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# Towards a sustainable use of primary boron. Approach to a sustainable use of primary resources

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ABSTRACT

The sustainable use of raw materials does not only concern the environmental impacts of their production and consumption, but also the intergenerational distribution of access to the raw material or the services provided by that material. From this sustainability perspective, current generations should not deprive future generations from economically accessible ores, but they have the responsibility to assure that a sufficient quantity of enriched deposits of primary materials continues to be available for future generations.

Comparing the extraction rate of different primary materials to their current use, some materials are scarcer than others. Elements like aluminum, magnesium, titanium and vanadium are relatively abundant and cannot be considered critical from a geological point of view. From a point of view of availability for future generations, action is not really urgent for these elements. However, other elements, like antimony, rhenium, gold, zinc and molybdenum are relatively scarce from a geological perspective. The current extraction rate of these elements is not sustainable.

Boron is also a relatively scarce element, comparing the current extraction rate to the geological availability. The accessible ores may be depleted within two hundred years. This may affect future generations negatively in securing services provided by boron. Therefore, we investigated whether the use of primary boron could be reduced to a sustainable level) without losing any of the services currently provided by boron. In this framework we have designed a generally applicable approach for investigating whether and to what extent a combination of substitution, material efficiency and recycling could reduce the use of a primary material to a sustainable level.

## 1. Introduction

The extraction and consumption of minerals have increased along with economic development. For consumables, communication and infrastructure, a growing range and quantity of minerals is essential. Global demand of minerals increases exponentially. There is debate whether or not further growth of mineral extraction from the earth's crust will be sustainable in view of the limited extractable quantities of these minerals in the earth's crust. Henckens et al. (2014) proposed an operational definition for the sustainable extraction of raw materials: The extraction rate of a material is sustainable, if a world population of 9 billion can be provided with that material for a period of at least 1000 years, assuming that the average per capita consumption level of the material is equally divided over the world's countries. Using this definition a (non-exhaustive) list of 15 geologically scarce materials has been identified. Boron is one of the materials that are relatively scarce from a geological point of view. In this paper we introduce an approach to assess the technical opportunities to (substantially) reduce mining of primary resources, and use this approach to assess whether a sustainable reduction of boron mining would be possible, without losing any of the services currently provided by boron. We first introduce the approach consisting of substitution, material efficiency improvement and/or recycling. This is then applied to boron. We end with discussion and conclusions.

## 2. Methodology

In an interpretation of the 3R approach (Reduce, Reuse, Recycle), there are three main technical options to reduce the consumption of raw materials:

- Substitution of the material by suitable alternatives in selected applications.

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**Table 1**
Types of substitution, derived from Ziemann and Schebek (2010).

| Substitution type | Explanation |
|---|---|
| Material substitution | Material A is re-placed by material B |
| Technological substitution | Reduction of material consumption by technological progress |
| Functional substitution | Product A is replaced by Product B or service C with the same function |
| Quality substitution | Product A is replaced by Product A' with a lower, but still sufficient quality |
| Non-material substitution | A product is replaced by a service with the same function |

- Reduced or more efficient use of the material.
- Increased recovery and recycling of the material.

The first step of our methodology is to develop a general approach for determining whether or not a reduction, required for sustainability, of the application of a primary resource is technically feasible by systematically exploring the opportunities and limitations of each of the above reduction options. The objective of the approach is not to determine the optimal mix of substitution, material efficiency and recycling for a particular case, from an economic or ecologic point of view. Nor is it the intention to make a technical or policy blue print of reduction measures. In practice the definitions of the three reduction categories may overlap, and may be combined in one innovation, making it difficult to assign the reduction in primary material use to a single category. Often several reduction scenarios may be possible, applying different mixes of the three measures.

The second step of the methodology is to apply the findings of the first step to determine the reduction potential of boron.

### 2.1. Substitution

If substitution of a material is possible, this approach may be seen as an interpretation of the first R of the 3R approach. According to Ziemann and Schebek (2010), five types of substitution can be distinguished (Table 1).

Four main factors determine the potential for substitution of a material:

1. The performance of the substitute compared to the original. An important condition for the adequate applicability of a substitute is that the services, provided by the original product, are maintained. For some uses the performance of the substitute may matter less than for other uses. A 100% equal performance compared to the original is not always necessary (i.e., quality substitution). Each specific application will have its own requirements.
2. The environment, health and safety (EHS) properties of the substitute compared to the original. The environment, health and safety properties of the substitute and the original are supposed to encompass all aspects, from cradle to grave, in all stages from the extraction until the end-of-life stage.
3. The financial characteristics of the substitute compared to the original. The (additional) costs of a substitute will depend on its availability, accessibility, and technology. While the effect of prices may be a relative factor, it can be a decisive element for substitutability in practice.
4. The geological availability of the substitute compared to the geological availability of the original. The aim of our investigation of the possible extraction reduction of a material is to conserve scarce materials for future generations. So substitutes should not be less scarce than the original.

**Table 2**
Overview of possibilities for material efficiency (ME)

| | |
|---|---|
| ME in production process | Prevention of material loss<br>Process optimization<br>ME in resources purchase<br>Recycling of production waste |
| ME in products | Light-weight or re-designing products<br>Design for recycling<br>Design for re-use and multi-purpose use<br>Design for longer use, maintenance, repair, remanufacturing |
| ME during consumption | Longer use and maintenance<br>Reuse<br>Shared use |

**Table 3**
Estimated material efficiency improvement potential range (expert judgment of our own based on literature)

| | Estimated material efficiency potential range |
|---|---|
| ME in production process | 1–10% |
| ME in products | 10–50% |
| ME during consumption(excl. recycling of EoL products | 10–50% |

Note that an application can be so specific that the material can hardly or not be substituted, e.g., the application of boron as micro nutrient in fruit and seed production. In such an application, material efficiency is the only option to reduce primary boron use. Substitution is not applicable in such case. Recycling only to a limited extent.

### 2.2. Material efficiency

Material efficiency (or resource productivity) reflects the quantity of services that can be provided by a given amount of a material, e.g., lightweighting of packaging may result in reduced material use to package the same product. Table 2 provides a general overview of possibilities for material efficiency increase.

In this paper, recycling of end-of-life products (consumption waste) will be addressed under recycling. Ordoñez and Rahe (2013) make plausible, that product designers are not in the first place focused on resources conservation, through design for recycling, reuse, maintenance, repair and waste minimization in general. Hence, potential for material efficiency may exist in many products and applications. According to Allwood (2013), generally, lightweight design, product life time extension and more intensive product use are the most effective means to increase material efficiency. Alternatively, Tukker (2004) explored whether Product Services Systems (PSS; e.g., product lease instead of product ownership) may improve material efficiency. His conclusion is that most types of PSS may have some environmental gains, but generally may not drastically improve material efficiency. According to Tukker most can be expected from PSS with the promise of a functional result. For example, international travel can be substituted by videoconferencing. In this case, the functional result is an adequate meeting with effective communication.

How can the potential effect of material efficiency be quantified? Current literature on material efficiency improvement provides mainly examples for specific materials or products, but no metastudies exist that provide a general overview of potentials. Based on the variety found in the literature, in Table 3, we provide an estimate by ourselves of the order of magnitude of the improvement potential of various types of measures. The efficiency potential indicates the reduction percentage of material use for providing the same quantity of services compared to the original material use. Considering a specific material, an efficiency potential of 25% means that for providing the same services only 75% of the original quantity of that material would be needed for delivery of the same services.

Although differing for particular materials and products, material efficiency has a large potential. Table 3 depicts the wide spread found in the literature for a variety of applications. However, this potential will not always be easily realized in practice. Therefore, if we have no data for specific applications of the materials we study, we assume a conservative (default) material efficiency potential of 10%, apart from the impact of increased recycling of materials from end-of-life products. However, material efficiency is an important option in case that substitution and recycling are not sufficient to reduce the consumption of a material to a sustainable level. More research may then be necessary for specific materials and applications.

### 2.3. Recycling

The recycling potential of a specific material from a specific product depends on the following factors (Graedel and Erdmann, 2012; Worrell and Reuter, 2014):

- Concentration. The higher the concentration, the higher the recycling potential. As a general rule the concentration should be at least as high as the minimally profitable concentration in virgin ore.
- Material composition. Alloys, composites and laminates of various materials make it difficult to isolate the mono-materials, which may limit (or even inhibit) recycling or result in down-cycling.
- Product composition. The more complex the composition or assemblage of the product, the lower the recycling potential.
- Dissipative uses. Dispersed or dissipative use of materials inhibits the (economic) recoverability of materials.
- Contamination. The more a (waste) product is contaminated, the lower the recycling potential.

UNEP (2011a) has made an extensive inventory of the actual and widely varying end-of-life recycling rate of 60 metals on a global scale. The UNEP experts have chosen five ranges of recycling rates (see Table 4).

Recycling rates will never be 100%, as not all materials may be recoverable due to the factors discussed above. To enable recycling, an infrastructure needs to be built that may include many stakeholders (e.g., manufacturers, households, waste management companies, recycling traders and processors, local governments), and may also encompass the generation of new (international) markets for recycled material. Building such an infrastructure may be capital and time-intensive, and may be affected by changes in product and material compositions. This may, in turn, affect the implementation of other reduction categories.

**Table 4**
Global average end-of-life recycling rate for 60 metals (from UNEP, 2011a).

| Current global average EoL recycling rates | | | | |
|---|---|---|---|---|
| <1 % | 1–10% | 10–25% | 25–50% | >50% |
| As | Hg | Cd | Ir | Ag |
| B | Sb | Ru | Mg | Au |
| Ba | | W | Mo | Co |
| Be | | | | Cr |
| Bi | | | | Cu |
| Ga | | | | Fe |
| Ge | | | | Mn |
| Hf | | | | Nb |
| In | | | | Ni |
| Li | | | | Pb |
| Os | | | | Pd |
| Sc | | | | Pt |
| Se | | | | Re |
| Sr | | | | Rh |
| Ta | | | | Sn |
| Te | | | | Ti |
| Tl | | | | Zn |
| Y | | | | |
| Zr | | | | |
| Lanthanides | | | | |

Yet, recycling is a core element of primary resource use reduction and material efficiency. Recycling will always be a part of the portfolio of measures to sufficiently reduce primary resources use.

### 2.4. Combining the potentials: evaluation and conclusion

The results of the different categories are not additional, as they may affect each other, or may result in double counting. Hence, the analysis of the reduction potential needs to assume a certain order of analyzing the different categories.

We propose a method consisting of three consecutive steps (see also Fig. 1):

1. Investigate the possibilities of substitution.
2. Find out, whether and to what extent the remaining quantity of the material requires further reduction, first through material efficiency.
3. Investigate further recycling measures on top of what is already being done at the moment.

We use this approach because, substitution may often result in a substantial reduction of the use of a material. This is important because of the large reduction that may be required to achieve sustainable consumption of a number of materials. Theoretically, substitution measures have a 100% result, and may be achieved by banning certain materials in certain applications. However, practice has shown that bans may be difficult to enforce. If a material

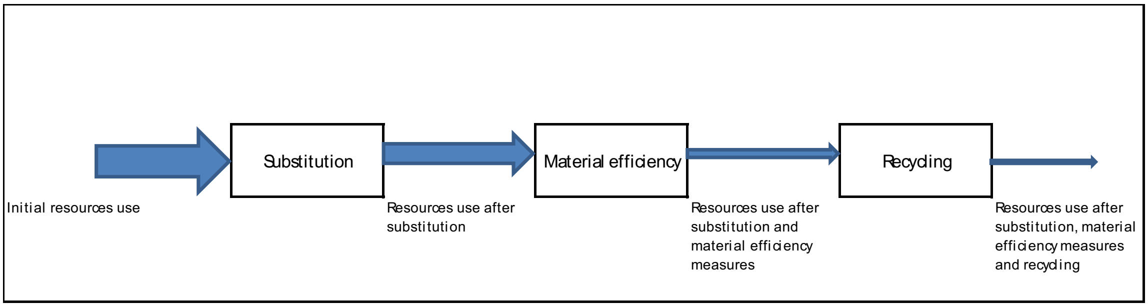

**Fig. 1.** Proposed sequence of investigation of measures for a substantial reduction of the use of a geologically scarce material.

**Table 5**
Overview of boron applications.

| | World (US Geological Survey, 2014a) 2012 data | USA (Average of the data between 1999 and 2003 (US Geological Survey, 2005)[e] | EU (European Commission, 2013) Year of data is not indicated |
|---|---|---|---|
| Glass | 60% | 80% | 55% |
| Glass wool | 39%[a] | 52% | |
| Fibre glass | 16%[a] | 21% | |
| Borosilicate glass | 5%[a] | 7% | |
| Ceramics | 10% | 4% | 14% |
| Detergents and soaps | 4% | 6% | 1% |
| Fertilizer | 4%[b] | 4% | 13% |
| Fire retardants | 3%[b] | 3% | 1% |
| Other applications | 19%[c] | 3% | 16% |
| Chemicals | 8%[d] | | 7% |
| Cosmetics, pharmaceuticals and toiletries | 2.5%[d] | | 2% |
| Industrial fluids | 2.5%[d] | | 2% |
| Metallurgical applications | 6%[d] | | 5% |
| Total | 100% | 100% | 100% |

[a] Global distribution of boron applications in glass is supposed to be similar to the distribution in the USA.
[b] Global use of boron in fertilizers and fire retardants is not provided by USGS. The relative global use is supposed to be similar to the use in the USA.
[c] Global use of boron in other applications is supposed to be the remainder of total global boron use.
[d] Global distribution of boron over the various other applications is supposed to be similar to the distribution in Europe.
[e] More recent data (2011) from USGS concerning the use of boron in the USA differ minimally (glass 80%, ceramics 3%, detergents, and soaps 4%, fertilizer 4%, fire retardants plus other applications 9%), but do not specify the use of boron in fire retardants (US Geological Survey, 2012).

is substituted, this may affect the opportunities for material efficiency improvement and/or recycling. Hence, we first need to understand the impacts of substitution on material and product composition to evaluate the need for e.g., setting up a dedicated recycling infrastructure. However, substitution is not a panacea, as the performance of the substitute, as well as economics, should be acceptable and may limit the actual substitution. Also, a scarce material should not be substituted by another scarce material, as that will just relocate the problem for future generations. The substitution should not result in a negative environmental impact compared to the original material, and, finally, as discussed above, substitution policies may not always be effective resulting not only in ineffectiveness, but, in some cases, also in a negative effect on recycling processes.

## 3. Boron: current applications and flows

In this section we will apply the approach to boron. Elemental boron is not found naturally on earth. Boron combines easily with oxygen to borates. Its presence in the earth's crust is mostly in borate minerals. More than two thirds of boron reserves are found in Turkey and the USA. Sea water contains about 5 ppm boron, while the average boron concentration in the continental earth's crust is 15 ppm (UNEP, 2011a). On the basis of data from Lyday (2003) and US Geological Survey (2014a,b) boron world production in 2010 is estimated at about 830,000 t expressed as boron.[1]

To meet a sustainable level of consumption to enable future generations to keep access to services provided by boron, this volume needs to be reduced by at least 44%, to a maximum of 465,000 t per year.[2] We start with discussing the current boron applications and flows, followed by a systematic evaluation of the opportunities to reduce current boron use.

### 3.1. *Boron applications*

Boron and its compounds have many different applications. Nowadays, more than three-quarters of the world's supply of boron is used in glass, ceramics, detergents and fertilizer (US Geological Survey, 2014a). Boron use in different parts of the world is quite divergent, as is shown in Table 5. In this analysis we will use the world average (as provided by US Geological Survey).

#### 3.1.2. *Glass*

Glass represents the most important boron application with an average of 60% globally (US Geological Survey, 2013). Borates improve the thermal shock resistance, increase the aqueous durability and chemical resistance, improve the mechanical strength, provide a higher resistance to devitrification during processing, lower the glass melting temperature (fluxing agent), improve the refining process and formability, and improve optical properties (Borax, 2014). About 90% of the application of boron in glass is in glass fibre (US Geological Survey, 2013); see Table 6.

A smaller part of boron application in glass (about 10%) is used for borosilicate glass. The applications of borosilicate glass are shown in Table 7. Generally, borosilicate glass contains around 5% $B_2O_3$.

#### 3.1.3. *Ceramics*

About 10% of the global boron consumption is used in ceramics (US Geological Survey, 2013). Borates are applied in ceramic glazes and enamels, increasing chemical, thermal and wear resistance. Enamel is a smooth, durable, vitreous coating on metal,

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[1] This figure is based on the following data: World production (excluding USA) in 2010 is 4080*1000 ton of boron concentrate (all forms) [90] % of this amount consists of 4 ores: borax (36.5% $B_2O_3$), kernite (51.0% $B_2O_3$), calcium borate colemanite (50.8% $B_2O_3$) and sodium-calcium borate ulexite (43% $B_2O_3$). The content of $B_2O_3$ in tradable boron oxide ores produced in the USA is about 50%. We shall assume that this is similar worldwide. From 2005 on, USGS does not provide production figures of boron in the USA. However, on the basis of de data between 1975 and 2005 and the difference between global production in 2005 (including the USA) and global production in 2006 (excluding the USA), the production of boron (all tradable forms) in the USA in 2010 is estimated at about 1300*1000 ton. So the world production of boron (all tradable forms) in 2010 can be estimated at (4080 + 1300)*1000 ton or 5380*1000 ton. About 50% of this is boron oxide ($B_2O_3$) or 2690*1000 tons. This matches with 834*1000 ton of boron (B).

[2] This figure is calculated as follows. According to UNEP (2011b), the extractable global resources of boron can be estimated at 600 million tons. Hence, according to the definition of the sustainable extraction of minerals, the sustainable per capita extraction rate (9 billion people, depletion in 1000 years) is 66.7 g/cap/year. The present annual per capita consumption of boron is 119 g/cap/year (extraction in 2010 divided by 7 billion people). This means that the necessary reduction is 1–66.7/119 = 44%.

**Table 6**
Glass fibre applications of boron (Crangle, 2012).

| Glass fibre applications | Function |
|---|---|
| Glass fibre textiles | Resistance against corrosion and heat, high strength |
| Insulation (glass wool) | Thermal insulation and acoustic insulation. Thermal insulation glass wool contains about 4–5% of boron oxide to aid melting, to inhibit devitrification and to improve the aqueous durability (Lyday, 2003) |
| Fibreglass reinforced plastics (GFRP or FRP), also called E-glass | Alumino-borosilicate glass with less than 1% alkali oxides E. Fitzer et al. (2008). Important applications are boats, wind turbine blades, pipes, light weight composite structural components for cars, trucks, trains and aircraft (Borax, 2014). The boric oxide concentration varies between 0 and 10% $B_2O_3$, but typically between 6 and 10% boron oxide (Lyday,2003) |

**Table 7**
Borosilicate applications (Borax, 2014)

| Borosilicate glass applications | Application examples |
|---|---|
| Heat resistant glass | Pyrex kitchenware, microwave dishes, laboratory glass |
| Display screens | LCD screens. This is one of the major boron consuming areas that has grown recently. Generally, flat screen glass contains 11–13 percent boron oxide. The cover glass of touch screens of smart phones and tablets consists of borosilicate glass. |
| Lighting glass | Head lights, halogen bulbs, fluorescent tubes |
| Sealing glasses | Tungsten filament lamps, lamps in street lighting, cathode ray tubes |
| Neutral glasses | Ampoules and vials for medicine for increased chemical resistance |
| Cosmetic containers | For chemical resistance |
| Solar glass | Cover glass and substrate glass for photovoltaic cells, and evacuated solar collector tubes |
| Glass microspheres | Airport runway reflector systems |
| Other | Optical glass, prisms, lenses, opal glassware, telescope mirror blanks |

glass or ceramics. It is hard, chemically resistant, and scratch resistant, has long-lasting color fastness, is easy to clean and cannot burn (Fedak and Baldwin, 2005). Enamels are mostly used on steel (Borax, 2014). A specific application of boron in ceramics is in light weight armour, in which boron carbide is a key ingredient (US Geological Survey, 2013). The use of borates in the production of ceramic tiles reduces the temperature and energy requirements. Moreover, borates increase the dry mechanical strength of unfired tiles between 30% and 80% (Lyday, 2003). Ceramic glazes with boron are applied in tiles and tableware (porcelain, china, stoneware and earthenware) (Borax, 2014). By far the largest consumers of boric oxide in ceramics are glazes for wall and floor tiles (Borax, 2014). The frits (materials of glassy nature) in wall tiles contain between 3 and 20% of $B_2O_3$, depending on the firing time and temperature (Borax, 2014). Enamels contain typically 14% $B_2O_3$.

### 3.1.4. Fertilizers

Fertilizers represent the third largest application of borates (US Geological Survey, 2013). Boron is a micro-nutrient primarily used in fruit and seed production (US Geological Survey, 2013). Normal plant leaves typically contain 25–100 ppm boron (US Geological Survey, 2014a). To sustain boron at this level, it is necessary to supply 1 kg per hectare per year (US Geological Survey, 2014a).

### 3.1.5. Detergents and soaps

The use of borates in detergents and soaps accounts for 4% of world consumption (US Geological Survey, 2012). Borates are used in detergents and soaps as alkaline buffers, enzyme stabilizers, oxygen-based bleaching agents, water softeners, for improvement of surfactant performance, and for soil removal (Borax, 2014). Sodium perborate, in contact with hot water, produces hydrogen peroxide, a very effective bleaching agent. Modern laundry detergents typically contain 15% sodium perborate.

### 3.1.6. Fire retardants

Zinc borate is used as flame retardant in plastic and rubber applications, in pressed boards, in paper boards, in cellulose-based insulation material, in gypsum board, in cotton batting in matrasses, and in fabrics requiring flame retardant treatment. It forms a glassy coating protecting the surface (EFRA, 2007). Normally, zinc borate is used in combination with other fire retardants, such as antimony trioxide, aluminium trioxide, magnesium hydroxide or red phosphorus (EFRA, 2007).

### 3.1.7. Other applications

Boron is used in a multitude of other products, including:

- Chemicals, used as insecticides and for wood preservation, pH—buffer, lubrification, in nuclear power plants as moderator, in semiconductors, air bags and magnets, in abrasives and ballistic vests, electrolytic capacitators, starch adhesives, paints, coatings and printing inks. Anhydrous Borax is used in gold refining as part of flux formulations to dissolve metal oxides.
- Cosmetics (e.g., cosmetic creams, skin lotions, hair shampoos, dyes and gels, bath salts and denture cleaners) (Borax, 2014) and pharmaceuticals. Boric acid is used as an antiseptic and as an antibacterial compound.
- Industrial fluids. According to Borax (2014), borates are used in antifreeze, lubricants, brake fluids, metalworking fluids, water treatment chemicals, fuel additives for the prevention of pre-ignition, in leather tanning as pH-buffer liquid, and in photo developing solutions (pH buffer).
- Metallurgical applications. Addition of boric oxide to steel slags prevents so-called dusty slag, resulting in a stable rock-like material (Borax, 2014). About 15 kg of $B_2O_3$ is used per ton of slag. Ferroboron in steel increases steel strength.

### 3.1.8. Developments

Future boron use (Lyday, 2013) may increase because of application in automotive fuel cells (i.e., sodium borohydride), in cars to replace metal parts with fibre glass reinforced plastics, as well as in batteries (i.e., titanium diboride).

### 3.2. Current boron material flows

A part of the use of boron is dissipative through usage: in detergents and soaps, in fertilizer, in cosmetics and pharmaceuticals, in metallurgical applications, in insecticides, in pH buffer liquids and in lubrication. Based on the relative amounts that are used for these applications, as presented in Table 5, we estimate that about 75% of the consumed boron remains in end-of-life products and about 25% is dissipated. According to US Geological Survey (2014a), current recycling of boron is insignificant. It is estimated that in the boron production phase about 5% of the extracted boron ends up in waste sludge. See Section 4.2.

Current boron material flows are represented in Fig. 2.

## 4. Pathway to sustainable boron use

### 4.1. Substitution of boron containing products

Application of boron compounds in products, from which direct human exposure could occur, is under scrutiny because of possible negative effects on human health (Risk and Policy Analysts, 2008),

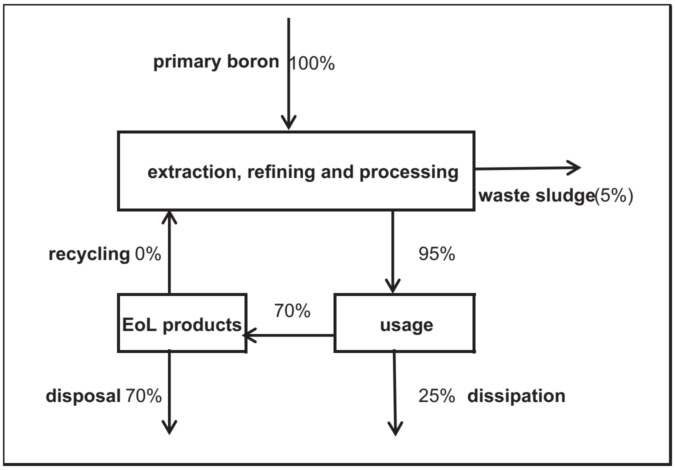

**Fig. 2.** Current global boron flows. Global primary boron production in 2010 is estimated at 830 kt B (based on data from the (US Geological Survey, 2014 a,b).

e.g., fertilizer, and detergents and soaps. In the other applications boron is chemically bound and any significant human exposure is improbable. Hence, there is already pressure to substitute certain boron containing products by less toxic products.

### 4.1.1. *Substitution of boron in glass*

- Glass wool can be substituted by various foams, rock wool or natural fibres. Especially rock wool has approximately the same properties as glass wool. Various insulation foams are currently used as an alternative for glass wool, such as expanded polystyrene, extruded polystyrene and polyurethane. Also natural materials can be used for insulation, such as cellulose and cork. Contrary to glass wool and rock wool, synthetic foams and natural materials have the disadvantage that they are inflammable. There are several new developments in this field such as vacuum insulation panels, gas-filled panels, aerogels and so-called phase change materials. An aerogel is a synthetic porous material derived from a gel, in which the liquid component of the gel has been replaced with a gas. The result is a solid with extremely low density and low thermal conductivity. For a review of the state of the art in this field we refer to the publications of Jelle (2011), Dewick and Miozzo (2002) and Papadopoulos (2005). The conclusion is that in principle it is possible to replace 100% of glass wool for insulation purposes by alternative materials.
- Glass fibres in fibre glass reinforced plastics may be partly substituted by other fibres such as carbon fibre, aramid fibre, high-modulus PE fibre, quartz fibre, basalt fibre, ceramic fibre and natural fibres. Each of these fibres has its specific application area. Glass fibre is the oldest and by far the most common reinforcement in applications used to replace heavier metal parts. Carbon fibre is the most used fibre in high-performance applications. The general performance of natural fibres is not yet as high as the performance of glass fibres, especially because of the hydrophilic nature of natural fibres. However there is quite some development in this area and according to Faruk et al. (2014) natural fibres may potentially replace a substantial part of glass fibres in reinforced plastics. The most popular natural fibres are: flax, jute, hemp, sisal, ramie, and kenaf (Faruk et al., 2014), while abaca, bamboo, wheat straw, curaua, and rice husk fibres are gaining interest. Hence, while substitution of glass fibre by other types of fibre seems possible, we shall conservatively and provisionally suppose that glass fibre in glass fibre reinforced plastics will not be substituted. An additional background for this assumption is the promising recycling potential of glass fibres from GFRPs (see below).
- The substitution of borosilicate glass by a non-boron containing material seems to be more difficult. Although in some applications glass may be replaced by other materials, we have supposed that for this boron application the substitutability is zero.

The substitution of boron in glass wool (currently one of the key applications of boron) as insulation material is not limited by the substituents' performance, EHS properties, costs or geological availability, as shown in Table 8.

### 4.1.2. *Substitution of boron in ceramics*

According to US Geological Survey (2014a), in enamel, boron may be replaced by phosphates. According to a paper of the European Commission (2010), boron in ceramics is substitutable, but at high costs. We therefore, conservatively assume that the substitutability of boron in ceramics is 0%. However, glass fibre from recycled glass fibre reinforced plastics, may (partly) replace the use of primary boron in ceramics (López et al., 2012a,b).

### 4.1.3. *Substitution of boron in detergents and soaps*

Perborate as bleaching agent in detergents may be replaced by sodium percarbonate and in soaps by sodium and potassium salts of fatty acids (US Geological Survey, 2014a). In their use as enzyme stabilizer borates are considered not to be substitutable (Risk and Policy Analysts, 2008). Over the period 2003–2008, the use of sodium perborate in detergents in Western Europe has decreased by around 80%, and has mostly been substituted by sodium percarbonate (Risk and Policy Analysts, 2008). Nevertheless, compared to the use in the USA and the rest of the world, use of perborates in detergents in Europe is still relatively high. In warmer climates sodium perborate performs better than sodium percarbonate (Risk and Policy Analysts, 2008). Table 9 presents the results of a substitutability assessment of the substitution of perborate in detergents by sodium percarbonate.

For more general functions as alkaline buffer, bleaching agent, water softener, surfactant performance improver and for soil

**Table 8**
Glass wool substitutability assessment.

| | Substitutes | | | References |
|---|---|---|---|---|
| | Rock wool | Foams | Natural fibers | |
| Performance | 0 | 0 | 0 | Jelle, 2011;<br>Papadopoulos, 2005 |
| EHS properties | 0 | – | + | Papadopoulos, 2005 |
| Costs | 0 | – | – | Papadopoulos, 2005 |
| Geological availability of substitutes | ++ | 0 | ++ | – |

Performance scale: ++: much better than original; 0: equal to original; – –: much lower than original.
EHS scale: ++: much better than original; 0: equal to original; – –:very negative compared to the original.
Cost scale: ++: much cheaper than the original; 0: equal to original; – –: much more expensive than the original.
Geological availability: ++: much less scarce than the original; 0: equal to original; – –: much scarcer than the original.

**Table 9**
Substitutability assessment of perborate in detergents.

| | Substitute | Reference |
|---|---|---|
| | Sodium percarbonate | |
| Performance | – – | Risk and Policy analysts, 2008 |
| EHS properties | + | Risk and Policy Analysts, 2008 |
| Costs | + | Alibaba, 30-10-2014 |
| Geological availability of substitutes | + | |

Performance scale: ++: much better than original; 0: equal to original; – –: much lower than original. EHS scale: ++: much better than original; 0: equal to original; – –: very negative compared to the original.

Cost scale: ++: much cheaper than the original; 0: equal to original; – –: much more expensive than the original.

Geological availability:++:much less scarce than the original; 0: equal to original; – –: much scarcer than the original.

removal, it is hardly imaginable that boron containing detergents and soaps cannot be partly substituted by non-boron containing products. It is assumed that the substitutability of boron in detergents and soaps is 50%.

### 4.1.4. *Substitution of boron in fertilizer*

Boron as micro-nutrient cannot be substituted.

### 4.1.5. *Substitution of boron in fire retardant*

There are several alternative fire retardant systems. Zinc borate is typically used as a synergist for other fire retardant systems and is hardly used as a fire retardant on its own. Therefore, it is supposed, that replacement might be possible, but would decrease the performance of the applications in which it is used currently. Therefore, we assume that boron compounds can difficultly be substituted in its fire retardant applications.

### 4.1.6. *Substitution of boron in various other applications*

- Chemicals. Some of the boron applications are specific (e.g., lubricants, neutron moderators in nuclear power plants, semiconductors, air bags and magnets, abrasives and ballistic vests, electrolytic capacitators, and gold refining). Other boron applications are less specific and may be easily replaced, such as the application in insecticides and wood preservatives, as pH buffer, in starch adhesives, paints, coatings and printing inks. Nevertheless, we (prudently) assume that only 10% of the boron applications in chemicals is substitutable and 90% is not.
- Cosmetics and pharmaceuticals. In many cosmetics and in pharmaceuticals, boron applications are not indispensable. Therefore, we assume that at least 25% substitution should be possible.
- Industrial fluids. Some of the boron applications in industrial fluids are relatively specific (as lubricant, in brake fluids, in metal working fluids, in fuel additives). But others are not specific (as pH-buffer or corrosion inhibitor). We assume that a 25% substitution of boron applications in industrial fluids should be possible.
- Metallurgical applications. The boron applications in steel production are so specific that it is assumed that substitution is not possible.

The effects for boron substitutability are summarized in Table 10.

Table 10 demonstrates that even with conservative assumptions the substitutability of primary boron could be as high as 43% of current use. This means that by substitution only, primary boron consumption can almost be reduced sufficiently to achieve the sustainable level of 56% of current primary boron use.

The results shown in Table 10 are not very sensitive for the various assumptions made. If the substitutability of boron in detergents and soaps, chemicals cosmetics and pharmaceuticals and industrial fluids would only be half of the ones supposed here above, then total substitutability would decrease from 43% to 41%. The determining factor for total substitutability is the 100% substitutability of glass wool by other materials.

## 4.2. *Material efficiency of boron containing products*

After a 100% substitution of glass wool by other non-boron containing insulation materials, 50% of boron containing detergents and soaps by other non-boron containing detergents and soaps and 15% of boron containing chemicals, cosmetics, pharmaceuticals and industrial fluids, in principle, additional material efficiency and, recycling measures would hardly be necessary to achieve a sufficient reduction of primary boron consumption. Nevertheless, to achieve a robust long-term consumption pattern, taking into account the possibility that new important boron applications might be developed in the future, we have also investigated the opportunities for improved material efficiency and recycling of boron.

We will focus on boron production and the most important boron applications: glass wool, fibre glass, and borosilicate glass. Together the applications mentioned represent about 60% of current boron use. More than half of the remaining boron use is dissipative and material efficiency is above all a matter of minimizing use and decreasing losses (e.g., through precision fertilizer application).

### 4.2.1. *Boron production*

An important material efficiency opportunity is offered by the recovery of boron contained in borax waste sludge (usually) disposed of at the boron production location in storage ponds. According to Özdemir and Kipçak (2010), and Boncukcuoğlu et al. (2003) in Turkey, the country with the highest boron reserves in the world, 5% of the extracted boron ends up in the waste sludge. According to Boncukcuoğlu et al., 2003, it is possible to recover 90% of the boron in the waste sludge by acid leaching followed by precipitation and crystallization. Others (Uslu and Arol, 2004; Kavas, 2006; Christogerou et al., 2009) studied the possible use of borax waste sludge as an additive in the production of red bricks and in heavy clay ceramics. While this solves the environmental problems of borax waste sludge and reduces the use of other primary materials, this will not contribute to the recovery and efficient use of boron.

### 4.2.2. *Glass wool, glass fibres and borosilicate glass*

As far as they are not substituted by other products, demand for glass wool, glass fibre and borosilicate glass can be expected to further increase. Losses of glass wool in construction are estimated at about 5% (Väntsi and Kärki, 2014), providing limited potential for efficiency improvement. All boron glass applications can potentially be recycled (see Section 4.3). Therefore, it is important that these boron containing products are designed in a way that recyclability at the end-of-life stage is facilitated. Further opportunities in this framework may be the potential minimization of glass fibre content in glass fibre containing products, and the potential reduction of losses in the production of glass fibre containing products.

### 4.2.3. *Boron material efficiency potential summarised*

Referring to Section 2.2 we will assume a default material efficiency potential of 10% after the boron substitution potential has been used.

## 4.3. *Recycling of boron containing products*

### 4.3.1. *Glass wool*

Waste glass wool is generated in three ways: construction, renovation, and demolition. It is relatively easy to reuse or recycle glass

**Table 10**
Potential substitutability of boron applications. Total boron use is normalized to 100 units.

| Main application | Consumption (units) | Sub-application | Consumption of sub-applications (units) | Substitutability (%) | Remaining primary boron use after substitution (units) |
|---|---|---|---|---|---|
| Glass | 60 | -Glass fibre in glass wool | 39 | 100% | 0 |
| | | -Glass fibre in fibre glass reinforced plastics and for high strength textiles | 16 | 0% | 16 |
| | | -Borosilicate glass | 5 | 0% | 5 |
| Ceramics | 10 | | 10 | 0% | 10 |
| Detergents and soaps | 4 | | 4 | 50% | 2 |
| Fertilizer | 4 | | 4 | 0% | 4 |
| Fire retardants | 3 | | 3 | 0% | 3 |
| Various | 19 | -Chemicals | 8 | 10% | 7 |
| | | -Cosmetics, pharmaceuticals | 2.5 | 25% | 2 |
| | | -Industrial fluids | 2.5 | 25% | 2 |
| | | -Metallurgical applications | 6 | 0% | 6 |
| Total | 100 | | 100 | 43% | 57 |

wool from construction sites, because it is not polluted and easily separable. Some glass wool producers offer a take-back scheme for their products (Väntsi and Kärki, 2014). It is possible to return waste glass wool in the glass wool production process. However, the fine particles potentially clog the feeding equipment for air and oxygen of the cupola furnace. To solve this problem it is possible to briquet the waste glass wool using binder materials (Väntsi and Kärki, 2014). Construction waste impurities in the waste glass wool may prevent recycling in the glass wool production process (Väntsi and Kärki, 2014). That is why state-of-the-art selective demolition and sorting are important for an adequate recycling of glass wool. Modern separation techniques are expected to enable achieving reasonable results with separation of mineral wool from a mix of construction and demolition waste. Nowadays, glass wool is still hardly recycled, because recycling costs (including the costs for separation and transport) are usually higher than the costs of the primary raw materials. The main challenges for the reuse of waste glass wool are the voluminous character, making transport relatively expensive, next to the varying composition and availability. Conservatively, we shall assume a glass wool recycling potential of 10%.

Waste glass wool may be used as a raw material in other products such as in cement and concrete (Shi and Zheng, 2007), in ceramics and in tiles and as an artificial substrate for growing plants (Väntsi and Kärki, 2014). This approach reduces the use of other primary raw materials, but this will not contribute to the sustainable use of boron. In doing so, boron is actually down-cycled and finally dissipated in the environment.

### 4.3.2. *Glass fibre in glass fibre reinforced plastics*

Literature describes three potential recycling methods for glass fibres: chemically, thermally, and mechanically. Asmatulu et al. (2014) compared the methods, suggesting that chemical recycling offers the highest tensile strength of the recycled fibers (98% of the original strength), while mechanical and thermal recycling result in lower quality fibers (75% and 50–75% of the strength of virgin fibers, respectively). Mechanical recycling consists of cutting and grinding the composite in small pieces, and separating the fibers from the rest of the particles. However, the recovered glass fibres have lost between 18 and 30% of their strength, potentially limiting applicability. Beauson et al. (2014), in an investigation of the recyclability of glass fibre from wind turbine blades, confirm this conclusion. Thermal treatment can encompass pyrolysis and combustion (López et al., 2012a,b; Zheng et al., 2009; Akesson et al., 2012; Asmatulu et al., 2014). The resulting glass fraction cannot be directly reused as glass fibre, but needs reprocessing, because of the relatively low quality mechanical properties. Contrary to this, Mizuguchi et al. (2013) report on a thermal method to decompose glass fiber reinforced plastics yielding the embedded reinforcing fibers in their original form without any noticeable difference between the virgin reinforcing fibers and the recovered ones. In the chemical treatment method, the polymeric matrix is dissolved in organic solvents or strong inorganic acids (see e.g., Liu et al., 2006). Thermal treatment of glass fibre reinforced plastics GFRP therefore may also be oriented to produce high-calorific oils and gases, next to glass for glass-ceramic applications (as glaze) in the building sector. The recycled fibre glass, which can be as much as 99% of the glass fibre in the GFRP, can be used as glazes on tiles and may reduce primary boron use for ceramics glazing (López et al., 2012a,b). Asmatulu et al. (2014) also mention the possibility of “direct structural composite recycling”. The concept is that large composite products are cut in smaller-size pieces that can be directly used in small composite products. García et al. (2014) investigated the addition of GFRP waste to micro-concrete. Under specific conditions the addition can be beneficial for the mechanical compressive and bending strength of the micro-concrete. Although the use of other primary materials is prevented in this way, the method will not reduce boron consumption.

Although recycling of glass fibre is still in a developmental stage, research results are promising. Recycling will depend on the costs of recovering and recycling glass fiber containing products versus the costs of primary boron. Conservatively, we shall assume a recycling potential of glass fibre from glass fibre reinforced plastics of 25%.

Borosilicate glass is recyclable, if it is separated from other waste glass. But borosilicate glass cannot be mixed with other glass for recycling, because of its impact on the viscosity of the melt. Recyclability is therefore, assumed to be limited. Therefore, we shall assume a recycling potential for borosilicate glass of 40% maximally.

### 4.3.3. *Recycling of boron in ceramics*

The majority of boron containing waste ceramics consists of tiles and sanitary ware in construction and demolition waste. The rest is in broken tableware in municipal waste. Waste composition is complex and overall boron concentration is low. We therefore, assume that boron from these waste flows cannot be recycled.

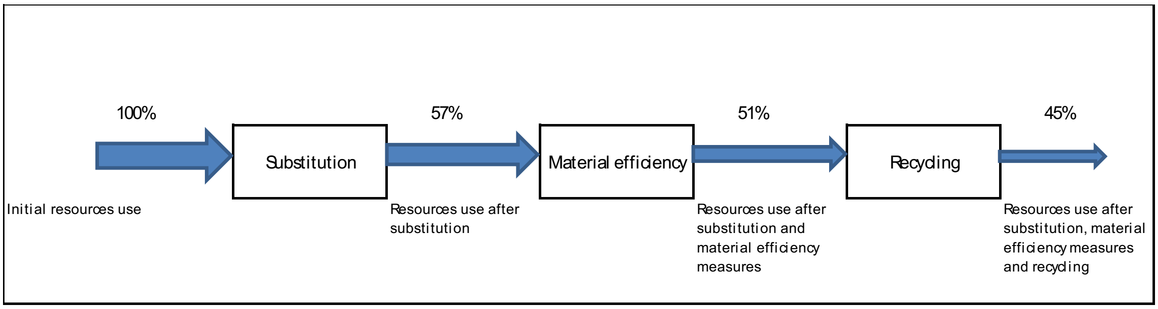

**Fig. 3.** Use reduction potential of primary boron with current technologies.

### 4.3.4. *Recycling of boron in other boron applications*

The other boron applications are dissipative or are used in quantities and concentrations that are assumed to be too low to be suitable for economical recycling.

### 4.3.5. *Boron recycling potential summarised*

Taking the various assumptions into consideration, the overall recycling potential of boron from products that are considered not substitutable for the time being (glass fibre in glass fibre reinforced plastics, and borosilicate glass) is about 12%.

## 5. Conclusion and discussion

In general, the consumption of a material can be reduced (1) by substituting the material, (2) by material efficiency and (3) by recycling. Different mixes of substitution, material efficiency improvement, and recycling may be applied. For ease of analysis, we have developed a method that starts with the assessment of the potential for substituting the critical material by suitable alternatives, followed by the opportunities for material efficiency improvement in production and processes of the non-substituted part. After that, the recycling potential of the remainder must be explored. In practice, the potential of the three approaches may influence each other, and an economic approach will contain all three elements. The method excludes a detailed economic analysis.

The approach has been applied to evaluate the opportunities to reduce boron use, as it is one of the elements that may be critical from a (temporal) sustainability perspective. In order to be sustainable, the 2010 extraction of primary boron needs to be reduced by 44%.

The results of the analysis are represented in Fig. 3.

The substitutability of current boron applications provide a reduction potential of about 43% of primary boron extraction. The replacement of glass wool by other insulating materials such as rock wool or organic foams and the replacement of boron containing detergents and soaps by non-boron containing detergents and soaps are most promising in this respect.

Material efficiency is estimated to have a reduction potential of 10% of the amount that remains after substitution. The highest potential in this respect is provided by a reduction of boron losses in waste sludge during the production.

Recycling measures can partly replace substitution and/or further decrease the use of primary boron. Most promising in this respect is the recycling of glass fibre from glass fibre reinforced plastics and the separate recycling of borosilicate glass. These recycling measures are estimated to have a realistic potential of about 12% of the amount of boron that remains after substitution and material efficiency measures.

The final conclusion is that the total reduction potential for the consumption of primary boron using existing technologies, is about 55%. This is sufficient to make the extraction of primary boron sustainable.

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