In this study also an attempt was made to derive additional characterisation factors for configurations, like sand, clay, gypsum, limestone et cetera. However for lack of reliable data on particularly the reserve of the resources it appeared not possible to derive such characterisation factors.

Finally a complete update of the characterisation factors, i.c. Abiotic Depletion Potentials or ADP's, for abiotic depletion has been made in this study applying the baseline method as recommended by Guinée et al. (2002) and updated data sets on extraction rates and reserves. Some of the calculations of ADP's are improved (see section 6.2 and table 1). ADP's have been calculated for the ultimate reserve, reserve base and economic reserve. To allow updates of the basic data and different choices in the characterisation method, the basic data for the calculation of the characterisation factors and normalisation factors are available at the CML web site, at [www.leidenuniv.nl/cml/ssp/](http://www.leidenuniv.nl/cml/ssp/) .

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# Contents

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<b>1</b>	<b>Introduction</b>	<b>9</b>
1.1	Topic	9
1.2	Problems to be tackled	9
1.3	Aim of this study	9
1.4	Reading guidance	9
<b>2</b>	<b>Baseline method for assessment of abiotic resources</b>	<b>11</b>
2.1	Definitions	11
2.2	Baseline method	12
<b>3</b>	<b>Theoretical framework of abiotic depletion</b>	<b>15</b>
3.1	Problem definition	15
3.2	Abiotic resource depletion: More than one impact category	16
3.3	Types of abiotic resources, time horizon of the problem	16
3.4	Types of category indicators	17
3.5	Depletion versus competition	18
3.6	Natural stocks versus stocks in the economy	19
3.7	How large are the stocks?	20
3.8	The geographical scale of the problem	20
3.9	LCI results	21
<b>4</b>	<b>Improvement options for the baseline method</b>	<b>23</b>
4.1	Problem definition	23
4.2	Abiotic resource depletion; more than one problem	25
4.2.1	Weighting between impact categories?	25
4.2.2	Grouping of functions into larger categories	25
4.3	Types of abiotic resources	26
4.4	Types of category indicators	26
4.5	Depletion versus competition	29
4.6	Natural stocks versus stocks in the economy	29
4.7	How large are the stocks?	30
4.8	The geographical scale of the problem	33
4.9	LCI results	33
<b>5</b>	<b>Selection of improvement options and test set of abiotic resources</b>	<b>35</b>
5.1	Approach	35
5.2	Selection of the improvement options	35
5.3	Selection of abiotic resources to be elaborated in this study	36
5.3.1	Elements	37
5.3.2	Configurations with specific physical-chemical composition	38
5.3.3	Materials with specific physical properties (function: construction)	39
5.3.4	Fossil fuels (function: energy supply)	39
<b>6</b>	<b>Results; new characterisation and normalisation factors</b>	<b>41</b>
6.1	Data availability	41
6.2	Update of the characterisation factors	42
6.3	Update of the normalisation factors	44
6.4	Differences between ultimate reserves, reserve base and reserve	47

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<b>7</b>	<b>Conclusions</b>	<b>49</b>
7.1	Summary of the theoretical definition of the problem and the delineation in this study	49
7.2	Conclusions on improvement options for the baseline method	50
<b>8</b>	<b>Recommendations</b>	<b>53</b>
<b>9</b>	<b>List of definitions</b>	<b>55</b>
<b>10</b>	<b>Literature</b>	<b>57</b>

#### Appendices

<b>1</b>	<b>List of resources that are monitored by U.S. Geological Survey</b>
<b>2</b>	<b>Occurrence, use and substitutes of some selected resources</b>
<b>3</b>	<b>Estimation of reserves of sand and kaolin</b>
<b>4</b>	<b>Estimation of ultimate reserves of weathered rock minerals</b>



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# 1 Introduction

## 1.1 Topic

'Abiotic resources' considered in this study are natural resources (including energy resources) such as iron ore, crude oil which are regarded as non-living. Abiotic resource depletion is one of the impact categories in Life Cycle Assessment (LCA) which is advised to be taken into account (Guinée *et al.*, 2002). Abiotic resource depletion is one of the most frequently discussed impact categories and consequently a wide variety of methods are available for characterising contributions to this category.

The Road and Hydraulic Engineering Division (DWW) of Public Works and Water Management of the Ministry of Transport, Public Works, and Water Management has commissioned this research. The DWW is involved in optimal resource utilisation of surface minerals like sand clay and gravel. This comprises the promotion of chain management, optimal use of primary raw materials, minimizing environmental effects of raw material extraction, reuse of secondary raw materials, material-poor design and the application of renewable materials.

## 1.2 Problems to be tackled

At present there are several operational methods for the assessment of abiotic resource depletion. Main difference between the methods is the definition of the (environmental) problem. Depending on the definition, the abiotic resource depletion impact category has only natural resources, or natural resources, human health and natural environment as areas of protection. Depending on the definition, different methodologies have been developed including different definitions of impact categories (e.g. possible environmental effects due to scarcity, exergy as measure for energy requirements), category indicators (e.g. economic value a measure of scarcity), characterisation models and different data sets (e.g. ultimate reserve, reserve base, economic reserve et cetera). This study will focus on the further development of the baseline method for the assessment of abiotic resource depletion as recommended in the LCA-Guide of Guinée *et al.* (2002) with respect to the issues mentioned above.

## 1.3 Aim of this study

This study is a feasibility study to explore possible improvements for the baseline method for the assessment of abiotic resource depletion as recommended in the LCA-Guide of Guinée *et al.* (2002). This baseline method is shortly described in chapter 2. We will not discuss other existing methods in this report; for such a discussion the reader is referred to Guinée *et al.* (2002).

## 1.4 Reading guidance

This report starts with a definition of the terms that are going to be used in this report when discussing the problem of the depletion of abiotic resources (Chapter 2). In chapter 2 also an outline is given of the baseline method recommended in the new Guide. Next a theoretical framework for abiotic resource depletion is described (Chapter 3). In chapter 4 an inventory is made of shortcomings of the baseline method and possible improvement options will

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be discussed. These improvement options may make use of elements from other abiotic resource depletion characterisation methods as discussed in Guinée *et al.* (2002). Finally some possible improvements are selected (chapter 5) and the practical consequences of these improvements will be tested using a limited group of 15 abiotic resources (chapter 6).

The issue of this study is to develop a method, which most likely is a compromise between the theoretical ideal assessment of abiotic resource depletion based on the total stock of useful potential functions to mankind and the practical easiest option to assess abiotic resources on the level of individual primary materials (elements and configurations, minerals and fossil fuels)

To allow updates of the basic data and changes in characterisation models that are described in this report the basic data and calculation of the characterisation factors and normalisation factors are available as a spreadsheet at the CML web site, at [www.leidenuniv.nl/cml/ssp/](http://www.leidenuniv.nl/cml/ssp/).

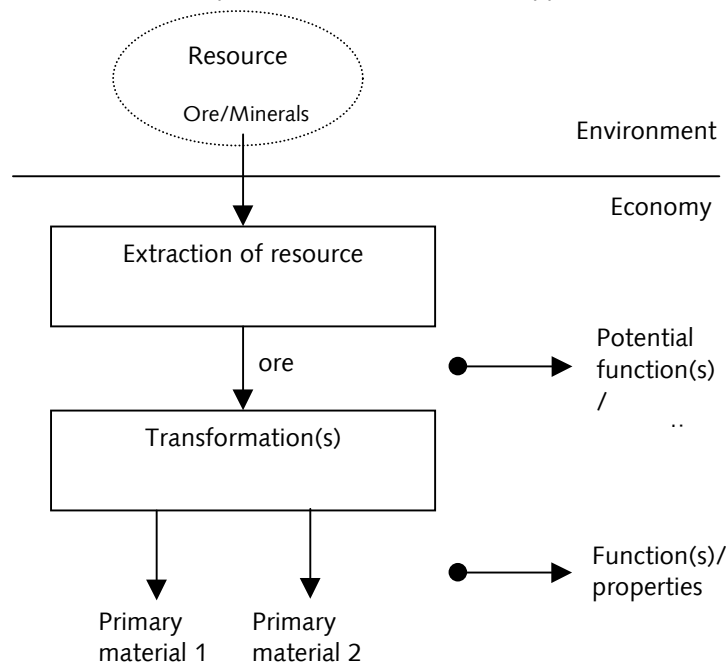
# 2 Baseline method for assessment of abiotic resources

## 2.1 Definitions

Before we start explaining the baseline method we will introduce some of the terminology and concepts which will be used in this report.

Abiotic resource depletion encompasses both the use of non-renewable and renewable abiotic resources (e.g. wind, flowing water etc.) but in this study we will limit the definition to the depletion of non-renewable resources only. Notice that the separation between non-renewable and renewable resources is not a very clear one. For instance when extracting sand from a river channel, the amount can be replenished within a few years by new weathering material derived from rocks. We will simplify that the resources, which will be characterised in terms of an abiotic depletion potential, are not replenished or broken down by geologic forces within a period of 500 years.

In Figure 1 the process of resource extraction leading to abiotic resource depletion is schematically shown. In the environment we will find resources which are in principal useful for mankind if they are mined and transformed into a substance with useful functions for mankind. The moment a resource has the (economic) potential to be extracted from the environment it is designated an ore or mineral deposit<sup>2</sup>. When this actually happens it enters the economy.



**Figure 1:** Schematic picture of the abiotic resource extraction process where resources are transformed to primary material with a certain function/property.

<sup>2</sup> We use both the term ore and mineral deposits for resources that have economic potential to be extracted. The term ore is often limited to metallic elements (e.g. copper ore, phosphate ore etc.) while the term mineral deposit is a more general term (e.g. clay deposit etc.).

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This choice of the location of the boundary between environment and economy can be put somewhere else, for example the moment the resource is considered to be technically and economically extractable, so when the resource is considered to be an ore or mineral deposit or the moment a permit is granted for the extraction of the resource.

In this report by definition the environment -economy boundary is crossed the moment the ore or mineral is actually extracted.

When the ore/mineral has been extracted that is done because it has some potential functions that can be expressed after the ore or mineral has in some way been transformed (e.g. removal of rock, washing, reduction, smelting etc.) Often the transformation process transforms the ore into two or more substances with different functions. For instance copper ore also containing silver is transformed into copper and silver metal. However also other copper ores with an other composition, not containing silver, might be used for the extraction of copper. This pleads for assessment of the depletion of individual substances instead of ores. The alternative would be to (economic) allocate the extraction of the 'ore with a very specific composition' to the different potential functions (read elements and/or configurations present in the ore) of the ore. Note that for the function related to copper not the 'ore with a very specific composition', but several ores containing copper might be used as alternative substitutes for the extraction of copper.

How abiotic resource depletion has been dealt with previously (the baseline method) will be explained in the next section.

## 2.2 Baseline method

The assessment of environmental problems (impact categories) can be based on several alternative models, describing the distribution, fate and effects of emissions and/ or extractions. Also for the assessment of depletion of abiotic resources several methods are available and operational. The baseline characterisation method is the method recommended in the Dutch LCA handbook (Guinée *et al.*, 2002) as the current best available practice for the impact category in question. The baseline method for the assessment of abiotic resource depletion as recommended in the Dutch LCA handbook is the method of Guinée (1995), which is slightly adapted for fossil fuels.

In this method the decrease of the resource itself is taken as the key problem. So the area of protection is natural resources. The characterisation model is a function of natural reserves of the resources combined with their rates of extraction. The method is made operational for many elements and fossil fuels (actually: the energy content of fossil fuels). The natural reserves of these resources are based on 'ultimate reserves', that is on concentrations of the elements and fossil carbon in the earth crust.

The characterisation factor is the abiotic depletion potential (ADP). This factor is derived for each extraction of elements and fossil fuels and is a relative measure with the depletion of the element 'antimony' as a reference.

In this method the LCI results, extractions of elements and fossil fuels (in kg), are multiplied with the characterisation factor (in kg antimony equivalents/kg extraction) to obtain the indicator result (in kg antimony equivalents).

$$\text{abiotic depletion} = \sum_i \text{ADP}_i \times m_i \quad [1]$$

with:

$$\text{ADP}_i = \frac{\text{DR}_i / (\text{R}_i)^2}{\text{DR}_{\text{ref}} / (\text{R}_{\text{ref}})^2} \quad [2]$$

and:

$\text{ADP}_i$  Abiotic Depletion Potential of resource  $i$  (generally dimensionless);  
 $m_i$  quantity of resource  $i$  extracted (kg);  
 $\text{R}_i$  ultimate reserve of resource  $i$  (kg);  
 $\text{DR}_i$  extraction rate of resource  $i$  ( $\text{kg}\cdot\text{yr}^{-1}$ )  
 $\text{R}_{\text{ref}}$  ultimate reserve of the reference resource, antimony (kg)  
 $\text{DR}_{\text{ref}}$  extraction rate of the reference resource,  $\text{R}_{\text{ref}}$  ( $\text{kg}\cdot\text{yr}^{-1}$ )

This method is partly operational. Guinée (1995) has developed ADPs for many elements, using antimony as the reference element.

For fossil energy carriers the method of Guinée (1995) was adapted and new ADPs have been calculated to replace those given in Guinée (1995). The reason is that, contrary to what was stated in Guinée (1995), fossil fuels are assumed to be full substitutes (both as energy carriers and as materials) which means that the ADPs should not be different, at least in terms of total energy reserve. Hence, an overall fossil energy ADP has first been calculated, using the equation:

$$\text{ADP}_{\text{fossilenergy}} = \frac{\text{DR}_{\text{fossilenergy}} / (\text{R}_{\text{fossilenergy}})^2}{\text{DR}_{\text{ref}} / (\text{R}_{\text{ref}})^2} \quad [3]$$

ADP = Abiotic Depletion Potential of fossil energy in kg antimony eq./MJ fossil energy;

$\text{R}_{\text{fossilenergy}}$  = ultimate reserve of fossil fuels in MJ;

$\text{DR}_{\text{fossilenergy}}$  = de-accumulation, or fossil energy production, in  $\text{MJ}\cdot\text{yr}^{-1}$

$\text{R}_{\text{ref}}$  = ultimate reserve of the reference resource, antimony, in kg

$\text{DR}_{\text{ref}}$  extraction rate of the reference resource, antimony, in  $\text{kg}\cdot\text{yr}^{-1}$ .

However, the ultimate reserve of fossil energy has first been derived from the proven reserve (WRI, 1994). A rough estimate of the ultimate reserve of fossil energy can be made on the basis of the fossil carbon content of the earth's crust, which has been estimated by Berner & Lasaga (1989). This fossil C-content can be converted to ultimate reserves for fossil energy (natural gas, crude oil, coal and the non-conventional reserves) by calculating *fossil C content*<sub>proven, total</sub> (the total fossil C-content in kg of the proven reserves of fossil energy fuels), for which data are available (WRI, 1994), and multiplying the proven reserves of fossil energy by the ratio of *fossil C content*<sub>geological</sub> (the total

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fossil C-content in kg as estimated by Berner & Lasaga) to *fossil C content*<sub>proven, total</sub><sup>3</sup>. This ratio equals  $13.6 \times 10^3$ .

Based on the figures for DR and R and the ratio given above (fossil fuel DR data based on WRI, 1994), the ADP of the use of 1 MJ of fossil energy equals:

$$ADP_{\text{fossilenergy}} = \frac{3.03 \times 10^{14}}{(4.72 \times 10^{20})^2} \times \frac{(4.63 \times 10^{15})^2}{6.06 \times 10^7} = 4.81 \times 10^{-4} \quad [4]$$

The ADPs for the individual fossil fuel per kg of fossil fuel extracted (as a result of the inventory analysis) can now be calculated as follows:

$$\begin{aligned} ADP_{\text{oil}} &= ADP_{\text{fossilenergy}} \times \text{heating value}_{\text{oil}} \\ &= 4.81 \times 10^{-4} \times 41.87 = 0.0201 \end{aligned} \quad [5]$$

$$\begin{aligned} ADP_{\text{gas}} &= ADP_{\text{fossilenergy}} \times \text{heating value}_{\text{gas}} \\ &= 4.81 \times 10^{-4} \times 38.84 = 0.0187 \end{aligned} \quad [6]$$

$$\begin{aligned} ADP_{\text{hardcoal}} &= ADP_{\text{fossilenergy}} \times \text{heating value}_{\text{hardcoal}} \\ &= 4.81 \times 10^{-4} \times 27.91 = 0.0134 \end{aligned} \quad [7]$$

$$\begin{aligned} ADP_{\text{softcoal}} &= ADP_{\text{fossilenergy}} \times \text{heating value}_{\text{softcoal}} \\ &= 4.81 \times 10^{-4} \times 13.96 = 0.00671 \end{aligned} \quad [8]$$

For consistency reasons the same heating values have been used as in WRI (1994). Note, however, that these values may differ from those provided by other sources (see e.g. Frischknecht *et al.*, 1993). Note also that the ADPs for most of these four fossil fuel types have changed considerably compared to the values published in Guinée (1995) among others due to the assumption of full substitutability.

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<sup>3</sup> For an explanation of these calculations we refer to appendix 2, page 106, of Guinée (1995). Note that in Guinée (1995), the ratio of the total C-content as estimated by Berner & Lasaga to the total C-content of the proven fossil fuel reserves was multiplied by proven reserves in kg. Here it is multiplied by the total proven reserve of fossil fuels in MJ.

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## 3 Theoretical framework of abiotic depletion

### 3.1 Problem definition

Interventions of man in the environment should be related to areas of protection in order to acknowledge the intervention as a problem. Natural resources are defined as an area of protection by the SETAC WIA (Udo de Haes, 1999). Other areas of protection are human health, man made environment and natural environment. Natural resources encompass both abiotic and biotic resources. This project is restricted to the abiotic resources.

The SETAC WIA-2 taskforce on Resources and land (Lindeijer, in prep) suggests distinguishing what was called the natural environment into functional and non-functional (intrinsic) values of non-human life. The *functional* part of the natural environment than is provided by so-called life support functions. The *intrinsic* values such as diversity and uniqueness, next to recreational and scientific functions, then mainly are provided by the area of protection biodiversity and natural landscapes.

It seems that this distinction between intrinsic value versus values for mankind, which is made for the natural environment also can be made for natural resources. Then the functional part of the natural resources is provided by so called Life Support Functions and the intrinsic value of the natural resources is part of an area of protection called abiotic and biotic diversity and natural landscapes.

From a functional point of view the interest of mankind for abiotic resources is not the resource itself (intrinsic value) but the potential it has to fulfil functions for mankind. The depletion of resources can be defined as follows:

**Abiotic resource depletion is the decrease of availability of the total reserve of potential functions of resources.**

Abiotic resources, usually after one or more transformation steps, fulfil typical functions for mankind. The reason to mine resources is because of their specific properties. One resource may have different potential functions, like for example zinc that is used as a metal, a corrosion inhibitor, a white pigment, a growth stimulator a fodder additive et cetera. On the other hand one specific function may be fulfilled by different primary materials, like for example the colour white can be made with a zinc oxide, a titanium oxide, chalk et cetera and building blocks can be made from clay, gypsum, granite, sand or gravel (as main ingredient of concrete). So within certain limits primary materials can be substituted.

Depletion of most resources is a long-term process. Also there is a continuous economic renewal process: new applications of resources are invented, other applications become obsolete. Future generations have plenty of time to do research on substitutes for depleting resources. However, extraction of resources by our generation does decrease their opportunities. Even depletion of specific resources which are unused at this moment, but may become important for new applications which are yet unknown, decreases the opportunities for future generations. Therefore not the current functions, but the potential functions of a resource should be considered. The potential

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function of resource depends on physical and chemical properties only and is not only related to the current functions.

If the intrinsic value of natural occurring minerals is the area of protection the problem of abiotic resource depletion can be defined as:

**Abiotic resource depletion is the decrease of the unique natural configurations of elements in resources in the environment.**

Most, if not all, methods until now acknowledge the depletion of natural resources from the functional point of view. This project also is focused on the potential functions of resources to mankind. So in this project the intrinsic value of minerals is not considered as an area of protection.

### **3.2 Abiotic resource depletion: More than one impact category**

If the intrinsic value of minerals is considered to be the area of protection, which is not the case in this project, the depletion of the different ores and minerals are separate impact categories. Each type of mineral is unique. So the depletion of the separate natural minerals represent different environmental problems. However the depletion of the different minerals can be added up equally to one overall depletion score. All minerals are equal because the definition of the problem is based on the intrinsic value of the minerals and therefore detached from subjective weighting by mankind.

However as stated in section 3.1 this project will focus on the depletion of resources from a functional point of view. Than the depletion of the different potential functions are separate impact categories. The functions are unique and can not directly be exchanged. So the depletion of potential functions represent different (environmental) problems. To add up the different depletions of potential functions to one overall depletion score subsequent subjective weighting step is needed. Note that not only present potential functions should be considered but also potential functions in the future.

### **3.3 Types of abiotic resources, time horizon of the problem**

Three types of abiotic resources can be distinguished: deposits, funds and flows. Deposits are resources that are not regenerated within human lifetimes. Examples of deposits are fossil fuels, minerals, sediments, clay, etc. Funds are resources that can be regenerated within human lifetimes. Groundwater and some soils are examples of funds. Flows are resources that are constantly regenerated, such as wind, river water and solar energy (Finnveden, 1996a). It is debatable whether all three types of abiotic resources can or should be aggregated into one measure for abiotic depletion. It will be difficult to combine Impact assessment for flows, for which there is no reserve to be depleted but rather a maximum utilisable flow, with that for deposits and funds (Guinée & Heijungs, 1995).

Notice that the definition of deposit and funds very much depends on the time horizon considered. On a very long geological timescale all resources can be regenerated. Due to biogeochemical processes on a geological timescale all elements and minerals, even those dispersed diffuse, will finally concentrate in ores and inorganic and organic minerals deposits. We will simplify that deposits are resources that are not replenished or broken down by geologic forces



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within a time horizon of 500 years. This project is restricted to the deposit type of abiotic resources.

### 3.4 Types of category indicators

The indicator for abiotic resource depletion is the (decrease in) availability. What means availability? The availability of a resource can be expressed in terms of concentration (see also figure 2 paragraph 4.4). Extraction and transformation of ores and minerals is a concentration process. The technical and economical possibility to explore the potential functions of the resources depends on the initial concentration of the resources in the earth crust. Resources are concentrated in ores and mineral deposits. (The estimate of the size of these (concentrated) reserves depends on technical and economical assumptions, see paragraph 3.7). During the extraction and transformation the functions of the resources are further concentrated into primary materials, like metal concentrates, purified sand, gasoline et cetera. In the economic processes that follow (production, use and disposal) the functions get diluted due to the combination of other materials into products and the distribution and use of the products. The useful properties of elements, like metal concentrates, get diluted and finally end up as emissions to air, water and soil. The specific properties of pure minerals (e.g. sand) end up as a mixture of impure materials like in concrete. So the quality of the pure material is decreased due to impurities. And the concentration of energy in fossil fuels ends up in emission of carbon dioxide, water and heat. Actually meaning that the function, energy supply, is lost.

**The decrease in availability of (potential functions of) abiotic resource can also be defined as the dilution of (potential functions of) resources due to processes in the economy.**

Note that on a geological timescale the biogeochemical will lead to a reorganisation and concentration of these diluted functions of elements and configurations into ores, mineral deposits and fossil fuels.

Possible elements of category indicators for the (decrease of) availability are (see for an overview also Finnveden, 1996, and Heijungs *et al.*, 1997):

- Size (rareness) of resources
- extraction rates of resources only (Goedkoop, 1995)
- degree of consumption of the resource in relationship of the size of the resource (Guinée, 1995)
- mineral concentrations (Goedkoop *et al.*, 1998)
- exergy content of resources (Finnveden, 1998)
- total material requirement (Adriaanse *et al.*, 1997)
- indicators related to other categories, such as energy requirements or land use
- economic value of the resources as an indicator of the value of the function
- emissions to air, water and soil as an indicator for dilution of the resource
- emissions in relationship of the size of the resource
- emissions in relationship of the extraction rate (inflow in economy) of the resource

The resource in the indicator can be defined as elements and/ or natural configurations of elements (ores, minerals, fossil fuels). Instead of resources you can also read 'potential functions of resources'.

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### 3.5 Depletion versus competition

Heijungs *et al.* (1997) makes a distinction between resources that can be depleted and those that are competitively used. Depletion implies that the resource quality is lost. However what is meant with quality? Is it the intrinsic value of the mineral or the functional value for mankind? From a functional point of view the extraction of an ore or mineral from the environment and the transformation into primary materials does not necessarily mean that the function is depleted. If oil is extracted and burned the energy content of the mineral is lost. So the energy carrier is depleted at least when a time horizon of 500 years is considered<sup>4</sup>. However if copper is mined and used in electric wires the potential function 'to conduct electricity' is not lost. After discarding of the wires the copper may be recycled from products or in the future maybe from landfill sites or even from sewer treatment plants. The recycled copper then can be used to fulfil all kinds of functions, like conducting electricity again, or it can be used as fodder supplement, as a pesticide et cetera.

From a functional point of view the extraction of copper from the environment for the use of electric conductivity is not a depletion problem, the copper has the (potential) function to conduct electricity both when produced from the natural ore, as in the economic product, the electric wire. If after discard of the wire the copper is recycled and used as an additive in fodder eventually the copper will dissipate into the environment and for a very long period of time (a geological timescale) the copper is not present in a concentrated form and its potential functions will be lost for mankind. This is a depletion problem. All though the potential function is still present, the dispersion of the resource makes the resource not available for mankind. The resource can be considered as lost for mankind.

Apart from depletion, there can also be competition over a resource. Competition means that there is a limited availability of a certain resource, and use of that resource implies less availability for other (human) users. When copper is used for electric conductivity it can't be used at the same time for other applications that make use of the electric conductivity or for other functions, like the use as pesticide et cetera. This is a competition problem. The issue of competition was already introduced in (Finnveden, 1996), as 'decreased availability for a limited period'. It is further defined in (Heijungs *et al.*, 1997), stating that competition measures how much of a certain resource or land (with a specified or an unspecified quality) is occupied by the product system for how long, reflecting the reduced availability for use by others *at the same time*. Resource competition however (as it has been introduced) does not refer to the *future availability* (Lindeijer *et al.*, in prep).

According to 'SETAC WIA-2 taskforce on resources and land' competition leads to mainly economic and societal sustainability impacts. Its relevance for natural resources is considered limited. (Lindeijer *et al.*, in prep).

According to 'SETAC WIA-2 taskforce on resources and land' the availability of the natural minerals in ores is the resource aspect to deal with. The reduction of economic availability of already extracted resources (competition) is not considered as an environmental problem but an economic or social problem.

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<sup>4</sup> Notice that on a very long timescale biogeochemical processes will regenerate elements, configurations and energy into fossil fuels again.

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So depletion deals with the decrease of availability of the total reserve of potential functions of resources in the future due to the use by the product systems at present. Competition deals with the problem of reduced availability due to the use of the resource by product systems at the same time.

### 3.6 Natural stocks versus stocks in the economy

Primary materials are not only produced from natural resource supplies but are also recycled from the growing amount of stocks in the economy. For example large amounts of heavy metals, like copper, lead and zinc, are recycled using discarded products from the economic stock as a source. In the future the large amount of materials in the economy, that are dumped on landfill sites or concentrated in the sewage sludge in the sewer treatment, may be a resource for mining. Should these stocks of materials in the economy, that can potentially be recycled, be considered when estimating the total amount of available functions? In other words should the reserve be based on the natural reserve or also on the reserve in economy.

From a functional point of view it is totally irrelevant whether the 'primary material' for future generations is available in the environment or economy. As long as the (potential) functions of the resource after extraction are still available in the economic stock there is no depletion problem (of functions). An element or mineral, with a certain function, that is produced from a natural resource and stored into a product (economic reserve) that can easily be recycled is not lost but only borrowed.

Stating that the function of a resource that is in use by an application in the economy is at present not available for other applications can not solve the problem. This is a competition problem between applications for a present function in the economy and is not considered an environmental problem. The function *at present* attached in economic goods is still available for *future applications*. This availability for *future* generations is not a competition problem but a depletion problem.

So, in theory, from a functional point of view the reserve of a resource includes both reserves in nature and in the economy (the total stock of products from which secondary materials can be recycled), as long as the potential functions of that material in economy are still available.

The reserve in landfills has a special position in this field. Technically, elements can be recycled from waste and in many cases the resource, even as mixed waste, is richer than the penultimate resource for elements: 'average' rock. However, the fact that a material is landfilled makes clear that under current technological and economical conditions, it is more difficult to recycle the material than to extract new material. There are also cases where, under current technological conditions, recycling elements from waste causes more environmental impacts than extracting the elements from primary resources. Therefore, it would underestimate the effect on future generations if material, which is landfilled, would be regarded to be of a similar quality as material, which is in the economy and can be recycled easily.

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### 3.7 How large are the stocks?

The estimate of an available reserve can be based on different assumptions depending on the ultimate or technically/economically availability of the resources. The following reserves can be distinguished:

'Ultimate reserves', i.e. the quantity of resource (as a chemical element or configuration) that is ultimately available, estimated by multiplying the average natural concentration of the resource in the primary extraction media (e.g. the earth's crust) by the mass or volume of these media (e.g. the mass of the crust assuming a certain depth of for example 10 km) (Guinée, 1995).

'Reserve base' is that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining practice. The reserve base may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources). (United States Department of the Interior - Bureau of Mines, 1993).

'(Economic) reserves', i.e. that part of the natural reserve base which can be economically extracted at the time of determination (United States Department of the Interior - Bureau of Mines, 1993)

The above made distinctions can both be applied to the natural reserves and the stocks in the economy, i.e. the reserves of materials in products that at present are in use in the economy. Also materials on landfill sites may be included.

Main problem of the stocks in the economy is how to derive the availability of these materials for secondary use? The availability for recycling depends on a large number of conditions, e.g. the concentration of the materials in the products, the ease to collect the products for recycling, the possible technologies to refine the materials from the discarded products, the loss of potential functions during the recycle cascade and the economic incentive to recycle et cetera.

Such an approach would lead to a totally different method for the assessment of depletion in LCA. Not the extraction of resources would be part of the inventory but the loss in quality of resources due to dilution and contamination. Development of such an approach is beyond the scope of this project.

### 3.8 The geographical scale of the problem

The market for elements and minerals is regional to global. Supply and demand of these materials are connected by transport of the materials ultimately all over the world. So the depletion of abiotic resources and their potential functions can be defined as a global problem.

Note that resources might be scarce on a regional level while on a global level they are abundant. If on a regional level the resources become scarce the resources are imported from other regions. This will lead to an increase in transport. So regional depletion of resources leads to an increase of the depletion of fossil fuels and other transport related environmental problems.

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Some resources with low value after their transformation into materials will not be transported far, because of transport costs. This is the case, e.g. for 'construction minerals', like clay, sand granite et cetera. These materials are abundantly available on a world scale. However in practice these materials are not shipped over large distances. So for these materials on a regional scale depletion of the resources could occur. It is the question however if this scarcity is only an economic problem? If scarcity does occur other alternative materials probably will be used or the materials will be shipped over larger distances.

### 3.9 LCI results

Depending on the characterisation model that is used the interventions for abiotic resource depletion are expressed in specific units, e.g. kg extracted element or kg extracted mineral/ore.

If in the characterisation model the reserve of a resource is based on the element (e.g. Guinée, 1995) the intervention should be expressed in kg element extraction. If in the characterisation model the reserve of a resource is based on a specific ore, which has a very specific content of combinations of elements, the intervention should be expressed in kg ore extraction of that very specific ore. Note that there is a large diversity of ores, so this approach is not easy to implement.

Also if the characterisation is based on the depletion of potential functions of abiotic resources the inventory can be expressed in kg extracted element or kg extracted mineral/ore.

Characterisation factors based on elements can not easily be translated into factors for ores and vice versa. Special attention should be given to the allocation problem when ores are mined. Very often an ore contains more than one element. For example zinc ores often also contain cadmium and other metals. So the mining and refining of elements from ores is a multi – output process. Meaning that the input of the process of mining, like the extracted ore, the consumed energy et cetera, should be allocated to the different economic outputs, for example zinc and cadmium et cetera. This allocation can be based on mass content of the different elements but can also be based on mass content in combination with economic value of the elements (economic allocation).

The recycling of functions of resources in economy is already discussed in paragraph 3.5 and 3.6. As long as functions are not depleted (read diluted) they can be recycled. The *allocation* problems of recycling should be dealt with in the LCI. Can recycling completely be solved in the LCI or is it also a problem, which should be taken care of in the characterisation model?



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## 4 Improvement options for the baseline method

### 4.1 Problem definition

In the baseline method for abiotic resource depletion (Guinée et al. (2002); an adapted version of Guinée (1995)), the decrease of the resource itself is taken as the key problem. The area of protection is natural resources. A closer look at this method shows that two problems are distinguished, that is 1) the depletion of elements and 2) the depletion of energy (by depletion of fossil fuels).

So the present baseline method is based on two different problem definitions for respectively elements and fossil fuels. For the elements the problem is defined as the depletion of the total natural reserves of elements (in kg element), without regard of the functions those elements could potentially fulfil. While the depletion of fossil fuels is defined at the level of functions, namely the energy content of the fuels, where the fossil fuels are considered as totally exchangeable. So the problem definition for fossil fuels is described as the depletion of total natural energy reserve (in MJ).

So at present the method is inconsistent because both the characterised LCI results for elements and fossil energy carriers are added to score for one category indicator, while implicitly the problem definition for respectively elements and energy carriers is different.

Most, if not all, methods until now acknowledge the depletion of natural resources from the functional point of view. The intrinsic value of minerals is neglected. Also this project will focus on the functional definition of the depletion abiotic resources:

#### **Abiotic resource depletion is the decrease of availability of the total reserve of functions of resources.**

The potential functions of resources are present at different levels. Functions might be delivered by elements or by configurations, that is a specific chemical and/or physical composition of elements, or might even be fulfilled by a physical appearance independent of elements or configurations. Some examples of properties are electric conductivity, electric isolation, heat resistance, hardness, white pigment, red pigment, corrosion inhibition, noise isolation, filling/levelling properties et cetera. Some examples of physical appearance are size of granule et cetera.

Now the problem is to categorise the different natural resources into a (limited) set of potential functions. This set should consist of unique functions and should represent all the natural resources. In this set of potential functions several primary materials might deliver a specific function. The total stock of the function is defined as the total stock of all the primary materials that have the potential to fulfil the function. On the other hand a specific resource may deliver different potential functions. So the depletion of one resource may contribute to the depletion of several different potential functions.

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function	primary material (elements, configurations)				
	A	B	C	D	E
I	x				
II		x		x	
III	x				x
IV		x			
V	x	x	x	x	x

In theory it is possible to make an inventory of materials and their specific functions. However there are some practical problems. Whether or not a material is considered as having a certain potential function may be an issue of debate based on arguments like:

- aesthetics; bricks (clay), concrete, granite are possible alternatives for the construction of a wall. And both zinc and titanium are possible alternatives to fabric a white pigment. However based on aesthetic grounds one might prefer one material for another. If aesthetics is an argument in the definition of the functional unit in an LCA the different reserves should be interpreted as separate reserves. However if the definition of functions is based on technical standards only, the materials clay, granite and concrete, can be considered as exchangeable construction materials and therefore the total reserve of construction material consists of the total of reserves of clay, granite and sand and gravel (for the production of concrete). Note that it will practically be very difficult to incorporate aesthetic, subjective, arguments in a functional unit. This means that in practice the definition of functions can only be based on technical standards.
- economics; at present for the fulfilment of a function most likely the most cost-effective material is used. However if materials become scarce but the demand to fulfil the function remains, other less cost-effective materials become an option.
- technical possibilities in the future; developments in technology make it possible to extend the possible applications of a raw material. So in the future for the fulfilment of certain functions without any doubt alternative materials can be developed based on materials which are not considered an alternative at present. For example the technology of polymerisation has made it possible to use oil as a material for the production of synthetics, like plastics. Nowadays plastics are certainly considered an alternative for many applications that before were fulfilled by other materials like glass (as in bottles) or zinc (as in gutters) or copper (as in waterpipes) or lead (as in food cans) et cetera. Also developments in the chemical industry have made it possible to synthesise 'materials', like diamond, mica, corundum, zeolite, quartz crystal. Instead of mining these materials from natural supplies these materials can be made out of other minerals that contain the most important elements and/or configurations. Scarcity of resources will be an important driving force to develop new technologies. So it will be difficult to judge possible alternative resources for a function in the future.

#### Conclusion

If abiotic resource depletion is defined in terms of the depletion of functions of materials the problem of substitution occurs. In practice it will be very difficult to determine in detail the possible groups of elements, minerals and products that are possible substitutes. There are two options:

- 1) do not take into account substitution possibilities. The result will be a large number of impact categories based on all possible functions.



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- 2) Only distinguish very rough groups of functions, e.g. elements for industrial processing (no further functions are distinguished, substitution is not considered), minerals for construction and energy carriers.

#### **4.2 Abiotic resource depletion; more than one problem**

As shown above the present baseline method for abiotic depletion of resources is based on two different problem definitions resulting in two different endpoints:

- The loss of natural elements availability and
- The loss of fossil energy availability.

So at least two different impact categories should be distinguished. In the present baseline method this is not the case. The depletion of elements and the depletion of energy are combined into one indicator result. The weighting is implicitly using equal weighting factors.

The summation of the different elements into one indicator result implies implicit weighting of the depletion of the different elements. The elements however have different functions for mankind that most likely are subjectively different appreciated. However in the present baseline method the depletion of the different elements is weighted equally.

So ideally the present impact category abiotic resource depletion should be divided into different impact categories based on the potential functions of the resources for mankind. Optional weighting factors should be derived for the categories in order to make aggregation into one impact category possible. Initially at present there are two impact categories 1) 'all kinds of potential functions elements can perform' and 2) 'energy content of fossil carbon'.

##### **4.2.1 Weighting between impact categories?**

Theoretically the depletion of the different functions are separate impact categories. The functions are unique and mostly can not be exchanged. So the depletion of functions represent different (environmental) problems. To add up the different depletions of functions to one overall depletion score subsequent subjective weighting step is needed. Possible weighting can be based on the economic value of the functions. The assumption is that the price of the material, and hence the derived price of the resource is an indicator for the present appreciation of the function in society. Of course this is not completely true because also scarcity of the resource will influence the price of the resource. The derivation of weighting factors for the depletion of functions of the separate resources is beyond the scope of this project.

##### **4.2.2 Grouping of functions into larger categories**

The classification of abiotic resource depletion into the depletion of functions might have the danger of leading to an enormous list of functions or unique combinations of properties leading to a very specific function defined for a specific application. So for practical reasons it might be necessary to group functions into larger categories, which are still relevant for the assessment of the depletion of potential functions.

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This study aims to explore the possibilities to categorise abiotic resources into functions, theoretically the best option, and elements, practically the most feasible option. The final optimum might be situated somewhere in between this spectrum.

An initial proposal for grouping of primary materials into 3 groups (impact categories):

- I primary materials for further industrial processing, including both
  - a) elements (e.g. Silicium)
  - b) configurations (e.g. siliciumoxide (SiO<sub>2</sub>) for the manufacture of glass)
- II primary materials for building applications (e.g. construction sand)
- III energy carriers (e.g. oil, natural gas)

The groups II and III more or less are a homogeneous group. The materials of group II are materials like construction sand, gravel, granite, clay et cetera that have (after some processing) functions suitable for construction of buildings and roads et cetera. The materials of group III are fossil fuels like oil, natural gas and coal, which are all energy carriers. Within these groups the materials can be regarded as substitutes. So the stock of the materials within group II and III is formed by the total amount of materials within the group.

Group I however is a heterogeneous group consisting of elements and configurations having heterogeneous functions. Possibly the functions can be limited by only focussing on the main functions of elements and configurations, so neglecting the minor applications

#### 4.3 Types of abiotic resources

In section 3.3 three types of abiotic resources were distinguished: deposits, funds and flows. The baseline method only considers deposit types of abiotic resources. Funds like groundwater and soil, and flows like wind, river water and solar energy are not considered. This project is restricted to the deposit type of abiotic resources.

#### 4.4 Types of category indicators

Figure 2 shows the parameters that can be used to define the category indicators for abiotic resource depletion. All kinds of combinations of parameters are possible (probably all based on a delicately different problem definition).

According to Guinée & Heijungs (1995) an indicator based on reserves in the environment ( $R_{env}$ ) in combination with rates of extraction (DR) gives the best indication of the seriousness of resource depletion: characterisation factor =  $DR/R_{env} * 1/R_{env} = DR/R_{env}^2$ . That both these quantities need to be taken into account is illustrated in the example in the text box.

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### Example of four hypothetical resources

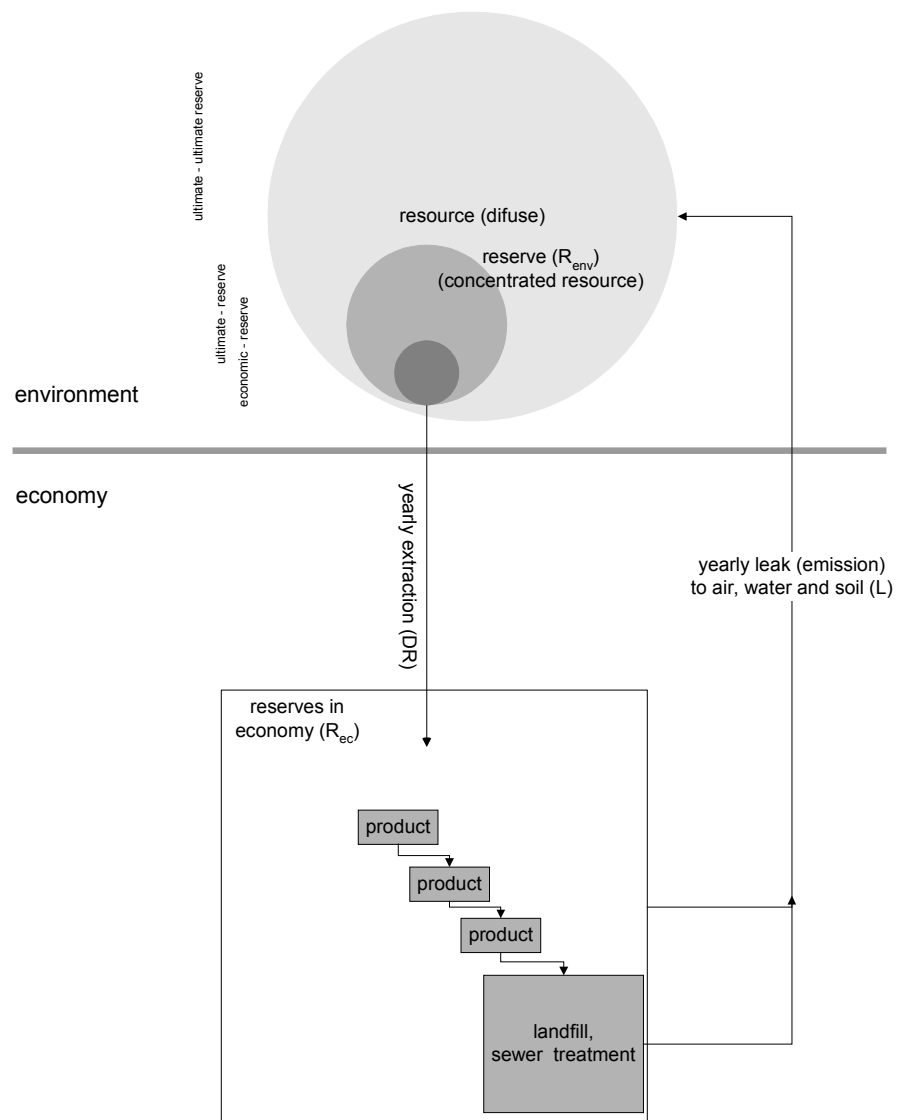
First, consider resources A and B, which differ only in scale of their reserves. Depletion of B seems to be a more serious problem than depletion of A, i.e. using 1 kg of B is worse than using 1 kg of A. Next, consider resources C and D. Their reserves are equal and the only difference is the higher deaccumulation rate of C. Intuitively, we consider extraction of 1 kg of C more problematic than extraction of 1 kg of D.

Table Reserves and deaccumulations of four hypothetical resources.

	Resource			
	A	B	C	D
Reserve (Gton)	1	0,0001	1	1
Deaccumulation (Gton / yr)	0.00000	0.00000	0.1	0.00001

In Guinée (1995) deliberately was chosen to make the rate in which the resource is extracted part of the problem definition. So the present background situation is part of the problem. In other impact categories in LCA, e.g. toxicity, this background situation is left out of the problem definition. So an alternative might be a characterisation factor based only on reserves (R) and not on extraction rates: characterisation factor =  $1/R$ .

The present indicator of Guinée et al. (2002) is based the reserve in the environment and on the inflow of resources in the economy, that is the yearly extraction of resources. This inflow in the economy will partly end up in products, partly on landfill sites and partly leak out to the environment. So compared to the indicator based on leak from the economy, the indicator based on the yearly inflow in the economy overestimates the depletion of resources at present, because also the accumulation of functions in products and landfill sites are considered to be lost for future generations.



**Figure 2:** relevant parameters for the abiotic resource depletion model

As already state in section 3.7 the development of an approach based on the leak of functions from the economy is beyond the scope of this project. However, a short description is given below. If depletion of abiotic resources is defined as the dilution (of potential functions) of the resources the leak (L) of elements, minerals and energy (heat) from the economy might be suggested as an alternative indicator. This leak (of potential functions) of resources can be combined with the total reserve (of potential functions) of resources in the environment (R<sub>env</sub>); characterisation factor =  $L/R_{env} * 1/R_{env} = L/R_{env}^2$ . Or the definition could be the percentage of the yearly consumption of functions in the economy (DR) that is diluted to the environment (L); characterisation factor =  $L / DR$ .

If the indicator is based on the leak of (functions of) resources from the economy it is assumed that as long as the elements and configurations are in the economy they are still concentrated and available for recycling (even from landfill sites and sewage sludge). As soon as they are emitted the functions are

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considered to be dispersed and therefore on the long term not available for extraction.

Another alternative might be factors based on exergy content developed by Finnveden (1996b) or Ayres *et al.* (1996), useful when focusing on declining global energy/exergy content. If the scarcity of useful energy/exergy in the world is taken as the key problem, it should be borne in mind that the resources would be 'valued' on the basis of exergy content only. However, it is debatable whether the value of the metals used in a particular process is dependent on the exergy content of the ore in question. Exergy might be used as a weighting factor to indicate the effort it takes to mine the resource. Instead of exergy for example also costs of the ore could be used to express the effort it takes to mine the resource. Exergy only partially is a measure for the economic availability of an ore or mineral deposit and it does however not indicate the potential functions for mankind .

#### 4.5 Depletion versus competition

The baseline method of Guinée *et al.* (2002) is only suitable for depletion, but not for competitive use, i.e. use of a resource that restricts the potential for others to use that same resource at the same time. SETAC WIA-2 states that competition can be considered as an economic problem and not an environmental problem (Lindeijer *et al.*, in prep.).

#### 4.6 Natural stocks versus stocks in the economy

In the baseline method thus far only natural reserves are included when estimating a reserve of a resource. So reserves in the economy (stocks, accumulation in products and waste on landfill sites et cetera) are not considered when defining the total reserve of the resource.

However as stated in paragraph 3.1.6 from a functional point of view it is totally irrelevant whether the material is extracted from the environment or from stocks in the economy. As long as the (potential) functions of the material after extraction are still available in the economic stock there is no depletion problem (of functions).

So ideally based on the definition of the depletion functions of abiotic resources the available resource should encompass both natural stocks and stocks in the economy. Criterion for depletion of the function is whether the (potential) functions of a resource from nature are still present and (easily) available in the stocks of materials in the economy.

So the problem definition can be redefined as:

**Abiotic resource depletion is the decrease of availability of functions of resources, both in the environment and the economy.**

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Possible solutions:

- 1) Redefine as the environmental problem is the depletion of environmental resources (as in the present baseline Guinée (1995)). One could argue that the materials that are already extracted from the environment and used in the economy are not *freely* available as primary material. At this moment they certainly are not available for other applications. This is the problem of competition, which is considered as an economic problem and not an environmental problem. Whether or not they are available for future generations is debatable and depends on whether or not a continuous accumulation of the materials in the economy is assumed. If a continuous accumulation of materials in the economy is assumed indeed the problem of abiotic resource depletion can be simplified to the depletion of freely available resources for the economy, that is resources in the environment. However if a certain material becomes freely available, because certain applications are diminished or vanished or mining of landfill sites and sewage sludge has become feasible, the material is freely available for other applications in the future. This could mean that in the future the extraction of the primary material might reduce because of secondary material that becomes available freely for new generations. The restriction to environmental resources than no longer holds. Note that in the method of Guinée et al. (2002) this problem is solved in the characterisation model. In the baseline method the depletion of abiotic resources is a function of the environmental reserve **and** the yearly extraction of materials from these reserves. This implies that implicitly also the reserves in the economy are incorporated because the yearly extraction will reduce if large amounts of materials become freely available due deaccumulation and recycling.
- 2) Loss of materials from economic stocks as measure for dilution of the materials. So environmental and economic stocks are considered as a total. The problem of depletion is the loss of the primary material due to emissions of elements and configurations to air, water and soil. The characterisation model might for example be the % leakage from the present primary production of the material. The measure is a rough approximate for the depletion of the function of the materials, only if the materials are emitted to the environment it is assumed that they are lost for recycling<sup>5</sup>.

In the present baseline of abiotic resource depletion the resources are restricted to the resources in the environment (option 1). The development of an approach based on the leak of functions from the economy is beyond the scope of this project

#### 4.7 How large are the stocks?

In the baseline method the size of the reserve of the resource is based on the 'ultimate reserves' of the elements. Ultimate reserves encompasses both the presence of the potential function concentrated in ores and mineral deposits, but also the scattered, not concentrated, occurrence in the earth crust. It is debatable whether this scattered presence in the earth crust ever becomes available, technically and economically. So ultimate reserves can not be

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<sup>5</sup> However part of the quality of the material can all ready be lost earlier in the recycling cascade. The loss in quality of materials can also be considered as a loss of function. Possibly the loss in economic value between the primary and secondary material can be used as an indicator for the loss of function.

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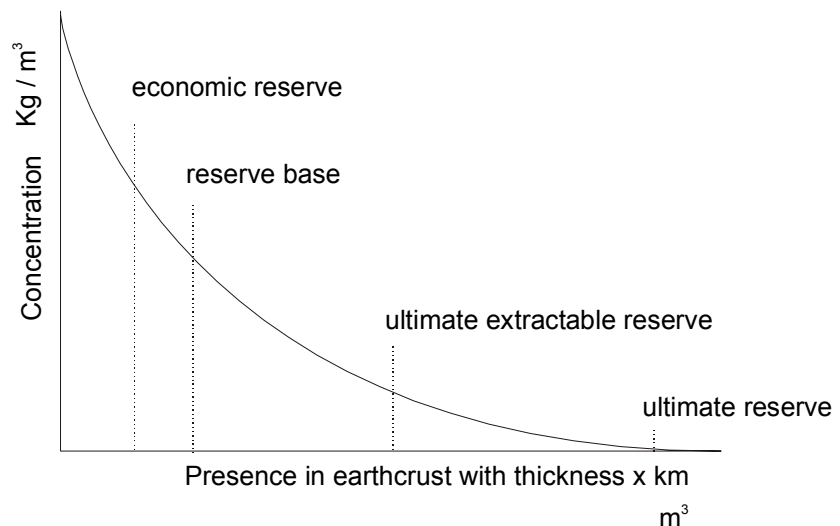
extracted completely because some locations will be inaccessible, e.g. reserves in the sea bed, or concentrations of the resources are too low for extraction, even in the far future.

Other possible estimates of reserves are 'reserve base' and 'economic reserves'. The United States Geological Survey (USGS) makes estimates of reserves of several elements and configurations (see appendix 1). These estimates are based on reserves of ores and not on the average composition of the earth crust<sup>6</sup>. The estimate of the size of these reserves is determined by technological and economical arguments and therefore by the time horizon considered. On the range from ultimate reserve to economic reserve, short term technical and economical feasibility of the extraction of the resource play an increasing role.

Those reserves that can ultimately be technically extracted may be termed the *ultimately extractable reserves*. The *'ultimately extractable reserve'* is situated somewhere between the ultimate reserve and the reserve base. Between the ultimate reserve and the ultimately extractable reserve is likely to be a substantial difference. However data on this type of reserve are unavailable and will never exactly be known because of their dependence on future technological developments.

In figure 3 the relative size of the different estimates of reserves are illustrated for a theoretical resource. The ultimate reserve of a resource is the surface enclosed by the curve. The size of the other estimates of the reserves is given by the surface enclosed by the curve and the given secant with the x-axis.

Figure 3 Presence of concentrations of resource y in the earth crust (with thickness x). The ultimate reserve of a resource is the surface enclosed by the curve.

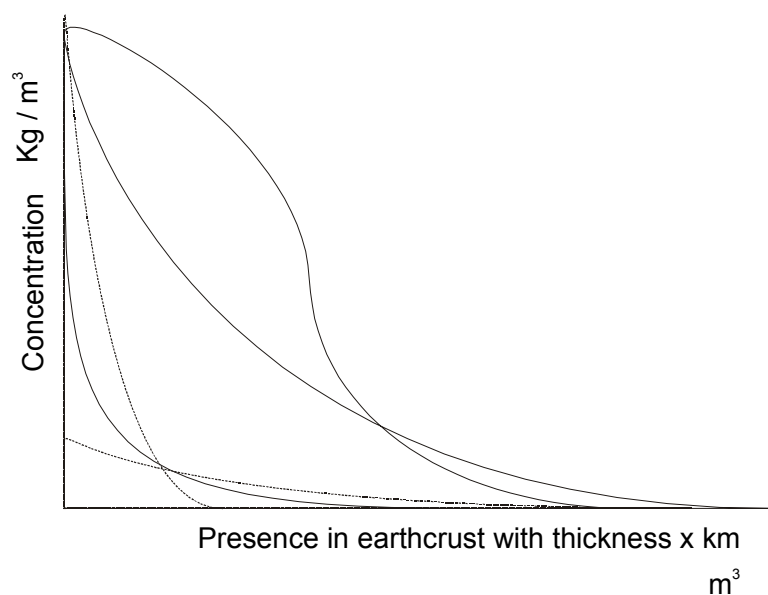


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<sup>6</sup> Note that 99% of rock minerals in the earth crust consists of the elements O (47%), Si (31%), Al (8%), Fe (3%), Ca (3%), K (3%), Na (3%) and Mg (1%). However, none of the rock minerals is considered to be an ore. For example Aluminium is (at present) not extracted from the abundantly present aluminumsilicates, but is extracted from the much scarcer ores that are part of the 'other' minerals like Gibbsite, Diaspore and Bohemite. The extractable reserves given by USGS are based on estimates on ores, the (scattered) ultimate reserve of aluminium is much much larger, infinite.

In Guinée (1995) it was provisionally proposed to apply the ultimate reserve concept implicitly assuming the ratio between the ultimately extractable and ultimate reserve to be equal for all resource types. So the ultimate reserve is used as an indicator for the *ultimate extractable reserve*. However, alternative indicators might be used, like the 'reserve base' and to a less extent 'economic reserve'. In all cases it is assumed that the concentration-presence-distribution is more or less the same for all resources. The relative size between the different resources of the ultimate reserves respectively reserve base respectively economic reserve should be the same as the relative size of the ultimate extractable reserves of the different resources. In reality this will not be the case, because the concentration-presence-distribution of different resources most likely will be different (figure 4).

Figure 4 Concentration-presence-distribution of several theoretical resources in the earth crust.



So there are large uncertainties in the size of the *ultimate extractable reserve*. Which estimated reserve, i.e. ultimate reserve, reserve base or economic reserve, is the best indicator for the ultimate extractable reserve? What is the relationship between the indicator and the ultimate extractable reserve (concentration-presence-curves)? And is this relationship for all resources the same? Because of these uncertainties, in this project characterisation factors will be derived based on the three different indicators. The different characterisation factors make it possible to execute a sensitivity analysis.

The disadvantage of the 'reserve base' and 'economic reserve' is that the estimate of the size of the reserve involves a variety of respectively technical and economic considerations not directly related to the environmental problem of resource depletion. The estimates, however, are relatively certain, because they are based on present practice. The 'ultimate reserve' is more directly related to the environmental problem of resource depletion. However, it is highly uncertain how much of the scattered concentrations of elements and configurations, will become available, because technical and economical developments in the far future are not certain.



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The scope of the LCA may influence the choice of the indicator for abiotic resource depletion. As stated before on the range from ultimate reserve to economic reserve short term technical and economical feasibility of the extraction of the resource plays an increasing role. So for example if the short term depletion of economically extractable reserves is considered to be a problem than the characterisation factors based on the economic reserves should be used.

Furthermore for some configurations there are estimates for the reserve base and economic reserves, while estimates for the ultimate reserves are missing. This can be an argument to use characterisation factors that are based on reserve base or economic reserve.

#### **4.8 The geographical scale of the problem**

The characterisation model of the present baseline method of Guinée et al. (2002) is a world model. The reserves of the resources and the annual extraction rates are based on world totals.

Because trade of the resources is or can be worldwide this global model is considered most appropriate to assess the depletion of abiotic resources.

To derive regional characterisation factors for abiotic depletion, both regional extraction rates and regional reserves should be used, with a clear but always somewhat arbitrary regional boundary definition. A proper geographical method wouldn't even use boundaries but a radius, for instance 100 km, around a certain location.

In this project characterisation factors will be derived for depletion of all the materials on a world scale. No regionally differentiated factors will be derived.

#### **4.9 LCI results**

In the baseline method characterisation factors have been derived for elements and fossil fuels only. The inventory results therefore should be given in kg extracted element or kg extracted fossil fuel.

From a functional point of view the large diversity of ores containing a specific element can be considered exchangeable. It therefore is not necessary to distinguish the different unique ores that are present in the earth crust. An inventory on the level of specific ores, with very specific content of combinations of elements, is not considered as an option that can easily be implemented since there is a large diversity of ores.

An important drawback of the present method of Guinée *et al.* (2002) is that the method is only partly operational, namely for elements and fossil energy carriers. However also other minerals are mined for reasons of the specific potential functions they have for mankind. Those specific functions can be the result of the specific natural configurations of the elements found in the environment (e.g. physical and/or chemical composition of elements like diamond or clay). The useful potential functions can also be based on physical properties, independent of their actual composition (like construction sand or other granules). In the present method of Guinée *et al.* (2002) these minerals are not considered.

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The method should be extended for other minerals that are mined for their specific potential functions, like sand, clay, granite, diamond, et cetera.

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# 5 Selection of improvement options and test set of abiotic resources

## 5.1 Approach

In this study 'update of characterisation factors for abiotic resources' an inventory is made of possible improvement options of the present baseline method to assess depletion of abiotic resources (a slightly adapted version of Guinée (1995) in Guinée et al., 2002). A selection will be made of the improvement options given in chapter 4. Characterisation factors will be derived for a limited list of resources (10 – 15) in order to assess the appropriateness and feasibility of the different options. The selected resources will also be used to analyse the sensitivity in choice of the different approaches on the final assessment of abiotic resource depletion.

Characterisation factors for abiotic resource depletion are based on extraction rates and/or reserves. The single best source for these kinds of data is the United States Geological Survey (USGS)<sup>7</sup>. Also others sources on the internet were consulted like the World Mineral Statistics, published by the British Geological Survey<sup>8</sup>, the Mining Annual Review, published annually by Mining Journal<sup>9</sup> and the publication series Roskill Reports on Metals and Minerals<sup>10</sup>. For some of the resources like gypsum, different kind of clays (kaolin, Ball clay, Fire clay, bentonite, Fuller's earth and common clay) and silica sand searches were carried out on the internet.

## 5.2 Selection of the improvement options

### Definition of different impact categories for abiotic depletion

Define groups of resources based on functions for mankind. In theory these groups should be based on possibilities of substitution. In practice however larger groups will be defined, only partly accounting for substitution.

Suggestion:

- I Elements and configurations, only main functions are specified, possible weighting between functions based on economic value of the functions.
- II Resources for buildings and construction
- III Energy carriers

### Types of category indicators

- extraction rate and reserve (in the environment)
- only reserve (in the environment)
- extraction rate only

### How large are the stocks?

- ultimate reserve
- reserve base
- economic reserves

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<sup>7</sup> <http://minerals.usgs.gov/minerals/>

<sup>8</sup> <http://www.mineralsuk.com/mineralsuk/wmsnet/WMSnew.htm>

<sup>9</sup> <http://www.mining-journal.com/index1.htm>

<sup>10</sup> <http://www.roskill.co.uk/>

## LCI results

- Include other minerals like sand, clay et cetera

### 5.3 Selection of abiotic resources to be elaborated in this study

In table 5.3-1 a summary is given of the resources that will be elaborated in this study. For each of the resources their main functions are given. A detailed description of the resources and their functions is given in the appendix.

Table 5.3-1 selected resources and their main functions

Category	Resource	Ore/Mineral	Location	Main function	Substitutes
A	Antimony	Stibnite (Sb <sub>2</sub> S <sub>3</sub> ), senarmonite etc.	?	Flame retardant	Cr, Sn, organic chemicals
	Copper	Cu-oxides, Cu-sulphides	Canada, Chile, Germany, etc.	Construction, Electricity production	Aluminium, Titanium
	Phosphorous	Phosphate -rock (apatite)	Morocco, Russia and USA	Fertiliser	no substitutes
	Tantalum	Tantalite/Tantallic oxide	Australia, Brazil, Mozambique, etc.	Electronic components	niobium, glass, platinum, etc.
	Lithium	Spodumene, lepidolite, petalite	North America, Brazil, USSR, Spain	Flux in ceramics glass	soda or potassium
	Calcium for lime production	Limestone, gypsum	various deposits world-wide	Cement industry	
	Silicon	SiO <sub>2</sub>	?	Electronic applications	dipotassium tartrate, gallium arsenide
	Industrial diamond	synthetic	n.a.	Stone cutting	boron nitride, silicon carbide
	Feldspar	rock forming materials	various deposits world-wide	flux in glass	talc, pyrophyllite etc.
	Gypsum	CaSO <sub>4</sub>	various deposits world-wide	Wallboard & plaster manufacture	wood, lime
C	Quartz sand/silica sand	Sands with high SiO <sub>2</sub> content	various deposits world-wide	Glass & fibreglass, silica gel	pplastics
	Clays	Clay deposits (kaolinite)	various deposits world-wide	Sanitary ware, pottery, tiles	Very limited; plastics, concrete
	Sand granulate/gravel	Sand deposits	various deposits world-wide	Road base/concrete	Crushed stone
	lime stone	CaCO <sub>3</sub>	various deposits world-wide	Building stone/ dressing stone	Bricks
D	fossil fuels	Oil, gas, coal, peat	Middle East, Venezuela, China etc.	Heating, Transportation	Renewable energy, nuclear energy

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The resources selected in the list cover the complete set of parameters that are considered important for the assessment, being:

A) reason of extraction of the element or mineral

B) methodological assumptions (e.g. ultimate reserve, reserve base, technical/economical reserve, proved reserve, economic value, possible supply and demand in the future (recycling, substitution et cetera).

The present baseline for the assessment of abiotic resource depletion is based on the ultimate reserve and yearly depletion of elements and energy carriers (Guinée et al., 2002). A dominance analysis on normalisation factors for the world (Oers et al., 2001) shows that energy carriers contribute most to the world depletion of resources (together 100%). Of the elements the most important are gold, antimony, lead, silver, copper and sulphur.

A quick review of some LCA case studies showed regular appearance of resources like fossil fuels, zinc ore, iron ore, copper ore, phosphate rock, rock salt, lime (limestone, dolomite), feldspar, sands, clays.

In the following list for each "reason of extraction" 4 to 5 resources were chosen. The resources are selected from a total list taken from USGS (see appendix). A detailed description of the resources and their functions are given in the appendix.

### 5.3.1 Elements

Antimony, because it is the reference substance in the present methodology (Guinée, 1995). It also has a large contribution in the normalisation factor (30%). Antimony occurs in different configurations in many different ores. Main ore is stibnite ( $Sb_2S_3$ ). Other ores are senarmontite and valentinite ( $Sb_2O_3$ ), cervantite and stibiconite ( $Sb_2O_4$ ), kermesite ( $Sb_2S_2O$ ), Jamesonite ( $Pb_2Sb_2S_5$ ) and stephanite ( $Ag_5SbS_4$ ). Sometimes gold and silver is contained in the ore.

Copper appears regularly in inventory tables of LCA. It also has a substantial contribution in the normalisation factor (4%). Copper has many applications, e.g. used as metal, as corrosion inhibitor, as pigment and additive in fodder. The average copper content of copper ores is low (1-2%) and copper would be an expensive metal if it were not for the valuable by-products: silver, gold, nickel, and other metals. The most important ore of copper is chalcopyrite ( $CuFeS_2$ , also containing gold and silver). Chalcocite ( $Cu_2S$ ) is also an important ore. There are about 15 copper ores of commercial importance.

Phosphorus a nonmetallic element is widely diffused in nature, and is found in rock materials, in ores, in the soil and in parts of animal organisms. However in its pure, concentrated form commercial phosphorus is obtained from phosphate rock or from bones. Phosphate rock is a calcium phosphate high in  $P_2O_5$ .

Tantalum is a noble metal. For abiotic depletion tantalum is an interesting example because of political actors that influence the possibilities to extract the ores. Its principle use is in electrolytic capacitors. It is also widely used for chemical processing equipment (resistant for many acids) and in heat resistant applications. The most important ore is tantalite ( $FeO.Ta_2O_5$ ). The ore may contain 10-70% tantalum oxide ( $Ta_2O_5$ ). It often also contains manganese, tin, titanium, tungsten, germanium, zirconium and columbium.

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Lithium is the lightest of all metals. For abiotic depletion lithium is an interesting example because of the expected growing demand of the element in future applications. It is found in more than 40 minerals but is obtained chiefly from lepidolite ( $\text{LiF.KF.Al}_2\text{O}_3.3\text{SiO}_2$ , also carrying rubidium and cesium), spodumene ( $\text{Li}_2\text{O.Al}_2\text{O}_3.4\text{SiO}_2$ , also carrying potassium and sodium oxides), amblygonite ( $\text{Al}_2\text{O}_3.2\text{LiF.P}_2\text{O}_5.\text{LiO}$ ), lithiophilite ( $\text{LiO}.2\text{MnO.P}_2\text{O}_5$ ), chryolithionite ( $3\text{LiF}.3\text{NaF}.2\text{AlF}_3$ ), petalite ( $\text{Li}_2\text{O.Al}_2\text{O}_3.8\text{SiO}_2$ ), manandonite ( $7\text{Al}_2\text{O}_3.2\text{LiO}:2\text{B}_2\text{O}_3.6\text{SiO}_2$ ). Lithium is used in glass, ceramics, batteries, aircraft applications, rockets (oxygen storage), light sensitive cells, as medicine et cetera.

Calcium occurs abundantly in nature, chiefly in combination with carbon and oxygen as calcium carbonate ( $\text{CaCO}_3$ ), in limestone (see also type III below), marble, chalk, coral, and shells. The calcium in lime is used in mortars and cement, as a flux in iron melting, in many chemical processes, as an absorbent, in water treatment, in air-pollution control, in glass manufacture, and for liming acid soils. Lime is also produced from gypsum (see type II below).

Silicon is a metallic element (Si) abundantly occurring in the earth crust. It is used chiefly in its combined forms (e.g.  $\text{SiO}_2$  in glass). Pure silicon metal however is used, as semiconductor, in transistors, rectifiers and electronic devices. Silicon for electronics is produced from very pure resources, like quartz rocks. Silicates ( $\text{SiO}_2$ ) for chemical applications and glass manufacture are produced from very pure sand deposits. It also can be produced after some processing from less pure sand deposits that are rich in silicon (Si). See also type II and III..

### 5.3.2 Configurations with specific physical-chemical composition

Industrial Diamond (so not diamond as gemstone) is a highly transparent and exceedingly hard crystalline stone of almost pure carbon. It is used as abrasive, for cutting tools, and for dies for drawing wire. Jewel diamonds have the formation in regular layers, while industrial diamonds are grown in all directions. There are natural diamonds (in ground) and artificial diamonds (made artificial from carbon).

Feldspar a general name for a group of minerals used for vitreous enamels, pottery, tile, and glass; in fertilisers, in fluxes; for roofing granules; and as an abrasive in soaps and cleaning configurations. There are many varieties of feldspar, but those of greatest commercial importance are the potash feldspars ( $\text{K}_2\text{O}:\text{Al}_2\text{O}_3.6\text{SiO}_2$ ), soda feldspars ( $\text{Na}_2\text{O}:\text{Al}_2\text{O}_3.6\text{SiO}_2$ ) and the Calcium feldspar ( $\text{CaO}:\text{Al}_2\text{O}_3.6\text{SiO}_2$ ).

Gypsum is a widely distributed mineral, which is a hydrated calcium sulfate ( $\text{CaSO}_4.2\text{H}_2\text{O}$ ). It is used for making building plaster, wallboard, tiles, as an absorbent for chemicals, as a paint pigment and extender, and for coating papers. It is also a raw material for producing ammonium sulfate for fertilizer. It is the raw material to produce sulfuric acid and lime (see also lime above). Raw gypsum is also used to mix with portland cement. Compact massive types of the mineral are used as building blocks. So it is used both as a material and for the extraction on configurations.

Quartz sands or silica sands are sands with high silica content. Quartz is the most common variety of silica ( $\text{SiO}_2$ ). Silicon dioxide is the most common of all materials, and in the combined and uncombined states it is estimated to form

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60% of the earth's crust. Many sands, clays and rocks are largely composed of small silica crystals. The most useful commercially are silica sands, often above 98% pure. Silica sands for making glass must be free of iron.

Clays are natural occurring sediments that are produced by chemical actions during the weathering of rocks. Earths that form a past with water and harden when heated. Most clays are composed chiefly of silica and aluminium. Clays may vary greatly in composition resulting in different types of plasticity and hardness. Clays at least should be distinguished in clays used for ceramics and bricks et cetera and clays used as sealing materials for example for dykes. If the clays are used for making ceramics and bricks et cetera the clay should have specific physical-chemical properties and therefore belongs to category II.

### **5.3.3 Materials with specific physical properties (function: construction)**

#### **Sand – Granulate (gravel)**

An accumulation of grains of mineral matter derived from the disintegration of rocks. It is distinguished from gravel only by size of the grains or particles. At least quartz sand (syn. silica sand or industrial sand) which is a type II resource (see above) should be distinguished from construction sand. The most valuable commercially are silica sands. Silica sands for making glass must be free of iron. Construction sand might be distinguished in concrete and mortar sand and filling sand. Concrete and mortar sands should be free of organic matter and have to meet certain demands on the grain size distribution. In the Netherlands they are produced by separating specific fractions from coarse natural sand deposits; usually the finer fractions are either sold as filling sand or flushed back into the extraction pit. For filling sand there are no strict demands on the grain size. In fact filling sand can be replaced by any other mineral or even waste granule.

#### **Clays as sealing material.**

Clay is be used for covering landfills and in construction. Insulating landfill covers are produced from specific clay types (e.g. bentonite) which should be seen as a type II resource. Non-insulating covers can be produced of regular clays.

Clay can be used for filling material (e.g. roads and dykes) in which case the demands are mostly related to the workability of the material. For the top layer of dykes clay has to fulfil specific physical and chemical demands, which however can be met by many regular clays.

Limestone (or other nature stone – dimension stone used as building product) a general name for a great variety of calcite rocks (see also lime). Limestone is used as a flux, for the manufacture of lime and as a building stone. So it is used both as a material and for the extraction on configurations. In the Netherlands limestone is distinguished in hard limestone, which is imported for use in road construction and concrete manufacturing and soft limestone used in the cement industry and milling industry (the milling industry produces lime stone powder as a filler in e.g. plastics, in building materials, flue gas desulphurisation and agricultural applications).

### **5.3.4 Fossil fuels (function: energy supply)**

For the extraction of materials for reasons of energy content no distinction will be made between different fuels like (oil, gas and coal et cetera). An attempt

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will be made to estimate the total amount of energy contained in carbon based minerals (including minerals, which are not considered commercial fuels at this moment, like heavy oil, shell oil et cetera).

Fossil fuels are not only used as energy carrier, but are also used as raw material for the production of plastics and bitumen (type II).



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## 6 Results; new characterisation and normalisation factors

### 6.1 Data availability

On the level of elements many data are available on extraction rates, reserves and reserve base. USGS is the single best resource for these kinds of data. The estimation of ultimate reserves of elements is based the concentration of the elements in the earth crust, ocean and atmosphere is used (Guinée, 1995).

Also on the level of specific configurations some data are given by the USGS. However, for many of these configurations (unique configurations of elements) no estimates are given for the reserves. For these minerals, like feldspar, gypsum, silica sand, construction sand, clays and limestone, it is stated that the reserves are infinite or very large or sufficient on a world level, although on a regional level sometimes scarcity may occur.

After extensive search on the internet for some of the minerals, like silica sand and clay (kaolin), estimates of reserves were found for a very limited group of countries. However the reliability of these estimates is poor. Estimates within countries sometimes differ. Often it is not indicated whether the estimate is an economic reserve or reserve base. Further more the extrapolation of these country reserves to a world level needs attention. A first very rough approach would be to extrapolate on basis of surface area (see appendix). However for some of the minerals this approach will be too rough and more geological information on climate, original soil matter, the presence of volcanoes, regions of sedimentation (rivers, lakes, seas) et cetera are needed.

For some of the weathered rock minerals on the earth surface, like feldspar, mica, quartz/industrial sand and clay, estimates are made of the ultimate reserve based on the average composition of the earth crust (Locher & de Bakker, 1989). However, these ultimate reserves are an overestimation of the amount of reserves that actually can be used in the industry. Although the weathering of rock minerals will lead to large amounts of fairly pure quartz sand (%SiO<sub>2</sub>>90), the pure sand (%SiO<sub>2</sub>=98) and very pure sands ((%SiO<sub>2</sub>>99.5) that are used commercially are however (very) scarce. So commercial use of the configurations requires very specific demands on purity and other physical and chemical properties dependent of the specific application in which the configuration is used. Therefore, the difference between the ultimate reserve and the reserve of configurations that meets these demands for commercial use can be very large.

For the lack of available data on configurations, especially data on reserves, reserve base and ultimate reserves, the derivation of characterisation factors for sand, gypsum, clays et cetera is not possible. Therefore the following sections will be focussed on elements and fossil fuels only. The update of characterisation factors however is carried out for all commodities reported by the USGS and so is not restricted to the selected elements in section 5.3. For a limited number of configurations for which data are available at USGS additional characterisation factors are derived.

## 6.2 Update of the characterisation factors

A spreadsheet has been developed containing data on elements, a limited number of configurations and fossil fuels. In the spreadsheet data are gathered concerning the extraction rates and estimates on the amount of resources on a world level. These estimates are distinguished in ultimate reserves, reserve base and reserves. The data are taken from the commodity statistics of USGS (<http://minerals.usgs.gov/minerals/pubs/commodity/>) and are based on the reference year 1999. Data concerning ultimate reserves are taken from Guinée (1995). Data on energy and fossil fuels are from the world Resource Institute (WRI) and the International Energy Agency (IEA). Estimates on reserve base of fossil fuels, including unconventional resources like heavy oils, tar sands and shale deposits, are based on Campbell & Laherrère (1998).

In this report only an update of the baseline method (Guinée *et al.*, 1995) is presented (table 1). In this method the characterisation model is a function of the extraction rate of the resource and the reserve of the resource. For characterisation factors only based on reserves or extraction rates is referred to the spreadsheet (available at the CML web site, at [www.leidenuniv.nl/cml/ssp/](http://www.leidenuniv.nl/cml/ssp/)).

Table 1 ADP (kg antimony eq. / kg emission) for characterising abiotic resource depletion based on extraction rates and ultimate reserves, reserve base or reserve (year 1999).

Substance	cas no.	group	ADP		
			<i>kg antimony eq. / kg extraction</i> <sup>1,2,3</sup>	ultimate reserve <sup>4</sup>	reserve base
aluminium (Al)	7429-90-5	element	1.09E-09	2.53E-05	2.14E-05
antimony (Sb)	7440-36-0	element	1.00E+00	1.00E+00	1.00E+00
arsenic (As)	7440-38-2	element	3.93E-03	2.40E+00	2.33E+00
barium (Ba)	7440-39-3	element	6.04E-06	3.37E-03	1.55E-02
beryllium (Be)	7440-41-7	element	1.26E-05	3.95E+00	
bismuth (Bi)	7440-69-9	element	4.11E-02	4.49E+00	1.08E+01
boron (B)	7440-42-8	element	4.27E-03	5.28E-03	1.74E-02
bromine (Br)	7726-95-6	element	4.39E-03		
cadmium (Cd)	7440-43-9	element	1.57E-01	1.11E+00	1.92E+00
chlorine (Cl)	7782-50-5	element	2.71E-05		
chromium (Cr)	7440-47-3	element	4.43E-04	1.96E-05	3.77E-05
cobalt (Co)	7440-48-4	element	1.57E-05	2.56E-02	4.89E-02
copper (Cu)	7440-50-8	element	1.37E-03	2.50E-03	3.94E-03
gallium (Ga)	7440-55-3	element	1.46E-07		
germanium (Ge)	7440-56-4	element	6.52E-07	1.95E+04	1.04E+04
gold (Au)	7440-57-5	element	5.20E+01	3.60E+01	3.99E+01
indium (In)	7440-74-6	element	6.89E-03	5.55E+02	1.15E+03
iodine (I2)	7553-56-2	element	2.50E-02	2.22E-03	3.10E-03
iron (Fe)	7439-89-6	element	5.24E-08	1.66E-06	3.64E-06
kalium (K;potassium)	7440-09-7	element	1.60E-08	9.00E-06	1.59E-05
lead (Pb)	7439-92-1	element	6.34E-03	1.50E-02	2.67E-02
lithium (Li)	7439-93-2	element	1.15E-05	1.33E-02	4.38E-02
magnesium (Mg)	7439-95-4	element	2.02E-09		
manganese (Mn)	7439-96-5	element	2.54E-06	2.35E-05	5.80E-04
mercury (Hg)	7439-97-6	element	9.22E-02	2.62E+00	4.52E+00
molybdenum (Mo)	7439-98-7	element	1.78E-02	7.11E-02	1.46E-01

Substance	cas no.	group	ADP		
			<i>kg antimony eq. / kg extraction</i> <sup>1,2,3</sup>		
			ultimate reserve <sup>4</sup>	reserve base	reserve
nickel (Ni)	7440-02-0	element	6.53E-05	4.18E-03	1.69E-02
niobium (Nb)	7440-03-1	element	1.93E-05	6.55E-02	6.96E-02
palladium (Pd)	7440-05-3	element	5.71E-01	9.36E+00	4.99E+00
phosphorus (P)	7723-14-0	element	5.52E-06	6.21E-05	2.54E-04
platinum (Pt)	7440-06-4	element	2.22E+00	9.09E+00	4.85E+00
rhenium (Re)	7440-15-5	element	6.03E-01	3.19E+01	2.66E+02
selenium (Se)	7782-49-2	element	1.94E-01	7.35E+00	1.09E+01
silicium (Si; silicon)	7440-21-3	element	1.40E-11		
silver (Ag)	7440-22-4	element	1.18E+00	8.42E+00	8.16E+00
Sodium (Na)	7440-23-5	element	5.50E-08		
strontium (Sr)	7440-24-6	element	7.07E-07	1.77E-01	2.38E-01
sulfur (S)	7704-34-9	element	1.93E-04	3.91E-04	1.05E-03
tantalum (Ta)	7440-25-7	element	4.06E-05	1.15E+01	2.28E+01
tellurium (Te)	13494-80-9	element	4.07E+01	7.21E+00	1.12E+01
thallium (Tl)	7440-28-0	element	2.43E-05	2.98E+03	3.75E+03
tin (Sn)	7440-31-5	element	1.62E-02	1.15E-01	7.77E-02
titanium (Ti)	7440-32-6	element	2.79E-08	1.52E-03	1.78E-03
Tungsten, Wolfram	7440-33-7	element	4.52E-03	2.54E-01	2.80E-01
vanadium (V)	7440-62-2	element	7.70E-07	4.93E-03	1.55E-02
yttrium (Y)	7440-65-5	element	5.69E-07	8.16E-01	4.23E-01
zinc (Zn)	7440-66-6	element	5.38E-04	3.65E-03	8.05E-03
Zirconium (Zr)	7440-67-7	element	5.44E-06	1.64E-02	2.30E-02
Barite		configuration		1.99E-03	9.16E-03
bauxite		configuration		8.70E-06	7.35E-06
industrial diamond <sup>1</sup>		configuration		3.28E+00	6.05E+00
diatomite		configuration			1.11E-04
fluorspar		configuration		2.62E-03	3.37E-03
garnet (industrial)		configuration		4.40E-03	5.80E-02
graphite (natural)		configuration		4.44E-04	1.10E-01
peat		configuration		5.67E-08	3.61E-05
perlite		configuration		3.88E-05	1.36E-04
rare earths		configuration		5.69E-04	2.96E-04
soda ash		configuration		5.56E-07	6.65E-07
sodium sulfate		configuration		9.92E-06	8.30E-06
talc and pyrophyllite		configuration		1.18E-03	4.99E-03
vermiculite		configuration		1.11E-03	7.66E-03
fossil fuels <sup>2</sup>		fossil fuel	1.95E-04	7.79E-09	1.17E-08

1 unit of ADP for diamond is kg antimony equivalents / carats

2 unit of ADP for fossil fuels is kg antimony equivalents / MJ

3 in the baseline method (Guinée et al., 2002) the elements and configurations and fossil fuels are part of one impact category. However if within this group different impact categories are defined based on different potential functions then the ADP should be expressed relative to a reference extraction specific for that function (section 2.2, and formula 2) and a weighting step as discussed in section 4.2 should be added. As a consequence also different normalisation factors should be derived for the separate impact categories (table 2 and 3). For example, if the depletion of energy carriers is treated as a separate impact category or sub category for the overall impact category 'abiotic resource depletion' the reference extraction of antimony should be replaced by the reference extraction of fossil energy (see formula 3 in

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section 2.2). As a result the numerator and denominator in the formula are the same leading to an  $ADP_{\text{fossil energy}}$  of 1. The indicator result for fossil fuel should subsequently be weighted against the result for configurations and elements.

4 estimates for ultimate reserves of configurations are not available

### **Comparison of results of this report with the characterisation factors from Guinée (1995)**

Compared to the set of factors derived by Guinée a number of elements are missing in this update; actinium, argon, cerium, cesium, dysprosium, erbium, europium, gadolinium, hafnium, holmium, krypton, lanthanum, lutetium, neodymium, neon, polonium, praseodymium, protactinium, radium, radon, rubidium, samarium, scandium, terbium, thorium, thulium, xenon and ytterbium. The USGS reports no extraction rates for these elements. In Guinée (1995) it was assumed that the extraction rates for these elements equals to the extraction of rhenium. In this update this assumption was not made.

The extraction rates of some of the elements in Guinée (1995) were mistakenly based on kg ores or configurations. In the updated calculations the figures for Phosphate rock, Bauxite, Arsenic trioxide ( $As_2O_3$ ) and Boric oxide ( $B_2O_3$ ) are translated to the elements phosphorus, Aluminium, Arsenic and Boric.

The figures on the extraction rate of Calcium in Guinée (1995) was based on the extraction of Fluorspar only. However, the production and reserves should also be based on other resources containing calcium, like lime, limestone, gypsum, calcereous marl, calcium carbonate, calcereous clays, shells, (milk), Wallastonite etc. For these resources however no data are published by USGS and therefore no characterisation factors can be calculated.

The calculations on fossil energy differ from Guinée et al. (2002) because of differences in literature sources on the estimated proven reserves of oil, natural gas and coal. In this update the estimated proven reserves are based on one source only (WRI, 1994) (for details on the calculation is referred to the spreadsheet). In this update, like in Guinée (1995), the proven reserves of the fossil fuels are still converted to a rough estimate of ultimate reserves, using the fossil carbon content of the earth crust (Berner & Lasaga, 1989) (see also section 2.2).

All the other differences between the characterisation factors of Guinée (1995) and the present update can be explained by differences in extraction rates of the resources between the year 1992 (reference year in Guinée, 1995) and the year 1999 (reference year in this report). Note that the production rate of antimony between 1992 and 1999 has been doubled. Because antimony is the reference substance (see section 2.2) as a result all the ADP's have been changed. Also, but to a less extent, sometimes the estimated reserves between the different years differ.

### **6.3 Update of the normalisation factors**

The update of characterisation factors in LCA implies that also normalisation factors must be updated. Normalisation is a procedure in LCA to relate outcomes of alternatives to a reference situation. External normalisation in LCA is defined as a step relating characterisation scores of a product system to the actual magnitude of the impacts within each impact category in a reference area and time period. In the case of abiotic resource depletion this reference situation is the extraction of resources on a world level in the year 1999. So the

normalisation factor is the sumproduct of the characterisation factors and the set of extractions on a world level in the year 1999. Note that each extraction also can be considered as a separate impact category (see sections 3.2 and 4.2).

Table 2 normalisation factors abiotic resource depletion of elements and configurations (kg eq..yr<sup>-1</sup>) based on extraction rates and ultimate reserves, reserve base or reserve (reference: world, year 1999).

Substance	cas no.	extraction rate kg.yr <sup>-1</sup> 1,2	ADP*extraction rate kg antimony eq..yr <sup>-1</sup>		
			ultimate reserve <sup>3</sup>	reserve base	reserve
aluminium (Al)	7429-90-5	2.31E+10	2.53E+01	5.85E+05	4.94E+05
antimony (Sb)	7440-36-0	1.22E+08	1.22E+08	1.22E+08	1.22E+08
arsenic (As)	7440-38-2	2.94E+07	1.15E+05	7.07E+07	6.85E+07
barium (Ba)	7440-39-3	3.33E+09	2.01E+04	1.12E+07	5.15E+07
beryllium (Be)	7440-41-7	3.01E+05	3.79E+00	1.19E+06	
bismuth (Bi)	7440-69-9	3.62E+06	1.49E+05	1.63E+07	3.91E+07
boron (B)	7440-42-8	1.37E+09	5.87E+06	7.26E+06	2.39E+07
bromine (Br)	7726-95-6	5.30E+08	2.33E+06		
cadmium (Cd)	7440-43-9	1.91E+07	2.99E+06	2.13E+07	3.66E+07
chlorine (Cl)	7782-50-5	1.27E+11	3.44E+06		
chromium (Cr)	7440-47-3	1.35E+10	5.98E+06	2.65E+05	5.08E+05
cobalt (Co)	7440-48-4	2.99E+07	4.69E+02	7.66E+05	1.46E+06
copper (Cu)	7440-50-8	1.26E+10	1.72E+07	3.15E+07	4.96E+07
gallium (Ga)	7440-55-3	1.00E+05	1.46E-02		
germanium (Ge)	7440-56-4	5.80E+04	3.78E-02	1.13E+09	6.00E+08
gold (Au)	7440-57-5	2.54E+06	1.32E+08	9.13E+07	1.01E+08
indium (In)	7440-74-6	2.15E+05	1.48E+03	1.19E+08	2.47E+08
iodine (I2)	7553-56-2	1.93E+07	4.82E+05	4.29E+04	5.98E+04
iron (Fe)	7439-89-6	5.07E+11	2.66E+04	8.43E+05	1.84E+06
kalium (K;potassium)	7440-09-7	2.13E+10	3.41E+02	1.92E+05	3.38E+05
lead (Pb)	7439-92-1	3.02E+09	1.91E+07	4.53E+07	8.05E+07
lithium (Li)	7439-93-2	1.40E+07	1.61E+02	1.86E+05	6.13E+05
magnesium (Mg)	7439-95-4	3.37E+09	6.80E+00		
manganese (Mn)	7439-96-5	6.99E+09	1.78E+04	1.64E+05	4.05E+06
mercury (Hg)	7439-97-6	1.80E+06	1.66E+05	4.72E+06	8.13E+06
molybdenum (Mo)	7439-98-7	1.22E+08	2.17E+06	8.68E+06	1.78E+07
nickel (Ni)	7440-02-0	1.12E+09	7.31E+04	4.68E+06	1.89E+07
niobium (Nb)	7440-03-1	2.36E+07	4.57E+02	1.55E+06	1.64E+06
palladium (Pd)	7440-05-3	1.74E+05	9.93E+04	1.63E+06	8.68E+05
phosphorus (P)	7723-14-0	1.85E+10	1.02E+05	1.15E+06	4.71E+06
platinum (Pt)	7440-06-4	1.69E+05	3.75E+05	1.54E+06	8.19E+05
rhenium (Re)	7440-15-5	4.60E+04	2.78E+04	1.47E+06	1.22E+07
selenium (Se)	7782-49-2	1.48E+06	2.87E+05	1.09E+07	1.62E+07
silicium (Si; silicon)	7440-21-3	3.40E+09	4.77E-02		
silver (Ag)	7440-22-4	1.77E+07	2.10E+07	1.49E+08	1.44E+08
Sodium (Na)	7440-23-5	9.84E+10	5.41E+03		
strontium (Sr)	7440-24-6	3.04E+08	2.15E+02	5.39E+07	7.22E+07
sulfur (S)	7704-34-9	5.71E+10	1.10E+07	2.23E+07	6.01E+07

Substance	cas no.	extraction rate $kg.yr^{-1}$ <sup>1,2</sup>	ADP*extraction rate $kg\ antimony\ eq..yr^{-1}$		
			ultimate reserve <sup>3</sup>	reserve base	reserve
tantalum (Ta)	7440-25-7	4.95E+05	2.01E+01	5.71E+06	1.13E+07
tellurium (Te)	13494-80-9	1.24E+05	5.04E+06	8.94E+05	1.39E+06
thallium (Tl)	7440-28-0	1.50E+04	3.64E-01	4.47E+07	5.63E+07
tin (Sn)	7440-31-5	1.98E+08	3.21E+06	2.29E+07	1.54E+07
titanium (Ti)	7440-32-6	2.76E+09	7.69E+01	4.20E+06	4.90E+06
Tungsten;	7440-33-7	3.10E+07	1.40E+05	7.88E+06	8.68E+06
wolfram					
vanadium (V)	7440-62-2	4.28E+07	3.30E+01	2.11E+05	6.62E+05
yttrium (Y)	7440-65-5	1.89E+06	1.08E+00	1.54E+06	8.00E+05
zinc (Zn)	7440-66-6	8.04E+09	4.33E+06	2.93E+07	6.47E+07
Zirconium (Zr)	7440-67-7	4.52E+08	2.46E+03	7.42E+06	1.04E+07
asbestos (kg)		1.90E+09			
Barite		5.70E+09		1.14E+07	5.22E+07
bauxite		1.27E+11		1.11E+06	9.33E+05
industrial diamond		5.63E+07		1.85E+08	3.41E+08
fluorspar		4.51E+09		1.18E+07	1.52E+07
garnet (industrial)		2.72E+08		1.20E+06	1.58E+07
graphite		6.85E+08		3.04E+05	7.54E+07
(natural)					
peat		2.70E+10		1.53E+03	9.75E+05
perlite		1.85E+09		7.18E+04	2.52E+05
rare earths		8.20E+07		4.66E+04	2.43E+04
sodium sulfate		2.50E+09		2.48E+04	2.07E+04
talc and pyrophyllite		9.47E+09		1.12E+07	4.72E+07
vermiculite		5.30E+08		5.89E+05	4.06E+06
<b>Normalisation factor for sum</b>			<b>3.6E+08</b>	<b>2.30E+09</b>	<b>2.54E+09</b>

1 unit of extraction rate for diamond carats.yr<sup>-1</sup>

2 unit of extraction rate for fossil fuels is MJ.yr<sup>-1</sup>

3 estimates for ultimate reserves of configurations are not available

Table 3 normalisation factors abiotic resource depletion of fossil fuels (kg eq..yr<sup>-1</sup>) based on extraction rates and ultimate reserves, reserve base or reserve (reference: world, year 1999).

Substance	cas no.	extraction rate $MJ.yr^{-1}$	ADP*extraction rate $Kg\ antimony\ eq..yr^{-1}$ <sup>1</sup>		
			ultimate reserve	reserve base	reserve
fossil fuels		3.54E+14	6.91E+10	2.76E+06	4.16E+06

1 In the baseline method (Guinée et al., 2002) the fossil fuels, elements and configurations are part of one impact category. The ADP is expressed relative to the extraction of the reference resource antimony (see note 3 table 1). If the depletion of energy carriers is treated as a separate impact category or sub category than the ADP of fossil fuels is 1 (see note 3 table 1). As a result the normalisation factor for the depletion of fossil energy will be equal to the world extraction in the year 1999, that is 3.54E+14 MJ eq..yr<sup>-1</sup>.

#### 6.4 Differences between ultimate reserves, reserve base and reserve

The consequences in the choice of the size of the resource that is used in the characterisation model, that is ultimate reserve, reserve base or reserve, are difficult to comprehend if looking at the set of characterisation factors. To compare the different possible choices the relative contribution of the extractions of the resources to the normalisation score is used. This relative contribution to the normalisation score shows which extractions on the present world level are the most dominant. Note that for the extraction of elements and configurations it is assumed that the characterised extractions between the different resources can be summarised and that the resources are weighted equally. In the sections 3.2 and 4.2 it was argued that each extraction also could be considered as a separate impact category.

Table 4 Relative contribution (%) of extractions of elements and configurations to the normalisation score for ADP based on extraction rates and ultimate reserves, reserve base or reserve.

Substance	cas no.	group	unit	Relative contribution to normalisation score		
				% ultimate reserve	% reserve base	% reserve
antimony (Sb)	7440-36-0	element	kg	34	5	5
arsenic (As)	7440-38-2	element	kg	0	3	3
barium (Ba)	7440-39-3	element	kg	0	0	2
bismuth (Bi)	7440-69-9	element	kg	0	1	2
boron (B)	7440-42-8	element	kg	2	0	1
bromine (Br)	7726-95-6	element	kg	1	0	0
cadmium (Cd)	7440-43-9	element	kg	1	1	1
chlorine (Cl)	7782-50-5	element	kg	1	0	0
chromium (Cr)	7440-47-3	element	kg	2	0	0
copper (Cu)	7440-50-8	element	kg	5	1	2
germanium (Ge)	7440-56-4	element	kg	0	50	24
gold (Au)	7440-57-5	element	kg	37	4	4
indium (In)	7440-74-6	element	kg	0	5	10
lead (Pb)	7439-92-1	element	kg	5	2	3
molybdenum (Mo)	7439-98-7	element	kg	1	0	1
nickel (Ni)	7440-02-0	element	kg	0	0	1
selenium (Se)	7782-49-2	element	kg	0	0	1
silver (Ag)	7440-22-4	element	kg	6	7	6
strontium (Sr)	7440-24-6	element	kg	0	2	3
sulfur (S)	7704-34-9	element	kg	3	1	2
tellurium (Te)	13494-80-9	element	kg	1	0	0
thallium (Tl)	7440-28-0	element	kg	0	2	2
tin (Sn)	7440-31-5	element	kg	1	1	1
zinc (Zn)	7440-66-6	element	kg	1	1	3
industrial diamond		configuration	*	0	8	14
fluorspar (kg)		configuration	kg	0	1	1
garnet (industrial; kg)		configuration	kg	0	0	1
graphite (natural; kg)		configuration	kg	0	0	3
talc and pyrophyllite (kg)		configuration	kg	0	0	2

\* = unit in carats. Note: zero (0) in the table means nearly zero (less than 0.5%), all elements and configurations which have a zero or nearly zero contribution for all characterisation models (i.e. based on ultimate reserves, reserve base or reserve) are left out.

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The contribution analysis in table 3 shows that the differences for the different characterisation models are large. The table shows that ADP based on reserve base and reserve are related. More or less the same resources show up to be dominant, but the extend to which they are dominating differs. However, the difference between ADP based on ultimate reserves and reserve base is larger. Other resources appear to be dominant and also the amount in which they are dominant differs.

As discussed in section 4.6 the assumptions on what is technical and economical possible differ between the different indicators, i.e. ultimate reserve, reserve base and (economic) reserve. The disadvantage of the 'reserve base' and 'economic reserve' is that the estimate of the size of the reserve involves a variety of respectively technical and economic considerations not directly related to the environmental problem of resource depletion. The estimates, however, are relatively certain, because they are based on present practice. The 'ultimate reserve' is more directly related to the environmental problem of resource depletion. However, it is highly uncertain how much of the scattered concentrations of elements and configurations, will become available, because technical and economical developments in the far future are not certain.

There is not sufficient information on which of these reserves gives the best indication of the *ultimate extractable reserve*. Because table 3 shows that the different characterisation models show very different relative contributions of resources to abiotic resource depletion it is advised to use more than one characterisation model so a sensitivity analysis can be carried out and the significance of differences for the score for abiotic resource depletion can be indicated for a specific LCA case study.



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## 7 Conclusions

In this study a theoretical description is given of the problem of abiotic resource depletion. In section 7.1 a summary is given of how the problem of abiotic resource depletion is defined in this study, indicating the items that are part of the problem but are not worked out in this study. Based on this delineation of the problem, options have been investigated for improving the baseline method to assess depletion of abiotic resources recommended in the new Dutch LCA Handbook (Guinée et al., 2002). The study focused on characterisation factors for configurations, in contrast to elements. The study has identified the following improvement options:

1. Distinguishing three sub-categories of abiotic resource depletion,
2. Distinguishing three types of extractable reserve.
3. Using these options, characterisation factors for a number of configurations have been calculated.

### 7.1 Summary of the theoretical definition of the problem and the delineation in this study

The differences between methods for the assessment of the problem of abiotic resource depletion very much depend on how the problem is defined. In chapter 3 a theoretical description is given of the problem distinguishing different items that might or might not be considered as part of the problem. Below a summary is given of what in this research has been considered to be part of the problem of abiotic resource depletion.

#### **Problem; Area of protection**

From a functional point of view the interest of mankind for abiotic resources is not the resource itself (intrinsic value) but its potential to fulfil functions for mankind. The depletion of resources can be defined as; **Abiotic resource depletion is the decrease of availability of the total reserve of potential functions of resources.**

#### **Sub-categories of the impact category abiotic resource depletion**

In theory the depletion of the different potential functions are separate impact categories. The functions are unique and can not directly be exchanged. So the depletion of potential functions represent different (environmental) problems. **To add up the different depletions of potential functions to one overall depletion score a subsequent subjective weighting step is needed. However this has not been worked out in this project.**

#### **Time scale of the problem; type of resource deposits, funds and flows**

Depending on the time scale in which a resource is replenished three different types of abiotic resources can be distinguished: deposits, funds and flows. **This project is restricted to the deposit type of abiotic resources.** In this project deposits are defined as resources that are not replenished or broken down by geologic forces within a time horizon of 500 years.

#### **Indicator; reserve and/or extraction rate**

The indicator for the depletion of abiotic resources can be based on **the reserve of the resource, the extraction rate of the resource or both reserve and**

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**extraction rate.** All three indicators have been worked out. Abiotic resource depletion can also be defined as a problem of dilution of (functions of) resources (e.g. diminishing of concentrations). This last indicator has not been worked out in this project.

#### **Depletion versus competition**

Depletion deals with the decrease of availability of the total reserve of potential functions of resources in the future due to the use by the product systems at present. Competition deals with the problem of reduced availability due to the use of the resource by product systems at the same time. **Competition is not considered as an environmental problem and is not worked out in this project.**

#### **Reserves in economy and environment**

In theory, from a functional point of view, the reserve of a resource includes both reserves in nature and in the economy (the total stock of products from which secondary materials can be recycled), as long as the potential functions of that material in economy are still available. In the present baseline of abiotic resource depletion **the reserves are restricted to the reserves in the environment.** The development of an approach based on environmental and economic reserves was beyond the scope of this project.

#### **Size of the reserve; ultimate reserve, reserve base or economic reserve**

The estimate of the reserve of resources is problematic. It is determined by the assumed technical and economic possibilities to extract the resource. The reserve that can ultimately be technically extracted may be termed the ultimate extractable reserve. This reserve is by definition impossible to determine and can only be approached by upper (ultimate reserve) or lower (economic reserve and reserve base) estimates. Because of these uncertainties, **in this project characterisation factors have been derived based on all three different reserve estimates.**

#### **Spatial scale of the problem; regional versus global**

The market for elements and minerals is regional to global. Supply and demand of these materials are connected by transport of the materials ultimately all over the world. So the depletion of abiotic resources and their potential functions can be defined as a global problem. In this project characterisation factors have been derived for depletion of all the materials on a **world scale.** No regionally differentiated factors have been derived.

## **7.2 Conclusions on improvement options for the baseline method**

### **Sub categories for abiotic resource depletion**

Potential (future) functions are the reason for the extraction of resources. A first attempt has been made to describe potential functions and possibilities of including substitution in the assessment of abiotic depletion for a limited group of 15 resources. Because the elements and configurations may have very different potential functions and because possible shifts in potential functions in the future are very difficult to anticipate, a detailed distinction of sub-impact categories based on potential (future) functions, including possible substitutions, is considered not to be feasible for the time being. Suggested is a more coarse distinction in sub-categories, related to three broad groups of functions:

- I Elements and configurations,
- II Resources for building and construction
- III Energy carriers

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Between these subcategories and in principle even within a sub-category, a subsequent weighting step may be needed. Especially subcategory I consists of many different elements and configurations with quite different potential functions.

It is suggested to base this weighting on the economic values of groups of elements or configurations or even individual elements or configurations "in the ground". Such weighting factors are not available, unfortunately, but they could be derived by taking the economic value of the function minus the costs for extraction and transformation. The assumption is that this price is an indicator for the present and future value of the resource for society. Of course, this is not completely true because also scarcity of the resource may influence its price to some extent. Furthermore the future value for society will be altered by technological developments and income changes. So present prices will only partly be indicative for the future value of functions. For the moment it seems the best option to be worked out further.

### Distinguishing three types of extractable reserve

The characterisation factors presented in this report are the result of a function of the yearly extraction of the resource and the reserve of the resource. As there exist several options for calculating the reserve of the resources, three main types have been defined covering the field of options:

- ultimate reserve,
- reserve base and
- economic reserve.

The estimates of the reserve of the resources are determined by the assumed technical and economical possibilities to extract the resource and therefore also will depend on the time horizons considered in the assessment of the problem. On the range from ultimate reserve, to reserve base, and to economic reserve, the short term technical and economical feasibility of the extraction of the resource plays an increasing role. The effort put into exploration also plays a disturbing role in the amount of economic reserves.

The contribution analysis executed for the different types of reserves showed large differences in the currently most dominant extractions of resources that contribute to abiotic depletion. It is not possible to determine one best type of reserve as the best available estimate for the *ultimate extractable reserve*. On the one hand the best available estimate may depend on the scope of a specific LCA-study. For example, for occasional decisions (e.g. short term optimisation; see Guinée et al, 2002) the best estimate may be the economic reserve, while for change-oriented structural decisions the best estimate may somewhere be in between the reserve base and the ultimate reserve. Having different sets of characterisation factors using the different reserve types make it possible to perform a sensitivity analysis on this.

With respect to the guideline on abiotic depletion as stated in the new Dutch Handbook on LCA, we propose to slightly rephrase this into:

Method status	Characterisation method/factor
baseline	based on ultimate reserves and extraction rates
alternative 1	based on <b>reserve bases</b> and extraction rates
alternative 2	based on ultimate or economic reserves only
alternative 3	based on exergy content
additional	–
variant	–

Source: Guinée et al. 2002; Part 2a.

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The changes in the Guinée et al (2002) guidelines on abiotic depletion thus are limited to alternative 1 (see bold text) and to the updated data used for calculating the characterisation factors for the baseline, alternative 1 and alternative 2.; the tables with these updated factors can be found in this report.

### **Calculating characterisation factors for configurations and resources for building and construction**

In this project also an attempt has been made to derive additional characterisation factors for configurations (like sand for glass productions, clay for ceramics) and resources for construction (like sand for concrete, limestone, granite et cetera). However, for lack of reliable data on particularly the reserve of these resources it appeared not to be possible to derive such characterisation factors. In USGS the size of these resources is generally qualified as infinite, very large or sufficient for a large period of time. It might therefore be assumed that depletion of these resources is not a problem<sup>11</sup>.

This most likely will be the case for resources for construction. Construction materials are produced from abundantly present minerals, like granite or limestone et cetera. There are no strict quality demands for these types of resources. Besides that these resources are abundantly available the properties of these resources not or hardly get depleted by their use, because the resources are only transported (e.g. filling sand) or only slightly transformed, mostly in a reversible form, like concrete and granulates.

However, configurations that are used as such in further industrial processing sometimes only can be used if specific high quality standards considering physical/chemical properties are met, e.g. silica sands free of iron for the manufacture of glass. These configurations with very strict physical/chemical properties are less abundant in the earth crust. The problem is that for the assessment of abiotic depletion in LCA configurations are generally not specified to these very specific physical/chemical properties. If specified in this way, this would easily lead to an enormous list of interventions, for which characterisation factors then have to be derived, i.e. data on reserves and yearly extractions should then be gathered on a detailed level of configurations with specified properties. Such data are not and will not become readily available. If in a specific LCA the depletion of very specific configurations is believed to be an issue, additional data could be gathered for these cases, taking into account the specific demands on physical and chemical properties.

### **Update of the characterisation factors of Guinée (1995)**

A complete update of the characterisation factors, i.c. Abiotic Depletion Potentials or ADP's, for abiotic depletion has been made in this study applying the baseline method as recommended by Guinée et al. (2002) and updated data sets on extraction rates and reserves. Some of the calculations of ADP's are improved (see section 6.2 and table 1). ADP's have been calculated for the ultimate reserve, reserve base and economic reserve. To allow updates of the basic data and different choices in the characterisation method, the basic data for the calculation of the characterisation factors and normalisation factors are available at the CML web site, at [www.leidenuniv.nl/cml/ssp/](http://www.leidenuniv.nl/cml/ssp/).

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<sup>11</sup> Note however that for another impact category 'transformation due to land use,' the extraction of these minerals may have very large impacts.

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## 8 Recommendations

The aim of this study was to spot improvement options for the baseline method of the depletion of abiotic resources. Based on this study the following recommendations are made.

### **Develop a function-based weighting method for elements and fossil fuels**

An important drawback of the present baseline method recommended by Guinée et al. (2002) is that the resources, elements and fossil fuels, are not classified into different (groups of ) functions and thus are added to one impact score without further weighting.

Based on this study we now recommend to weight the impact scores for different elements because they fulfil quite different functions to mankind. It is suggested to base this weighting on the economic value of the element or configuration "in the ground".

### **Estimate reserves of configurations**

The USGS is the main source for data on reserves and extraction rates. However for many configurations data, on particularly the reserves, are missing. Even after extensive search on the internet reliable data appeared to be not present. In order to be able to derive characterisation factors for configurations estimates should be made of reserves of configurations. The estimation of reserves, like ultimate reserve, reserve base and (economic) reserve, is specialised work best carried out by geologists, like at USGS. An alternative might be to buy data from commercial geological consulting groups, e.g. Roskill (<http://www.roskill.co.uk/>).

Some products require configurations with very specific physical/chemical properties. If in a specific LCA the depletion of very specific configurations is believed to be an issue, additional data could be gathered for these cases, e.g. by industry having expert knowledge on this particular resource.

### **Sensitivity analysis based on the alternatives of the baseline**

For the assessment of the depletion of abiotic resources it is recommended to perform a sensitivity analysis. The assessment of the depletion of abiotic resources depends on the type of characterisation factors used in an LCA study, that is the choice of the reserve (i.e. ultimate reserve, reserve base or economic reserve) and characterisation model (function of reserve or extraction rate only or function of reserve and extraction rate). There is no such thing as the best set of characterisation factors; it simply depends on the definition of the abiotic depletion problem. This report provides sets of characterisation factors necessary to carry out such a sensitivity analysis. The characterisation factors are available in a spreadsheet that can be downloaded from the CML website, <http://www.leidenuniv.nl/cml/lca2/index.html>.



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## 9 List of definitions

(Economic) reserve i.e. that part of the reserve base which can be economically extracted at the time of determination (United States Department of the Interior - Bureau of Mines, 1993)

Resource a naturally occurring solid, liquid, or gaseous material in or on the Earth's crust that has a potential function for mankind. Note that the definition differs from the definition given by USGS. By USGS the term resources is restricted to those concentrations of the materials in such form and amount that economic extraction of the commodity from the concentration is currently or potentially feasible.

Reserve base is that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining practice. The reserve base may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources). (United States Department of the Interior - Bureau of Mines, 1993).

Ore/Mineral deposit We use both the term ore and mineral deposits for resources that have economic potential to be extracted. The term ore is often limited to metallic elements (e.g. copper ore, phosphate ore etc.) while the term mineral deposit is a more general term (e.g. clay deposit etc.).

Ultimate reserves, i.e. the quantity of resource (as a chemical element or configuration) that is ultimately available, estimated by multiplying the average natural concentration of the resource in the primary extraction media (e.g. the earth's crust) by the mass or volume of these media (e.g. the mass of the crust assuming a certain depth of for example 10 km) (Guinée, 1995).

For definitions on LCA related items is referred to the Dutch LCA handbook (Guinée et al., 2002)





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# Appendix 1

Substance	cas no.	group
actinium (Ac)	7440-34-8	element
aluminium (Al)	7429-90-5	element
antimony (Sb)	7440-36-0	element
argon (Ar)	7440-37-1	element
arsenic (As)	7440-38-2	element
barium (Ba)	7440-39-3	element
beryllium (Be)	7440-41-7	element
bismuth (Bi)	7440-69-9	element
boron (B)	7440-42-8	element
bromine (Br)	7726-95-6	element
cadmium (Cd)	7440-43-9	element
calcium (Ca)	7440-70-2	element
cerium (Ce)	7440-45-1	element
cesium (Cs)	7440-46-2	element
chlorine (Cl)	7782-50-5	element
chromium (Cr)	7440-47-3	element
cobalt (Co)	7440-48-4	element
copper (Cu)	7440-50-8	element
dysprosium (Dy)	7429-91-6	element
erbium (Er)	7440-52-0	element
europium (Eu)	7440-53-1	element
fluorine (F)	7782-41-4	element
gadolinium (Gd)	7440-54-2	element
gallium (Ga)	7440-55-3	element
germanium (Ge)	7440-56-4	element
gold (Au)	7440-57-5	element
hafnium (Hf)	7440-58-6	element
helium (He)	7440-59-7	element
holmium (Ho)	7440-60-0	element
indium (In)	7440-74-6	element
iodine (I2)	7553-56-2	element
iridium (Ir)	7439-88-5	element
iron (Fe)	7439-89-6	element
kalium (K;potassium)	7440-09-7	element
krypton (Kr)	7439-90-9	element
lanthanum (La)	7439-91-0	element
lead (Pb)	7439-92-1	element
lithium (Li)	7439-93-2	element
lutetium (Lu)	7439-94-3	element
magnesium (Mg)	7439-95-4	element
manganese (Mn)	7439-96-5	element
mercury (Hg)	7439-97-6	element
molybdenum (Mo)	7439-98-7	element
neodymium (Nd)	7440-00-8	element
neon (Ne)	7440-01-9	element
nickel (Ni)	7440-02-0	element
niobium (Nb)	7440-03-1	element
osmium (Os)	7440-04-2	element
palladium (Pd)	7440-05-3	element

Substance	cas no.	group
phosphorus (P)	7723-14-0	element
platinum (Pt)	7440-06-4	element
polonium (Po)	7440-08-6	element
praseodymium (Pr)	7440-10-0	element
protactinium (Pa)	???	element
radium (Ra)	7440-14-4	element
radon (Rn)	10043-92-2	element
rhenium (Re)	7440-15-5	element
rhodium (Rh)	7440-16-6	element
rubidium (Rb)	7440-17-7	element
ruthenium (Ru)	7440-18-8	element
samarium (Sm)	7440-19-9	element
scandium (Sc)	7440-20-2	element
selenium (Se)	7782-49-2	element
silicium (Si; silicon)	7440-21-3	element
silver (Ag)	7440-22-4	element
Sodium (Na)	7440-23-5	element
strontium (Sr)	7440-24-6	element
sulfur (S)	7704-34-9	element
tantalum (Ta)	7440-25-7	element
tellurium (Te)	13494-80-9	element
terbium (Tb)	7440-27-9	element
thallium (Tl)	7440-28-0	element
thorium (Th)	7440-29-1	element
thulium (Tm)	7440-30-4	element
tin (Sn)	7440-31-5	element
titanium (Ti)	7440-32-6	element
tungsten (W); wolfram	7440-33-7	element
uranium (U)	7440-61-1	element
vanadium (V)	7440-62-2	element
xenon (Xe)	7440-63-3	element
ytterbium (Yb)	7440-64-4	element
yttrium (Y)	7440-65-5	element
zinc (Zn)	7440-66-6	element
Zirconium (Zr)	7440-67-7	element
asbestos (kg)	-	configuration
Barite	-	configuration
bauxite	-	configuration
clays	-	configuration
industrial diamond	-	configuration
diatomite	-	configuration
feldspar	-	configuration
fluorspar	-	configuration
garnet (industrial)	-	configuration
graphite (natural)	-	configuration
gypsum	-	configuration
kyanite & others	-	configuration
lime	-	configuration
mica (natural),scrap&flake	-	configuration
mica (natural),sheet	-	configuration
atmospheric nitrogen-(fixed) ammonia (kg N)	-	configuration
peat	-	configuration
perlite	-	configuration
pumice and pumicite	-	configuration

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Substance	cas no.	group
quartz (industrial)	-	configuration
rare earths	-	configuration
salt	-	configuration
sand and gravel (construction)	-	configuration
sand and gravel (industrial)	-	configuration
soda ash	-	configuration
sodium sulfate	-	configuration
stone (crushed)	-	configuration
stone (dimension)	-	configuration
talc and pyrophyllite	-	configuration
vermiculite	-	configuration

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## Appendix 2 Occurrence, use and substitutes of some selected resources

In this appendix the occurrence use and substitutes of some selected resources will be discussed. Most of the material presented here is quoted from the mineral commodity summaries published by the US Department of the interior, US Geological Survey (USGS, 2001) especially their data on possible substitutes is unique. Data on the occurrence and use of the resources have been supplemented by data from numerous sources on internet (i.e. webelements, 2001) and handbooks (i.e. Brady & Clauser, 1991)

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### Antimony ores

#### Occurrence

Ores include stibnite ( $Sb_2S_3$ ), senarmonite ( $Sb_2O_3$ ), Valentinite ( $Sb_2O_3$ ), cervantite ( $Sb_2O_4$ ), Stibiconite ( $Sb_2O_4 \cdot H_2O$ ), Kermesite (red antimony,  $Sb_2S_2O$ ), Jamenosite ( $Pb_2Sb_2S_5$ ) and stephanite  $Ag_5SbS_4$  which is more a silver ore containing antimony.

#### Use

Flame retardant in plastics ,lead batteries, chemicals, in alloys (hardening lead-based alloys, corrosion resistant pumps, antifriction bearings), ceramic and glass (a decolourising and refining agent in some forms of glass such as optical glass), pigments for paint and rubber(orange red).

#### Substitutes

Configurations of chromium, tin, titanium, zinc, and zirconium substitute for antimony chemicals in paint, pigments, and enamels. Combinations of cadmium, calcium, copper, selenium, strontium, sulphur, and tin can be used as substitutes for hardening lead. Selected organic configurations and hydrated aluminium oxide are widely accepted substitutes as flame-retardant.

### Copper ores

#### Occurrence

Copper is sometimes found as the free element and is present in many minerals. Important deposits are located in Canada, Chile, Germany, Italy, Peru, U.S.A., Zambia, and Zaire. The most important copper ores are the oxides, sulphides, and carbonates.

#### Use

As pure metal it is chosen for its high conductivity, chemical resistance, high ductility and high thermal conductivity. Therefore the "pure metal" finds wide application in electrical wire, water pipes, heat exchangers, gaskets and

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architectural applications. Other applications are as pigment in paints and linoleum. Furthermore copper is widely used in alloys like brass or bronze.

#### Substitutes

Aluminium substitutes for copper in various products, such as electrical power cables, electrical equipment, automobile radiators, and cooling/refrigeration tubing. Titanium and steel are used in heat exchangers, and steel is used for artillery shell casings. Optical fibre substitutes for copper in some telecommunications applications. Plastics also substitute for copper in water pipe, plumbing fixtures, and many structural applications.

### **Phosphorous ores**

#### Occurrence

Phosphate rock, (apatite, impure calcium phosphate), is an important source of the element. Large deposits are found in Morocco, in Russia, and in the USA.

#### Uses

Phosphate rock ore is used to manufacture wet-process phosphoric acid and superphosphoric acid, which are used as intermediates in the manufacture of granular and liquid ammonium phosphate fertilisers and animal feed supplements. Wet-process phosphoric acid produced is sold in the form of upgraded granular diammonium and monoammonium phosphate fertiliser, triple superphosphate fertiliser, and merchant grade phosphoric acid. Phosphate rock is also consumed for the production of elemental phosphorus in electric furnace facilities. Elemental phosphorus is used to produce high-purity phosphoric acid and phosphorus configurations, which are used in a variety of industrial applications such as the production of yellow or red phosphor.

#### Substitutes

There is no substitutes for phosphate in agriculture.

### **Tantalum ores**

#### Occurrence

Most important ore is tantalite which is often mixed with tantalum oxide. Ores are found in Australia, Brazil, Mozambique, Thailand, Portugal, Nigeria, Zaire and Canada. It is also a byproduct from the extraction of tin.

#### Use

Tantalum (Ta) is ductile, easily fabricated, highly resistant to corrosion by acids, and a good conductor of heat and electricity and has a high melting point. The major use for tantalum, as tantalum metal powder, is in the production of electronic components, mainly tantalum capacitors. Major end uses for tantalum capacitors include portable telephones, pagers, personal computers, and automotive electronics. Alloyed with other metals, tantalum is also used in making carbide tools for metalworking equipment and in the production of superalloys for jet engine components.

#### Substitutes

The following materials can be substituted for tantalum, niobium (in the U.S. called columbium) in carbides; aluminium and ceramics in electronic capacitors; niobium, glass, platinum, titanium, and zirconium in corrosion-resistant



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equipment; and niobium, hafnium, iridium, molybdenum, rhenium, and tungsten in high temperature applications.

### Lithium ores

#### Occurrence

Lithium does not occur as the free metal in nature because of its high reactivity. Deposits are known all around the world. It is a minor component of nearly all igneous rocks and is a component of many natural brines (see below). Large deposits are located in California and Nevada (both in the USA) in several rock forms, particularly spodumene. The four main lithium minerals are spodumene, lepidolite, petalite, and amblygonite.

- spodumene:  $\text{LiAlSi}_2\text{O}_6$ . This is the most important and abundant of the lithium ores. Deposits are located in North America, Brazil, USSR, Spain, parts of Africa, and Argentina.
  - lepidolite:  $\text{K}_2\text{Li}_3\text{Al}_4\text{Si}_7\text{O}_{21}(\text{OH},\text{F})_3$ . Deposits are located in Canada and parts of Africa. The mineral sometimes contains caesium and rubidium.
  - petalite:  $\text{LiAlSi}_4\text{O}_{10}$ . Deposits are located in parts of Africa and Sweden.
  - amblygonite:  $\text{LiAl}(\text{F},\text{OH})\text{PO}_4$ . Amblygonite occurs in only minor deposits
- Lithium is also recovered from lakes such as Searles Lake (California, USA) and Clayton Valley (Nevada, USA). Lithium is extracted from the brine by solar evaporation, precipitation of Group 2 elements if necessary, and precipitation of lithium carbonate by addition of sodium carbonate to the hot brine.

#### Use

The largest use of lithium is ceramics and glass manufacturing processes. These additions, which can be made as lithium carbonate or ore concentrates, lower process melting points, reduce the coefficient of thermal expansion and the viscosity, and eliminate the use of more toxic configurations (boron). The manufacture of black-and white television picture tubes consumed significant amounts of lithium concentrates overseas vanuit welk land bezien. Adding lithium carbonate to aluminium potlines lowers the melting point of the bath, allows a lower operating temperature for the potline, increases the electrical conductivity, and decreases viscosity of the bath. Domestically (Nederland?), the third largest and the fastest growing end use for lithium configurations is as catalysts in the production of synthetic rubbers, plastics, and pharmaceuticals. Pharmaceutical-grade lithium carbonate is used in the treatment of manic-depressive psychosis. The multipurpose grease industry is another important market for lithium. Lithium hydroxide monohydrate was the configuration used for the production of lithium lubricants. Lithium-based greases were favoured for their retention of lubricating properties over a wide temperature range; good resistance to water, oxidation, and hardening; and formation of a stable grease on cooling after melting. Lithium is also used in batteries. New, more efficient types of rechargeable (secondary) lithium batteries have been developed and older designs improved to meet the requirements of the EV market and of electronic equipment, such as portable telephones, portable computers, and video cameras. Lightweight aluminium-lithium alloys for wing and fuselage skin or structural members in different types of aircraft. In aeroplane construction, these alloys faced direct competition from composite materials consisting of boron, graphite, or aramid fibres imbedded in polymers. Small quantities of other lithium configurations were important to many industries. Lithium chloride and lithium bromide were used in industrial air-conditioning and commercial dehumidification systems and in the production of sophisticated textiles. Sanitisers for swimming pools, commercial glassware,

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and public restrooms contained lithium hypochlorite, as did dry bleaches for commercial laundries. Lithium metal was used as a scavenger to remove impurities from copper and bronze, and anhydrous lithium chloride was used as a component in fluxes for hard-to-weld metals, such as steel alloys and aluminium.

#### Substitutes

Substitutes for lithium configurations are possible in manufactured glass, ceramics, greases, and batteries. Examples are sodic and potassic fluxes in ceramics and glass manufacture; calcium and aluminium soaps as substitutes for stearates in greases; and zinc, magnesium, calcium, and mercury as anode material in primary batteries. Lithium carbonate is not considered to be an essential ingredient in aluminium potlines. Substitutes for aluminium-lithium alloys as structural materials are composite materials consisting of glass, polymer, or boron fibres in engineering resins.

### Calcium ores

#### Occurrence

It occurs as limestone ( $\text{CaCO}_3$ ), gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), and fluorite ( $\text{CaF}_2$ ). Apatite is calcium fluorophosphate or chlorophosphate.

#### Use

Major markets for lime were concrete, steel, flue gas desulphurisation, mining, construction, pulp and paper, precipitated calcium carbonate, and water treatment.

#### Substitutes

Limestone is a substitute for lime in many applications, such as agriculture, fluxing, and sulphur removal. Limestone contains less reactive material, is slower to react, and may have other disadvantages compared with lime depending on the application; however, limestone is considerably less expensive than lime. Calcined gypsum is an alternative material in industrial plasters and mortars. Cement and lime kiln dust and fly ash are potential substitutes for some construction uses of lime. Magnesium hydroxide is a substitute for lime pH control, and magnesium oxide is a substitute for lime flux in steelmaking.

### Silicon ores

#### Occurrence

Very high purity silicon ( $\text{SiO}_2$ ) used in the production of quartz crystals (crystalline) and silicon wafers (for chip making) is produced from lascas. Lascas is the industrial term for a product made from milky vein quartz. The lascas is produced from hydrothermal vein deposits. It consists of cleaned (of clay and iron and manganese staining) milky to clear quartz that has been graded for chemical purity. The milky vein quartz along with any rock crystal is first mined, and crushed to about 1.25 to 1.5 inch size, and washed over screens to remove the bulk clay and fines. Then it is heated in an oxalic acid bath to remove any iron or manganese staining and, after cooling, is rinsed to remove the acid. It is then dried and graded. Grading is done visually over special light tables, where lower grade quartz with matrix attached and off colour quartz is removed by hand. It is separated into 4 grades, the highest purity being water clear, then transparent milky, then two lower grades of

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milky. The only difference between lascas and any ungraded piece of quartz is that the lascas consistently has very low alkali and aluminium content. Lascas is what is used as the chemical feedstock in the industrial process of growing synthetic quartz.

#### Use

Quartz crystal is a piezoelectric material which forms the basis of quartz resonators used widely in quartz watches, computers and microprocessors for frequency control, and in crystal filters for waveband selection in communications devices. Since the 1970s cultured or synthetic quartz crystals have replaced natural quartz in these applications. Brazil is a major supplier of quartz crystal in the form of lascas. Almost all cultured quartz is consumed in quartz crystal filters and oscillators used in telecommunications equipment, watches and clocks and in microprocessor circuits for personal computers and for military and industrial machinery. The fused silica industry is considerably larger than that of crystalline quartz, account for 20,000 tpa of lascas and high purity quartz sand. Like its crystalline counterpart, it is finding a growth market in the electronics and related industries: it is also an important material in the production of fibre optic cables, where demand is expected to increase by 7% to 8% per annum. Some high purity silica is being used in speciality optical applications.

#### Substitutes

Quartz crystal is the best material for frequency-control oscillators and frequency filters in electronic circuits. Other materials, such as dipotassium tartrate, are usable only in specific applications, such as oscillators and filters.

### **Industrial diamond**

#### Occurrence

Virtually all industrial diamond is from synthetic origin; more than 90% of the industrial diamond market is now accounted for by synthetic diamonds. It is made in the form of grit and powder.

#### Use

Most consumption was accounted for by the following industry sectors: computer chip production, construction, machinery manufacturing, mining services (drilling), stone cutting/polishing, and transportation systems (infrastructure and vehicles). Stone cutting and highway building and repair accounted for most of the industrial stone consumption.

#### Substitutes

Materials that can compete with industrial diamond in some applications include manufactured abrasives, such as cubic boron nitride, fused aluminium oxide, and silicon carbide.

### **Feldspar**

#### Occurrence

Feldspars are one of the rock forming minerals and they make up an average of 595 g.kg<sup>-1</sup> of igneous rock, 300 g.kg<sup>-1</sup> of shale, and 115 g.kg<sup>-1</sup> of sandstone.

#### Use

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Feldspar is ground for industry use to about 20 mesh for glassmaking and to 200 mesh or finer for most ceramic and filler applications. In pottery and glass, feldspar functions as a flux. Estimated end-use distribution of domestic feldspar was glass, 68%, and pottery and other, 32%. In glassmaking, alumina from feldspar improves product hardness, durability, and resistance to chemical corrosion. In ceramics, feldspar is used as a flux, lowering the vitrifying temperature of a ceramic body during firing and forming a glassy phase.

#### Substitutes

Feldspar can be replaced in some of its end uses by feldspar-silica mixtures, clays, talc, pyrophyllite, spodumene, or electric-furnace slag. Imported nepheline syenite, however, was the major alternative material.

### Gypsum

#### Occurrence

Gypsum is mined from various deposits that occur world-wide. In addition to mined gypsum, synthetic gypsum is generated as a by-product by various industrial processes. The primary source of synthetic gypsum is flue gas desulphurisation (FGD) at coal-fired electric powerplants. Smaller amounts of synthetic gypsum are derived from acid neutralisation processes. Synthetic gypsum was used as a substitute for mined gypsum, principally for wallboard manufacturing, agricultural purposes, and cement production.

#### Use

Most of domestic consumption, was accounted for by manufacturers of wallboard and plaster products. Other large consumers of gypsum are cement production and agricultural uses. Small amounts of high-purity gypsum are used for a wide range of industrial processes, such as smelting and glassmaking.

#### Substitutes

Other construction materials may be substituted for gypsum, especially cement, lime, lumber, masonry, and steel. Gypsum has no practical substitute in the manufacturing of portland cement. Synthetic gypsum generated by various industrial processes is becoming more important as a substitute for mined gypsum in wallboard manufacturing, cement production, and agricultural applications.

### Quartz sand/silica sand

#### Occurrence

Industrial sand and gravel, often called "silica," "silica sand," and "quartz sand," includes sand and gravel with high silicon dioxide (SiO<sub>2</sub>) content. These sands are used in glassmaking; for foundry, abrasive, and hydraulic fracturing (frac) applications; and for many other industrial uses. The specifications for each use vary, but silica resources for most uses are abundant. In almost all cases, silica mining uses open pit or dredging mining methods with standard mining equipment.

#### Use

In the fiberglass industry. Continuous glass fiber specifications are very strict. Batch grain-size control is very important, so ground silica (ultrafine powder) is used. Iron, potassium, and sodium oxide content is tightly controlled. The raw

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mix is fused at 1,600° C and then passed through platinum bushings at 1,300° C. Various mineral wools are fabricated using basalt and diabase (rock wool), glass (glass wool), or blast furnace slag (slag wool). Optical fiber production involves a series of highly sophisticated manufacturing methods. For the optical fiber, a glass core is required with a high refractive index, surrounded by glass with a lower refractive index. This problem has been solved by using several manufacturing methods, such as producing all the fiber with fused silica but doping its core with an element that increases the refractive index. High-purity fused silica used by the electronics industry is typically at least 99.95% SiO<sub>2</sub> and has a very low expansion coefficient, high electromagnetic radiation transparency, and good insulation properties. By reacting sodium silicate with hydrochloric acid, synthetic precipitated silica and silica gel are produced. Precipitated silica has been used increasingly in tires but more so in Europe than in the United States. Through replacement of a proportion of carbon black with precipitated silica in the tread, the reinforcing action of the silica particles extends tire life. European consumers seem to prefer the “green” tires made with precipitated silica, and it is used in 70% to 80% of tires for passenger cars. Although these tires reportedly produce greater gas mileage, deficiencies in tread wear and higher costs to consumers and manufacturers account for their lack of popularity in the United States. Precipitated silica is also used in battery separators and as a flattening agent in coatings, mainly high-solid, low-volatility organic configuration coatings.

#### Substitutes

Silica sand continues to be the major material used for glassmaking and for foundry and molding sands; alternates are zircon, olivine, staurolite, and chromite sands.

#### Clays

##### Occurrence

Clay should be divided into two groups: the speciality clays and commodity clay. The speciality clays are high purity, highly processed clays with unusual physical and chemical properties. Known deposits for these speciality clays are very small. Commodity clay deposits are ubiquitous but are subdivided according the type of clay. This category does not include clay for levelling, dike or dam building purposes.

##### Use

Speciality clays are used in applications which require a white or near white colour, chemical inertness, resistance to biological degradation, a long shelf life, reduced solids content, lubricity and high temperature resistance. Speciality clays are used in greases, paints, cosmetics, and pharmaceuticals in addition to drilling muds. Domestic uses for commodity clays are estimated as follows: for ball clay, floor and wall tile, sanitaryware, pottery; for bentonite, foundry sand bond, pet waste absorbent, drilling mud, iron ore palletising; for common clay, brick, cement, lightweight aggregate; for fire clay, refractories; for fuller's earth, absorbent uses, fertiliser and pesticide carriers; for kaolin, paper, refractories.

#### Substitutes

Limited substitutes and alternatives, such as calcium carbonate and talc, are available for filler and extender applications.

#### **Sand Granulate/gravel**

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#### Occurrence

Occurs everywhere in the world. Large amounts are found in river flood plains, river channels and glacial deposits. However, because of their geographic distribution, environmental restrictions, and quality requirements for some uses, their extraction is uneconomic in some cases. Offshore deposits are also used, mainly for beach erosion control.

#### Use

As concrete aggregates, for road base and coverings and road stabilization, asphaltic concrete aggregates and other bituminous mixtures, as construction fill, for concrete products, such as blocks, bricks, pipes, etc., for plaster and gunite sands; and the remainder for snow and ice control, railroad ballast, roofing granules, filtration, and other miscellaneous uses.

#### Substitutes

Crushed stone remains the predominant choice for construction aggregate use.

## Appendix 3 Estimation of reserves for sand and kaolin (type of clay)

Silica Sand/Industrial Sand; scarce data found after internet search				
	Region	Surface [km <sup>2</sup> ]	Resource	Reference
1)	Nieuw-Zeeland	27053	80 Mt Parengarenga Harbour 10 Mt Kaipara Harbour	<a href="http://www.med.govt.nz/crown_minerals/minerals_info/99_indust_mins.html">http://www.med.govt.nz/crown_minerals/minerals_info/99_indust_mins.html</a>
2)	India, tripura provincie	10492	proved 11000 tonnes probable 115000 tonnes possible 74000	<a href="http://nerdatabank.nic.in/tr_minerals.htm">http://nerdatabank.nic.in/tr_minerals.htm</a>
3)	India, meghalaya provincie	22429	probable 0.54 million tones	<a href="http://nerdatabank.nic.in/me_phosphat.htm">http://nerdatabank.nic.in/me_phosphat.htm</a>
4)	Australia, Queensland	1.700.00	defined resources 300 Mt further potential: 1500 Mt	<a href="http://www.dme.qld.gov.au/resdev/commod/silsand.pdf">http://www.dme.qld.gov.au/resdev/commod/silsand.pdf</a>
5)	Jordanië	8921	> 10 billion tonnes	<a href="http://www.nic.gov.jo/economics/mena96/glass.html">http://www.nic.gov.jo/economics/mena96/glass.html</a>

Silica Sand/Industrial Sand; the interpretation								
Region	surface [km <sup>2</sup> ]	possible [kg]	proved [kg]	probable [kg]	possible [kg.km <sup>-2</sup> ]	proved [kg.km <sup>-2</sup> ]	probable [kg.km <sup>-2</sup> ]	
Nieuw-Zeeland	27053		9.00E+10			3.33E+06		
India, tripura provincie	10492	1.10E+07	7.40E+07	1.15E+08	1.05E+03	7.05E+03	1.10E+04	
India, meghalaya provincie	22429			5.40E+08			2.41E+04	
Australia, Queensland	170000		3.0E+11	1.5E+12		1.76E+06	8.82E+06	
Jordanië	8921			1.00E+10			1.12E+06	
	238895	11000000	3.90074E+11	1.51066E+12				
Average 1	average based on concentrations					1.05E+03	1.70E+06	2.49E+06
Average 2	average based on total reserve / total surface					1.05E+03	1.88E+06	7.13E+06
World	133289789				1.40E+11	2.27E+14	3.33E+14	Total based on average 1
					1.40E+11	2.51E+14	9.50E+14	Total based on average 2



**Clays; Kaolin only; scarce data found after internet search**

	Region	surface [km <sup>2</sup> ]	Resource [kg]				production year 1995	Reference
			possible	probable	proved	known		
Swaziland	Mahlangatsha kaolin deposit	1.74E+04				1.00E+09	<a href="http://www.mines2000projects.com/html/swazi.htm#mpe">http://www.mines2000projects.com/html/swazi.htm#mpe</a>	
Mongolia, China	Zunger Banner of Inner Mongolia	9.60E+06				1.00E+12	<a href="http://www.glorycome.com.au/chinakaolin.html">http://www.glorycome.com.au/chinakaolin.html</a>	
Shanxi Province, china	Datong and Shuozhou district					2.00E+11		
Northwest of Zhejiang province, China						8.00E+10	<a href="http://www.linanwindow.com/english/index.htm">http://www.linanwindow.com/english/index.htm</a>	
India		3.30E+06				9.86E+11	<a href="http://miningindia.com/writeups/798/7.htm">http://miningindia.com/writeups/798/7.htm</a>	
Ukraine	Zakarpattya	6.04E+05				5.00E+09	<a href="http://ukrainebiz.com/Articles/ZakarpattyaFacts.htm">http://ukrainebiz.com/Articles/ZakarpattyaFacts.htm</a>	
Brazil		8.50E+06				1.70E+12	<a href="http://www.tradeport.org/ts/countries/brazil/isa/isar0001.html">http://www.tradeport.org/ts/countries/brazil/isa/isar0001.html</a>	
Canada	Western Canada Sedimentary Basin	9.98E+06				2.00E+11	<a href="http://www.ags.gov.ab.ca/AGS_PUB/">http://www.ags.gov.ab.ca/AGS_PUB/</a>	
nigeria		9.24E+05				3.00E+12	<a href="http://www.nigeriatoday.com/investment_opportunities.htm">http://www.nigeriatoday.com/investment_opportunities.htm</a>	
Georgia, USA	Georgia	6.97E+04				7.50E+12	<a href="http://minerals.usgs.gov/minerals/pubs/commodity/clays/">http://minerals.usgs.gov/minerals/pubs/commodity/clays/</a>	
	total	<b>3.30E+07</b>				<b>1.47E+13</b> total		

**Clays; Kaolin only; the interpretation**

Region	possible [kg.km <sup>-2</sup> ]	probable [kg.km <sup>-2</sup> ]	proved [kg.km <sup>-2</sup> ]	<b>known</b> [kg.km <sup>-2</sup> ]
Swaziland				5.76E+04
China				1.33E+05
India				2.99E+05
Ukraine				8.28E+03
Brazil				2.00E+05
Canada				2.00E+04
nigeria				3.25E+06
Georgia, USA				1.08E+08
		average 1		1.39E+07
		average 2	average based on concentrations	
			average based on total reserve / total surface	4.45E+05

**Average**

World	133289789				
		possible [kg]	probable [kg]	proved [kg]	<b>known</b> [kg]
					1.86E+15 total based on average 1
					5.93E+13 total based on average 2

## Appendix 4 Estimation of ultimate reserves of weathered rock minerals

Below an estimation of the ultimate reserves of weathered rock minerals is given (table 2). The estimates are based on an average mineral composition of the earth surface (see table 1). The depth of the earth surface that is explorable for extraction of the minerals is set at 1 km.

Table 1 average mineral composition of rock in the earthcrust (0-16 km depth) and sedimental rock on the earth surface (mass percentage).

(source: page 88 Table 6.13 Locher W.P. & H de Bakker, 1989. Bodemkunde van Nederland. Deel 1. Algemene bodemkunde. Malmberg, Den Bosch.)

	rock (0-16 km depth)	sedimental rock (earth surface)
	Mass %	Mass %
silicats	17	
mica's	4	20
feldspar	60	7
silica	81	27
quartz	12	38
other minerals	7	6
carbonates		20
clays		9
Average density (kg/m <sup>3</sup> )		2670
Surface of the earth (m <sup>2</sup> )		5.1E+14

Table 2 The ultimate reserves of weathered rock and the resulting ADP<sub>ultimate</sub>, the depth of the extractable earth crust is set at 1 km

	kg	P-G/R2	ADP ultimate
mica's	2.72E+20	4.17E-33	7.33E-10
feldspar	9.53E+19	9.88E-31	1.74E-07
quartz, industrial sand	5.17E+20	4E-31	7.02E-08
other minerals	8.17E+19		
carbonates, (lime)	2.72E+20	1.56E-30	2.75E-07
clays	1.23E+20	-	-

The relative contribution (%) to the depletion of abiotic resources based on the normalisation data for the global extraction of elements and configurations is zero for the above mentioned weathered rock minerals.