



*Sustainable Innovation and  
Technology Transfer  
Industrial Sector Studies*

# **CRITICAL METALS FOR FUTURE SUSTAINABLE TECHNOLOGIES AND THEIR RECYCLING POTENTIAL**

UNITED NATIONS ENVIRONMENT PROGRAMME



---

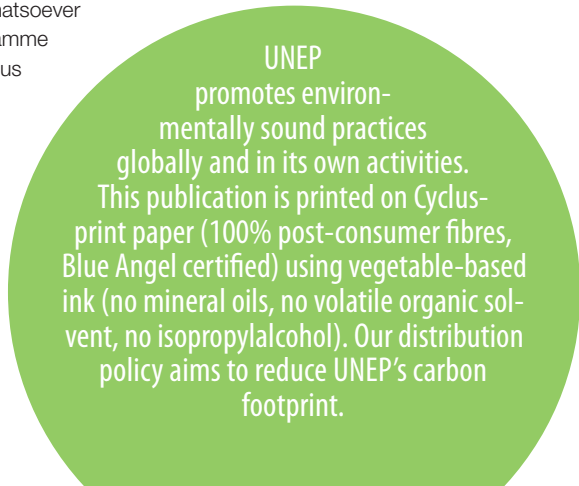
Copyright © United Nations Environment Programme & United Nations University, 2009

This publication may be reproduced in whole or in part and in any form for educational or non-profit purposes without special permission from the copyright holder, provided acknowledgement of the source is made. UNEP and UNU would appreciate receiving a copy of any publication that uses this publication as a source.

No use of this publication may be made for resale or for any other commercial purpose whatsoever without prior permission in writing from the United Nations Environment Programme and United Nations University.

**Disclaimer**

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the United Nations Environment Programme and United Nations University concerning the legal status of any country, territory, city or area or of its authorities, or concerning delimitation of its frontiers or boundaries. Moreover, the views expressed do not necessarily represent the decision or the stated policy of the United Nations Environment Programme and United Nations University, nor does citing of trade names or commercial processes constitute endorsement.



*Sustainable Innovation and  
Technology Transfer  
Industrial Sector Studies*

**CRITICAL METALS FOR  
FUTURE SUSTAINABLE  
TECHNOLOGIES AND THEIR  
RECYCLING POTENTIAL**

**July 2009**

# ***Acknowledgements***

## **Authors**

Matthias Buchert, Öko-Institut e.V.  
Doris Schüler, Öko-Institut e.V.  
Daniel Bleher, Öko-Institut e.V.

## **Assistance**

Nicole Neurohr, Öko-Institut e.V.  
Lorenz Hagelüken, Öko-Institut e.V.

## **Supervision and technical editing**

Guido Sonnemann, UNEP DTIE  
Bas de Leeuw, UNEP DTIE

## **Design**

Marcel Locher, UNEP DTIE  
Brita Schneider, 3f design, Germany

## **Printing**

## **We would like to thank the following persons for their input and constructive comments:**

Umicore Precious Metals Refining, Hoboken, Belgium:  
Christina Meskers  
Christian Hagelüken  
Thierry Van Kerckhoven  
Kris Van den Broeck

This publication received the support of the European Commission, Directorate-General for the Environment.

# **I Table of Content**

## **II Executive Summary ..... I - XIV**

## **III Final Report**

<b>1</b>	<b>Introduction and background .....</b>	<b>1</b>
<b>2</b>	<b>Objectives .....</b>	<b>2</b>
<b>3</b>	<b>Scientific approach &amp; methodology .....</b>	<b>4</b>
<b>3.1</b>	<b>Data Sources .....</b>	<b>4</b>
<b>3.2</b>	<b>Classification and prioritization of Critical Metals .....</b>	<b>5</b>
<b>4</b>	<b>Future sustainable technologies (FST) .....</b>	<b>8</b>
<b>4.1</b>	<b>Electrical and Electronic Equipment (EEE) .....</b>	<b>9</b>
<b>4.2</b>	<b>Photovoltaic Technologies (PV) .....</b>	<b>10</b>
<b>4.3</b>	<b>Battery technologies.....</b>	<b>11</b>
<b>4.4</b>	<b>Catalyst technologies .....</b>	<b>11</b>
<b>5</b>	<b>Current recycling of critical metals .....</b>	<b>13</b>
<b>5.1</b>	<b>Recycling technologies for critical metals .....</b>	<b>13</b>
<b>5.2</b>	<b>Recycling infrastructure for critical metals .....</b>	<b>23</b>
<b>6</b>	<b>Characteristics 'critical metals'.....</b>	<b>26</b>
<b>6.1</b>	<b>Selected metals in EEE technologies .....</b>	<b>26</b>
<b>6.1.1</b>	<b>Tantalum (Ta) – characteristics.....</b>	<b>26</b>
<b>6.1.2</b>	<b>Indium (In) - characteristics .....</b>	<b>29</b>
<b>6.1.3</b>	<b>Ruthenium (Ru) – characteristics .....</b>	<b>33</b>
<b>6.2</b>	<b>Selected metals in photovoltaic technologies .....</b>	<b>36</b>
<b>6.2.1</b>	<b>Gallium (Ga) - characteristics.....</b>	<b>36</b>
<b>6.2.2</b>	<b>Tellurium (Te) - characteristics.....</b>	<b>39</b>
<b>6.2.3</b>	<b>Germanium (Ge) - characteristics .....</b>	<b>42</b>

<b>6.3</b>	<b>Selected metals in battery technologies .....</b>	<b>45</b>
6.3.1	Cobalt (Co) - characteristics .....	45
6.3.2	Lithium (Li) - characteristics.....	47
<b>6.4</b>	<b>Selected metals in catalyst technologies.....</b>	<b>50</b>
6.4.1	Platinum (Pt) - characteristics.....	50
6.4.2	Palladium (Pd) - characteristics.....	53
6.4.3	Rare earths (RE) - characteristics .....	56
<b>7</b>	<b>Prioritization of critical metals .....</b>	<b>60</b>
7.1	General prioritization (1 <sup>st</sup> step) .....	60
7.2	Focused prioritization regarding demand (2 <sup>nd</sup> step) .....	61
7.3	Focused prioritization regarding supply (3 <sup>rd</sup> step).....	63
7.4	Focused prioritization regarding recycling (4 <sup>th</sup> step).....	65
7.5	Summarized prioritization and urgency regarding timeline.....	67
<b>8</b>	<b>Preconditions for an optimized recycling of critical metals</b>	<b>68</b>
<b>9</b>	<b>Conclusions and recommendations.....</b>	<b>72</b>
<b>10</b>	<b>Literature .....</b>	<b>74</b>

## Table of Figures

### Executive Summary

Figure 1:	Graphical illustration of the basic work process of this study .....	II
Figure 2:	Graphical basis of the prioritization process in this study (graphic by Öko-Institut) ...	III
Figure 3:	Application cluster and exemplary metals belonging to the particular cluster (graphic by Öko-Institut).....	IV
Figure 4:	Post consumer scrap - automotive catalyst and E-scrap - circuit boards (photo by courtesy of Umicore Precious Metals Refining) .....	VI
Figure 5:	Recycling chain for automotive catalysts from scrapped cars .....	VII
Figure 6:	Summarized prioritization regarding timeline of this study.....	IX
Figure 7:	“Low-tech” gold recycling in Bangalore/India (photo by courtesy of EMPA, Switzerland) .....	XII

### Final Report

Figure 2.1:	Graphical illustration of the basic work process of this study .....	2
Figure 2.2:	Table of the elements with green highlighted metals, which are in focus of this study; illustration by Öko-Institut.....	3
Figure 3.1:	Graphical basis of the prioritization process in this study (graphic by Öko-Institut) ....	6
Figure 5.1:	Post consumer scrap - automotive catalyst (photo by courtesy of Umicore Precious Metals Refining) .....	15
Figure 5.2:	E-scrap - circuit boards (photo by courtesy of Umicore Precious Metals Refining) ..	16
Figure 5.3:	Material flows and main process units at Hoboken plant (by courtesy of Umicore Precious Metals Refining) .....	18
Figure 5.4:	Material flows and main process units of Umicore’s battery recycling process (by courtesy of Umicore Precious Metals Refining) .....	20
Figure 5.5:	Materials flow of platinum/palladium in refinery catalysts in Germany (all percentage data relates to 100% input flow).....	21
Figure 5.6:	Materials flow of PGMs in the glass industry [GFMS 2005] .....	22
Figure 5.7:	Recycling chain for automotive catalysts from scrapped cars [GFMS 2005] .....	23
Figure 6.1:	Tantalum demand scenarios, calculation Öko-Institut based on RWI growth forecast .....	27
Figure 6.2:	Indium pearls (photo by courtesy of Umicore Precious Metals Refining) .....	29
Figure 6.3:	PV Production Capacities 2006 and forecast (Source: Jäger-Waldau 2007) .....	31
Figure 6.4:	Indium demand scenarios, calculation Öko-Institut .....	32

Figure 6.5:	Ruthenium demand (net) scenarios based on Öko-Institut calculations. ....	35
Figure 6.6:	Gallium demand scenarios based on calculations from the Öko-Institut.....	38
Figure 6.7:	Tellurium (photo by courtesy of Umicore Precious Metals Refining).....	40
Figure 6.8:	Tellurium demand scenarios based on calculations from the Öko-Institut .....	41
Figure 6.9:	Germanium demand scenarios, calculation Öko-Institut based on RWI growth forecast .....	44
Figure 6.10:	Cobalt demand scenarios based on Kapusta growth forecasts .....	46
Figure 6.11:	Lithium demand (net) scenarios based on Öko-Institut calculations .....	49
Figure 6.12:	Platinum demand (net) scenarios based on RWI growth forecasts .....	52
Figure 6.13:	Palladium demand (net) scenarios based on RWI growth forecasts.....	55
Figure 6.14:	Rare earths oxides demand scenarios based on calculations from the Öko-Institut.....	58
Figure 7.1:	Prioritization step 1: general assignment of critical metals .....	60
Figure 7.2:	Prioritization step 2: Distinction of rapid/moderate demand growth .....	61
Figure 7.3:	Visual transfer of differentiated growth rates for demand .....	62
Figure 7.4:	Prioritization step 3: Focused distinction of supply restriction .....	63
Figure 7.5:	Visual transfer of differentiated supply restrictions .....	64
Figure 7.6:	Prioritization step 4: Focused distinction of recycling restrictions .....	65
Figure 7.7:	Visual transfer of differentiated recycling restrictions.....	66
Figure 7.8:	Summarized prioritization regarding timeline of this study.....	67
Figure 8.1:	Indium bullion (photo by courtesy of Umicore Precious Metals Refining) .....	69
Figure 8.2:	“Low –tech” gold recycling in Bangalore/India (photo by courtesy of EMPA, Switzerland) .....	71



# **EXECUTIVE SUMMARY**



## Background and objectives

The focus of this study lies on future sustainable technologies (FST), such as renewable energies and energy efficient technologies, which will make use of **indium (In), germanium (Ge), tantalum (Ta), PGM [platinum group metals, such as ruthenium (Ru), platinum (Pt) and palladium (Pd)], tellurium (Te), cobalt (Co), lithium (Li), gallium (Ga) and RE (rare earths)**<sup>1</sup>. These are also classified as ‘**green minor metals**’, which are the basis for cleaner technology innovation. Other interesting metals like titanium or magnesium (used for light weight applications) are not addressed by this study but should be also an issue for further UNEP investigations and activities in the future.

- first objective is to analyse in depth the global availability and expectations for the development of the ‘critical metals’ demand, supply and prices
- second, the study focuses on the comprehensive analysis of their recycling potential and identification of gaps
- third, the study will explore favourable framework conditions, proposed course of actions, policies, incentives, funds, etc.; instruments, models etc. to predict and monitor the availability of critical metals and recycling systems

This study is in line with UNEP’s mission and vision, in particular in regard to resource efficiency/ sustainable consumption and production, which is one priority of UNEP’s mid-term strategy. The results of this study<sup>2</sup> will feed into the work of the resource panel, the preparation of the 10-year framework of programs on SCP (Marrakech Process), and hence finally into the 2010/2011 cycle of the Commission on Sustainable Development. These activities will help to accomplish the ultimate goal to stimulate sustainable innovation leading to decoupling of economic growth from environmental degradation.

The specific objectives of the study are:

- Identification and analysis of the global availability, geographical spread and prices of critical metals. Possible increasing pressure on the supply due to a growing demand through rising uptake of certain innovative technologies. Prioritization of critical metals regarding growing demand and possible scarcities
- Analysis of recycling potential for the identified critical metals with high prioritization:
  - Assessment of the recycling potential considering existing recycling technologies for the identified critical metals including the identification of gaps;
  - Feasibility assessment for potential innovative technologies for the recycling including the identification of opportunities and barriers.
- Identification of framework conditions that could help to foster technologies which enable the implementation of closed-loop recycling systems for critical metals.

---

<sup>1</sup> The rare earths under investigation in this study include the 16 elements: yttrium (Y), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu).

<sup>2</sup> As well as the results of parallel UNEP-DTIE studies: e.g. “Recycling – from e-waste to Resources”

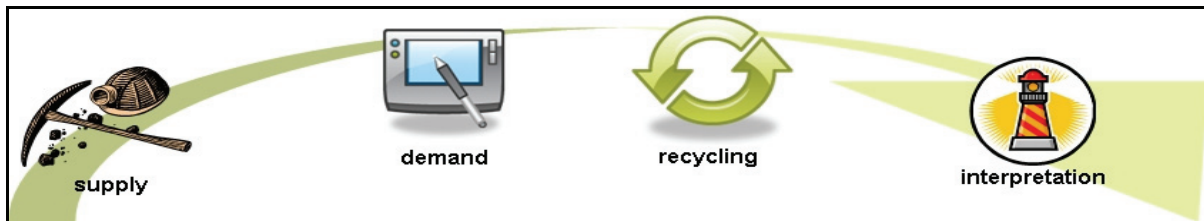


Figure 1: Graphical illustration of the basic work process of this study

For every metal under concern in this study, the specific characteristics are worked out and interpreted (**see final report, chapter 6**). Öko-Institut has confirmed UNEP DTIE that an important issue of the study is to work out a prioritization of the different metals focussing on the attribute 'critical'. The results from the prioritization will be assessed to a timeline – as critical in a short-term perspective (next 5 years), in a mid-term perspective (until ca. 2020) and in a long-term perspective (2050). This provides an important data source for decision-makers about the temporary exigency of certain critical metals.

## Scientific approach & methodology

Öko-Institut takes the most interesting methodologies regarding the term 'critical metals' into account. Nevertheless, **Öko-Institut includes often underestimated but very important issues like minor-product phenomena on the demand side and special challenges like post-consumer recycling of metals in dissipative usages**. Furthermore it should be mentioned that some of the criteria published by national bodies are helpful from a national perspective of certain countries, but not necessarily for an international point of view, which is focus of this study in co-operation with UNEP. For instance the recycling sectors regarding critical metals in Europe and Japan are in a quite different state of the art compared with other regions in the world. Of course, regions with a currently weak performance of recycling industries and infrastructures are – even more – dependent from regions with a very strong mining sector – especially in the case of a high regional concentration regarding the mining of certain metals.

Figure 2 reflects the issues of the UNEP project and helps to communicate the provided facts. All metals under investigation are classified according the three main topics:

- Demand growth
- Supply risks
- Recycling restrictions

Figure 2 shows the graphical basis illustration from the identified results in this study. The fundament of the illustration is three different coloured circles, representing the three main topics of this report. The database of each investigated metal allows the Öko-Institut to assign each metal to a certain position in the restriction circles. The position indicates which main topic is relevant for the certain metal. As the restriction circles are overlapping each other, this enables to express the importance / relevance of two or three main topics for the metal. For example, due to its position, Metal 1 shows recycling restrictions. Metal 5 – situated in the overlapping zone between 'demand growth' and 'recycling restrictions' – possesses aspects from both critical topics.

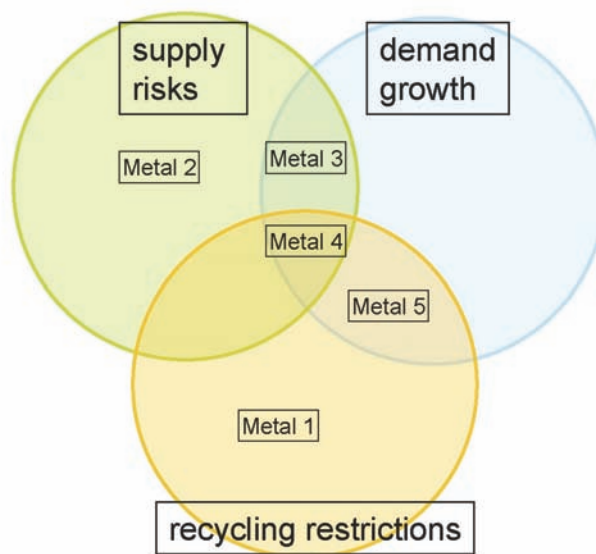


Figure 2: Graphical basis of the prioritization process in this study (graphic by Öko-Institut)

For a profound classification and differentiation of the metals, the following sub-criteria are taken into account by the Öko-Institut:

- **Demand growth**
  - Rapid demand growth: > 50% increase of total demand until 2020
  - Moderate demand growth > 20% increase of total demand until 2020
- **Supply risks**
  - Regional concentration of mining (> 90% share of the global mining in the major three countries)
  - Physical scarcity (reserves compared to annual demand)
  - Temporary scarcity (time lag between production and demand)
  - Structural or technical scarcity (metal is just a minor product in a coupled production and inefficiencies occur in the mining process, production and manufacturing)
- **Recycling restrictions**
  - High scale of dissipative applications
  - Physical/chemical limitations for recycling
  - Lack of suitable recycling technologies and/or recycling infrastructures
  - Lack of price incentives for recycling

The different metals under investigation will be screened with the help of the (sub-)criteria and then hereby prioritized. E.g. a metal fulfilling several of the sub-criteria for supply risks will be 'labeled' as 'serious supply risks'.

The metals will be finally classified regarding the timeline – as critical in a short-term perspective (next 5 years), in a mid-term perspective (until ca. 2020) or in a long-term perspective (2050). This prioritization and its highlighted facts and arguments have been discussed with UNEP; EU Commission and the external experts on 30 September in Paris for comments and verification.

## Future sustainable technologies (FST)

Basis for this report is a comprehensive analysis of eleven ‘green minor metals’, which are important for **certain future sustainable technologies (FST)**. The term ‘sustainable technologies’ has no official definition; it rather describes an assumption of technologies, their use implicates positive environmental effects.

- FST replace an obsolete technology and hereby reduce environmental impacts
- FST lead to emission reductions (e.g. automotive catalysts)
- FST provide power efficiency during the production or consumption phase (e.g. energy efficient LED lamps)
- FST can be used to monitor political or social behaviour causing negative environmental effects (e.g. electronic devices in satellites for environmental surveillance)

Each of the analyzed metals is used at least in one FST-application. Nevertheless, many of the introduced metals are also used for other applications, which can not directly be regarded as FST. In consideration of possible scarcities of availability among the checked metals, it is exceedingly necessary to describe all demand-driving applications and their predicted development. To improve the comprehension and readability of the analyzed metals, the Öko-Institut decided to appoint 4 major application clusters:

- I. EEE Technologies
- II. Photovoltaic Technologies
- III. Battery Technologies
- IV. Catalysts

Figure 3 shows the major cluster and a belonging box containing several metals which are needed for applications out this sector. Therefore, some metals occur twice (e.g. germanium) due to their adaptability in different application clusters. It is important to mention that the listed metals represent a selection; it is not to be understood as entire.

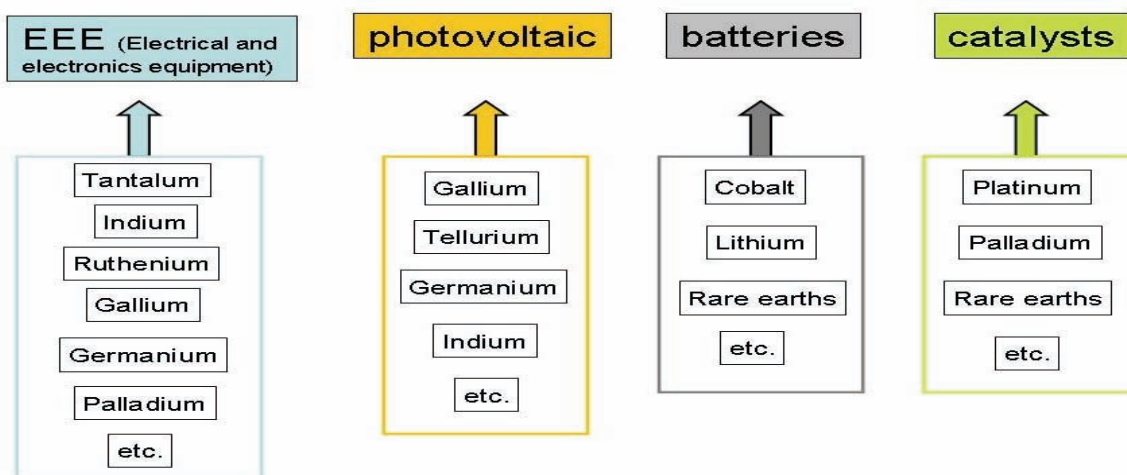


Figure 3: Application cluster and exemplary metals belonging to the particular cluster (graphic by Öko-Institut)

Beside the main FST-cluster the Öko-Institut investigation has identified some further innovations/applications, which could be considered as FST and which are associated with critical metals. For example specific alloys of aircraft turbines implicating higher security levels and reductions of fuel consumption as well as greenhouse gas emissions.

## Current recycling of critical metals

A successful recycling of the assessed critical metals is very important regarding increase of resource efficiency, avoidance of possible scarcities and reduction of the overall environmental impacts<sup>3</sup> linked with the life cycles of the critical metals. Furthermore the positive contribution of the recycling sector to employment and to adding value should be taken into account.

Concerning the recycling of metals two major fields should be differentiated:

In the most cases **pre-consumer recycling**, which means the recycling of production scrap of manufacturing processes ('new scrap') is the easier task compared to post-consumer recycling. The following general advantages can be stated for pre-consumer recycling:

- Mostly high concentrations of the distinguished metal in new scrap,
- Well-known and definite source of waste generation,
- Continuous new scrap formation (logistic friendly),
- Very often high volumes of new scrap formation (economy of scale).

**Post-consumer recycling** of critical metals is often a much more difficult task – even in the case of valuable precious metals. The main reasons are:

- Low metal concentrations in waste flows: dissipative applications;
- The critical metal is a minor composition in a complex material matrix (many other metals, plastics etc.);
- Regarding consumer applications like automobiles or electrical and electronic equipment (EEE), metal concentration in a single unit is very low and the final end-use often takes place in emerging or developing countries without sufficient take-back and collection systems for secondary materials.

Despite these restrictions today the post-consumer recycling of many critical metals is in a ripe status due to sophisticated and continuously improved recycling technologies. The next figure shows a post-consumer automotive catalyst. Typically a range between 2g and 5g per unit is the content of Platinum Group Metals (PGM) like platinum, palladium and rhodium in automotive catalysts. **This means a PGM concentration of > 1000 ppm – more than 100 times higher compared to natural ores. Therefore automotive catalysts are interesting secondary materials for the recycling of critical metals like PGM and special refining plants are working with very high recovery rates (> 90% for the PGM).** A more detailed technical insight is given in the final report of this study. A very relevant secondary material in a global scale is waste of EEE (WEEE) which fulfilled the criteria of a complex matrix

---

<sup>3</sup> Besides the entire saving of natural resources the recycling of metals usually shows much lower environmental impacts (lower energy demand, greenhouse gas emissions etc.) compared with the production of primary metals from natural ores.

material with dissipative concentrations of critical metals like palladium and indium. But besides the mentioned disadvantages, e-scrap (WEEE)<sup>4</sup> has also interesting recycling characteristics. Typical e-scrap like circuit boards contains a spectrum of metals like copper, tin, cobalt, gold, silver, indium, palladium, platinum etc. Due to its complexity e-scrap is a really challenging task for recycling technologies. Appropriate recycling of e-scrap promises parallel recovery of several interesting and valuable metals.

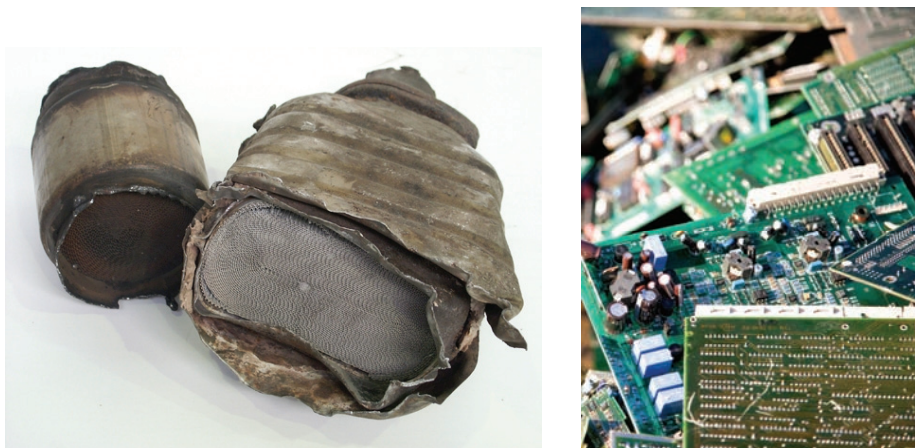


Figure 4: Post consumer scrap - automotive catalyst and E-scrap - circuit boards (photo by courtesy of Umicore Precious Metals Refining)

In the final report, an overview about Umicore's integrated metals smelter and associated metals separation units at Hoboken/Antwerp is given. This plant with a clear focus on end-of-life materials and by-products is able to recover 17 different metals – many of them under focus in this UNEP study. Typical input in Hoboken is e-scrap, spent industrial and automotive catalysts etc. The plant has an input capacity of about 350,000 tons.

For some metals like tantalum in dissipative applications (cell phones), lithium (e.g. batteries), rare earths (broad spectrum of applications), gallium and germanium there are until today none recycling technologies in commercial scales running or at most first steps in small (pilot) plants are initiated.

Furthermore **some applications of critical metals are so new, that relevant mass flows of post-consumer materials will reach the waste management sector not until in a few years.** A prominent field are solar cells for photovoltaic. Depending on the solar cell type indium, tellurium gallium and/or germanium are used in growing amount in this future sustainable technology. Compared to the rapidly growing installation of many million square meters of solar cells per year there are still no appropriate capacities and technologies installed.<sup>5</sup>

---

<sup>4</sup> Directive 2002/96/EC on waste electrical and electronic equipment (WEEE) of the European Parliament and of the Council -January 2003

<sup>5</sup> It should be mentioned, that the expected lifetimes of solar cells should be at least one or two decades.



In the case of battery applications the European Battery Directive is a driver for action due to soon mandatory collection and recycling rates for different battery types. Umicore is running a special plant for the common smelting of lithium ion and Ni-metal hydrid batteries in Sweden. The main products of the overall recycling steps are cobalt oxides and nickel hydroxide, which are used for the manufacturing of new batteries. Copper is an important side-product within the process. Nevertheless the recycling of lithium compounds is not purpose of this process (lithium moves as slag component out of the process).

The assessment of the current recycling technologies has shown that a couple of interesting technologies and real working plants are already available for the recycling of many critical metals (see final report for more details).

### Recycling infrastructure for critical metals

As an example in the next figure the recycling chain for automotive catalysts is performed. It has been stated that post-consumer automotive catalysts are quite uncomplicated materials compared with others like e-scrap, batteries etc. Nevertheless the illustrated recycling chain gives an idea about possible weak points, which could cause severe total losses of platinum group metals.

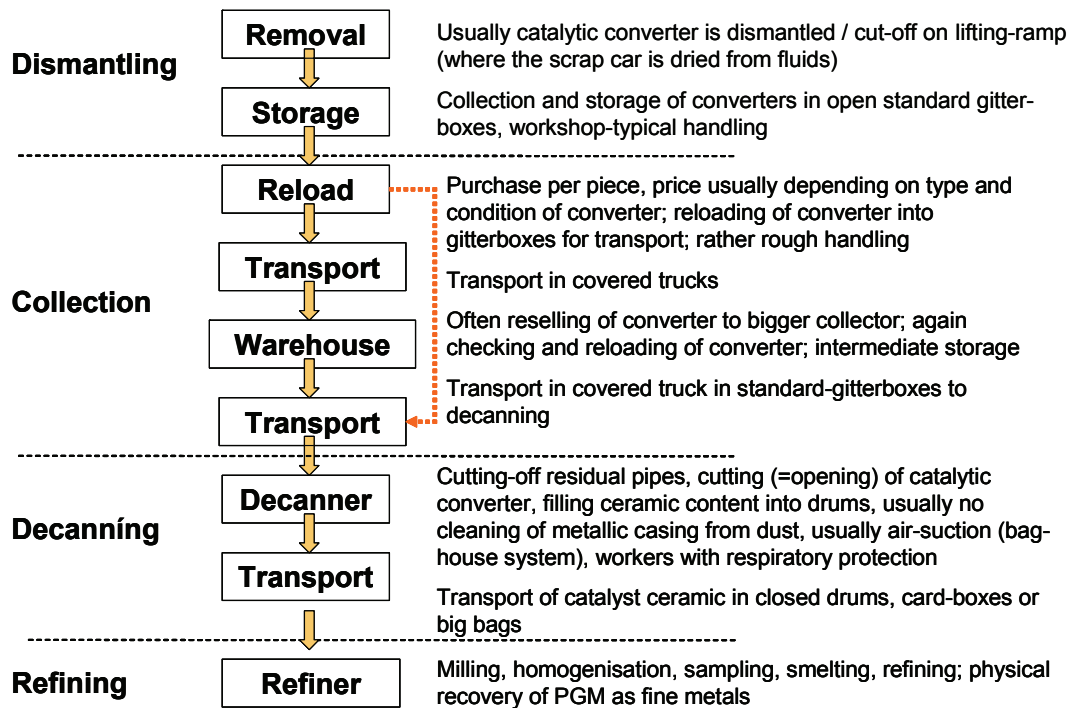


Figure 5: Recycling chain for automotive catalysts from scrapped cars

One problem could be the non-appropriate handling during transport (open boxes) and transfers steps. The valuable precious metals are located on the surface of the shock-sensitive ceramic. So, diffuse losses could occur in the case of non-sensitive handling by non-professional actors. Furthermore the de-canning step (separation of the metallic casing from the ceramic which contents the precious metals) needs an installation with a good dust collection system. **If good housekeeping rules are violated or dismantling takes place in**

**'backyards' in the grey market zones, serious losses of the desired critical metals are very probably.** The ELV<sup>6</sup> has set clear rules for the handling of automotive catalysts in the EU and in 2007 28 t platinum and 31 t palladium are recovered from automotive catalysts in a global scale (almost 15% of the global mining production). But despite this pleasant development it has to be underlined that even in the EU (especially in the new member states) the collection systems are not perfect at all. But far more concern has to be taken on to the fact, that via used vehicles (transport via seaports or highways) serious amounts of automotive catalysts leave developed countries with legislation systems like in the EU. In Germany, for instance, about 80% of the de-registered passenger cars leave the country. Many of them to other EU states like Poland. But a large number of cars have the destination Africa, Middle East etc. Because of the fundamental lack of take-back and collection systems for post-consumer materials like automotive catalysts in many of the destination countries, bad road conditions and lack of technical maintenance (damage of the catalysts), the total loss of increasing amount of platinum group metals is likely. This is backed by field studies in Africa.

Concerning the current recycling infrastructure for other types of pre- and post-consumer scraps which are relevant within the focus of the study, the following short statements can be made:

- Industrial catalysts: mature recycling infrastructure systems all over the world realized; the suppliers of the catalysts are very often also the institutions for the recycling of the containing special and precious metals,
- Photovoltaic: recycling infrastructure for pre-consumer recycling are initiated or improved in the last years; post-consumer recycling has to be developed in the next years in Europe and world wide
- Batteries: collection systems are initiated since a couple of years in Europe, further improvements could be expected due to the collection and recycling quotas of the European Battery Directive<sup>7</sup>; serious lack of recycling infrastructure in developing countries has to be addressed in the future,
- EEE applications: recycling infrastructure in Europe was developed in the last years, but further progress is necessary to address an optimized recycling of the metals despite the very heterogeneous applications (cell phones, TVs, note books, etc.); recycling infrastructure in emerging economies and developing countries are a very crucial challenge due to an almost total lack of basic collection and infrastructure systems.

The details of the required recycling infrastructure depend mainly on the types of products and the applications. In the case of batteries for instance separations steps before entering the metallurgical processes are not necessary (except large batteries for hybrid electric vehicles for which a dismantling of the casing makes sense). In the case of EEE, a

---

<sup>6</sup> ELV = End of life vehicles, Directive 2000/53/EC of the European Parliament and of the Council - September 2000

<sup>7</sup> Directive 91/157/EEC on batteries and accumulators and waste batteries and accumulators and repealing of the European Parliament and of the Council – June 2006

separation of the different main types of EEE (large consumer goods etc.) are common as well as manual first separation steps of main components (e.g. separation of cathode ray tubes from TVs).

### Prioritization of critical metals

In Figure 6 the overall results for the critical metals under investigation in this study (for details see final report) are summarized and the results of the prioritization process are delivered. Final step of the prioritization process is to interpret the conclusions from the detailed restriction-analyse and bring them together with a short-, mid- and long-term timeline. Figure 6 shows the results of this time-regarding classification. Each time category is composed of a criteria-setting with the above-explained distinguishing in rapid or moderate demand growth and serious or moderate risks.

Within the next five years (short-term perspective), Öko-Institut estimates that the metals tellurium, indium and gallium to be regarded as most critical due to rapid demand growth as well as serious supply risks combined with moderate recycling restrictions. In a mid-term perspective, the metals: rare earths, lithium, tantalum, palladium, platinum and ruthenium are becoming crucial. Finally, in a long-term perspective till 2050, only germanium and cobalt are regarded to become critical (details see final report).

Need for coordinated action is necessary for all of the investigated critical metals to reduce environmental burden of the primary production (enhanced production share of secondary metals) and ensure the resource base for important sustainable future technologies like solar cells, catalysts etc. **Nevertheless in the case of tellurium, indium and gallium special activities of UNEP and other international and regional bodies are recommended due to the urgency of possible critical supply situations etc.**

timeline	Metal
<b>short-term (within next 5 years)</b> + rapid demand growth + serious supply risks + moderate recycling restrictions	Tellurium Indium Gallium
<b>mid-term (till 2020)</b> + rapid demand growth and + serious recycling restrictions  or: + moderate supply risks + moderate recycling restrictions	Rare earths Lithium Tantalum  Palladium Platinum Ruthenium
<b>long-term (till 2050)</b> + moderate demand growth + moderate supply risks + moderate recycling restrictions	Germanium Cobalt

Figure 6: Summarized prioritization regarding timeline of this study

## Preconditions for an optimized recycling of critical metals

Taken the current situation and upcoming developments into account Öko-Institut identifies three different spheres of activities to promote the recycling of critical metals in the future decisively and insure the supply base for future sustainable technologies:

- The enlargement of recycling capacities,
- The development and realization of new recycling technologies and
- The accelerated improvement of international recycling infrastructures.

### Enlargement of recycling capacities

As punctuated on important examples successful technologies for the recycling of many critical metals are already realized in a couple of special plants worldwide (mainly in Europe and Japan). But it is obvious that **the existing capacities of these very particular plants will not be sufficient in the near future** for the rapidly growing pre-consumer and more important post-consumer material flows, which will contain increasing total amounts of very valuable and important metals. This statement is backed by three different examples.

#### Platinum group metals from automotive catalysts

In chapter 0 of this UNEP study it is noted that in 2007 28 t platinum and 31 t palladium were recovered from automotive catalysts worldwide. In the same year the global gross-demand for the production of new automotive catalysts was 131 t platinum<sup>8</sup> and 138 t palladium. The Umicore plant at Hoboken/Antwerp – one of the world largest sites for the recycling of precious metals in the world – has current capacities for 18 t platinum and 24 t palladium – from different waste inputs. That means in a about 10-15 years (average lifetimes of cars) a global capacity which is about six times higher than the total current capacity in Hoboken will be necessary for optimized global recycling capacities of platinum and palladium from spent automotive catalysts only. Furthermore optimized collection infrastructure for spent automotive catalysts will be required in the emerging economies and developing countries.

#### Indium

The second example is the important critical metal indium, which shows special urgency regarding the timeline due to rapid demand growth in different applications (LCD, solar cells). Umicore again announces for Indium a current recycling capacity of 50 t in its large Hoboken plant. But starting from a current net demand of about 610 t indium (and additionally 600 t indium delivered from mainly new-scrap recycling) and taking the expected strong increase rates for indium into account the amount of indium in post-consumer waste flows will be at least 3 times higher in 2015 compared with 2007. That means capacities for pre-treatment and refining of indium have to be enhanced remarkably in the next 5 years to address the upcoming post-consumer indium flows from applications with often quite low life-times like computer notebooks.

---

<sup>8</sup> For instance, the platinum demand for automotive catalysts has shown a strong growth in the last 20 years. E.g. in 1998 the global platinum demand for this application was just 69 t.

### Tellurium from photovoltaic applications

The tellurium demand is rapidly growing triggered by a boom of Cd-Te thin film solar cells. This could double or even triple the global tellurium demand in the next years and tellurium recycling will get a key role to ensure a satisfying tellurium demand in the future due to serious supply restrictions from natural resources. Therefore the global recycling infrastructures and capacities for the recycling of solar cells, new scrap and as well for post-consumer solar cells have to be built up. In this context the expansion of the current EU WEEE Directive on solar cells for photovoltaic should be focused seriously in the next years.

The demonstrated enormous demand for an expansion of the recycling capacities in the EU and worldwide respectively means a tremendous need for investments in particular technical installations (several billions of USD investment costs). Furthermore there is a continuous need for knowledge transfer and education of more skilled people, who have to plan and run further recycling plants in the future.

### **Development and realization of new recycling technologies**

Taken the results of this study into account, there is urgent need for further improvements and optimizations of existing recycling technologies – especially on the interface of suitable pre-treatment steps with core refinery plant performances. For instance further improvements for gallium, indium and tellurium which focus on quite new LCD and solar cell applications are necessary and should be backed by national, EU and international research programs. The growth of photovoltaic for example demands on a secure supply base of these important critical metals. **Need for research and development of total new technical procedures and recycling and refining concepts could be stated for:**

- tantalum in dissipative EEE applications like cell phones,
- distinguished rare earth metals like europium etc. and
- lithium applications (current problem: missing economic incentives)

### **Accelerated improvement of international recycling infrastructures**

In several cooperative research activities with Umicore Öko-Institut has proved the fact that the main problems of the current recycling of critical metals are the lack of suitable take-back and collecting systems for post-consumer waste flows in most parts of the world. It should be underscored that practices like shown in the following figure are the reality for the recycling of critical metals today in most parts of the world. This means serious health risks for the people and tremendous losses of valuable critical metals.

Therefore there is an enormous need for know-how and technology transfer from the developed countries to the emerging economies in Asia, Africa and Latin America and to the developing countries, too. The global recycling for critical metals will fail in a large scale if a decisive improvement of the basic recycling infrastructure (first step: appropriate local and regional take-back and collecting systems; second step: appropriate pre-treatment steps → no open use of fire and chemicals in backyards!) in these countries will not succeed in the next 5-10 years. Especially Europe has the experiences and premises (leading level of technical, legal and logistical know-how to build up circular economies!) to contribute to these global target decisively. This means a serious responsibility for the EU and also Japan, USA etc. But on the other hand side **the leading countries in the recycling of critical metals will get also in an economic, technological and political pole position.**



Figure 7: “Low-tech” gold recycling in Bangalore/India (photo by courtesy of EMPA, Switzerland)

In the next five to ten years the following potentials for critical metals could be achieved if the above - performed measures will be realized consequently:

- For platinum and palladium 70% share of the gross demand could be satisfied through recycling until 2020 (today about 45%).
- In case of cobalt further moderate increase of the recycling percentage of at least 30% is regarded as realistic until 2020 (depending on applications with long-term lifetime).
- Concerning the “new” critical metals indium, gallium, germanium, tellurium and ruthenium in the next five years appropriate post-consumer recycling infrastructures and well shaped pre-treatment and refining technologies will be essential. By achieving these tasks, remarkable recycling quotas for these important critical metals for FST are possible.
- Regarding tantalum, lithium and the rare earths basic research in suitable recycling processes are required due to their crucial chemical behaviour in actual recycling processes.

## Conclusions and recommendations

Öko-Institut likes to give the following conclusions and recommendations concerning the investigated critical metals within this short term study:

- The expected demand growth for the investigated critical metals could indicate different developments:
  - Growth of environmental-friendly technologies (e.g. photovoltaic, energy storage devices, catalysts for emission reductions etc.);
  - growth of overall mining production combined with related environmental stress;
  - enormous increase of the meaning of recycling technologies and related infrastructures in the next 5-10 years,

- Investments of several billions USD will be essential for an enhanced circular economy regarding critical metals to satisfy demand growth and to reduce overall environmental impacts!
- A further successful development concerning the recycling of critical metals will create additional employment in the developed countries as well in the emerging economies and the developing countries.
- We would like to recommend UNEP and its Resource Panel as well as the EU (on the occasion of their new strategy to address EU critical needs for raw materials) to give the investigated critical metals with short term risks (gallium, tellurium, indium) a special focus in their work and policies during the next years; furthermore the tremendous resource efficiency potentials of the other metals should also be targeted.
- We would like to suggest profound research and development regarding to single metals of the rare earth elements due to their demand growth, supply risks (regional concentration) and their identified serious recycling restrictions. Also basic research on metals with serious technical recycling problems like tantalum in dissipative applications is very important.
- Furthermore research, development and initiation of recycling technologies corresponding to specific fields of applications (e.g. solar panels & indium containing LCD-monitors) is an urgent task, as well as legislation measurements (WEEE etc.)
- We would like to support regional (EU) as well as international organizations (UNEP, OECD) to multiply their engagement for the monitoring and controlling of illegal scrap-exports usually containing critical metals (e.g. WEEE, ELV etc.)
- Finally we would like to underscore that enhanced know-how transfer and international cooperation regarding the increasing stocks of used products in developing countries (e.g. old cars containing auto catalysts, electronic devices etc., used consumer electronics, batteries etc.) is crucial in order to avoid serious supply restrictions regarding valuable critical metals for future sustainable technologies.

The most important framework conditions that could help to foster technologies for the implementation of closed-loop recycling systems for critical metals are summarized as results of the study:

- Financial support by the EU regarding new recycling technologies for critical metals: A specified EU critical metals recycling program could include the encouragement of **research & development** activities as well as the installation of first demonstration plants. Such a program should focus on issues demanding for new technological solutions like the closed-loop recycling of lithium and rare earths from batteries and tantalum from electronic scraps etc.
- Special **investment programs** including low interest credits are important building blocks (e.g. by the by the Member States) to support the design and realization of large scale recycling plants for critical metals.

- Continuous improvements of the **EU legislation system** to ensure high plant utilizations for critical metals:
  - Extension of the WEEE Directive regarding the collection and recycling of post-consumer photo-voltaic modules (recycling of indium, gallium, tellurium etc.).
  - Further development of the ELV concerning critical metals due to the dismantling and recycling of large batteries from electric vehicles.
  - Improved legal frameworks for the distinction of used goods and scraps (e.g. in the case of WEEE, ELV) designated for the export in non-EU countries to rise the collection rate.
- Establishment of **Best Practice Guidelines** for the entire recycling value-chain for different applications / types of critical metals, inclusive product-design, collection, dismantling and pre-treatment on European level, bringing together the knowledge of the different stakeholders and considering different regulative area.
- **Campaigns and initiatives** by the EU and the Member States to draw attention of the public to the importance and value of critical metals: The activities should focus on used consumer goods, which are often bunkered for many years attempt less in households (e.g. mobile phones in drawers).
- **Comprehensive adaption** of technological issues regarding the recycling of critical metals in existing courses of study (special programs and professorships).
- **Technology transfer** and international cooperation should be decisively accelerated by international recycling conferences, technological implementation programs in emerging economies and developing countries and specific scientific exchange programs.



# **FINAL REPORT**



## 1 Introduction and background

UNEP DTIE has commissioned Öko-Institut e.V. in August 2008 to carry out a small scale funding project entitled "Critical metals for future sustainable technologies and their recycling potential" in line with the activities agreed on in the Grant signed between UNEP and the European Commission and in relation to UNEP's work on Sustainable Innovation. Basis for this study regarding contents is UNEP's ToR "Proposal of sustainable innovation and technology transfer, industrial sector studies, including final draft Terms of Reference: Critical metals for future sustainable technologies and their recycling potential."

The focus of this study lies on future sustainable technologies, such as renewable energies and energy efficient technologies, which will make use of indium (In), germanium (Ge), tantalum (Ta), PGM [platinum group metals, such as ruthenium (Ru), platinum (Pt) and palladium (Pd)], tellurium (Te), cobalt (Co), lithium (Li), gallium (Ga), RE (rare earths)<sup>9</sup> and other 'high tech metals'. These are also classified as 'green minor metals', which are the basis for cleaner technology innovation. The first objective is to analyse in depth the global availability and expectations for the development of the critical metals' demand, supply and prices. Secondly, the study focuses on the comprehensive analysis of their recycling potential and moreover the study will explore favourable framework conditions for critical metals recycling systems. As examples for previous pioneer studies related to these issues could be suggested the Öko-Institut's work on automotive catalysts, [Hochfeld 1997], Andersson's very readable PhD thesis "Material constraints on technology evolution: the case of scarce metals and emerging energy technologies" [Andersson 2001] and the joint Umicore/Öko-Institut's in-depth analysis "Materials flow of platinum group metals" [GFMS 2005].

This study "Critical metals for future sustainable technologies and their recycling potential" is in line with UNEP's mission and vision, in particular in regard to resource efficiency/sustainable consumption and production, which is one priority of UNEP's mid-term strategy. The results of this study<sup>10</sup> will feed into the work of the resource panel, the preparation of the 10-year framework of programs on SCP (Marrakech Process), and hence finally into the 2010/2011 cycle of the Commission on Sustainable Development. These activities will help to accomplish the ultimate goal to stimulate sustainable innovation leading to decoupling of economic growth from environmental degradation.

---

<sup>9</sup> The rare earths under investigation in this study include the 16 elements: yttrium (Y), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu).

<sup>10</sup> As well as the results of parallel UNEP-DTIE studies: e.g. "Recycling – from e-waste to Resources"

## 2 Objectives

The overall objectives of this study are:

- Analysis of the availability of critical metals that might become increasingly costly and short in supply due to the increased uptake of certain innovative technologies (e.g. renewable energy and energy efficient technologies)
- Analysis of the recycling potential including the existing recycling technologies for the identified metals and identification of gaps
- Proposed course of actions (policies, incentives, funds, etc.; instruments, models etc. to predict and monitor the availability of critical metals)

The selection of the above-mentioned metals and other 'high tech metals', also classified as 'green minor metals', follow the focus of this study: metals as basis for cleaner innovative technologies like energy-efficient batteries and lights, fuel cells and photovoltaic cells (e.g. thin film), catalysts etc. Other interesting metals like titanium or magnesium (used for light weight applications) are not addressed by this study but should be also an issue for further UNEP investigations and activities in the future.

The specific objectives of the study are:

- Identification of critical metals and analysis of the global availability, geographical spread and prices of critical metals, which might experience an increased pressure on the supply due to a growing demand through the rising uptake of certain innovative technologies (e.g. renewable energy and energy efficient technologies); Prioritization of critical metals regarding growing demand and possible scarcities
- Analysis of recycling potential for the identified critical metals with high prioritization:
  - Assessment of the recycling potential considering existing recycling technologies for the identified critical metals including the identification of gaps;
  - Feasibility assessment for potential innovative technologies for the recycling of the identified metals including the identification of opportunities and barriers.
- Identification of framework conditions that could help to foster technologies which enable the implementation of closed-loop recycling systems for critical metals.



Figure 2.1: Graphical illustration of the basic work process of this study

The green minor metals under investigation are highlighted for an overview with green colour in the periodic system on the next page. For every metal under concern in this study the

specific characteristics concerning the supply and demand side and the current and future recycling potential are worked out and interpreted (see chapter 6).

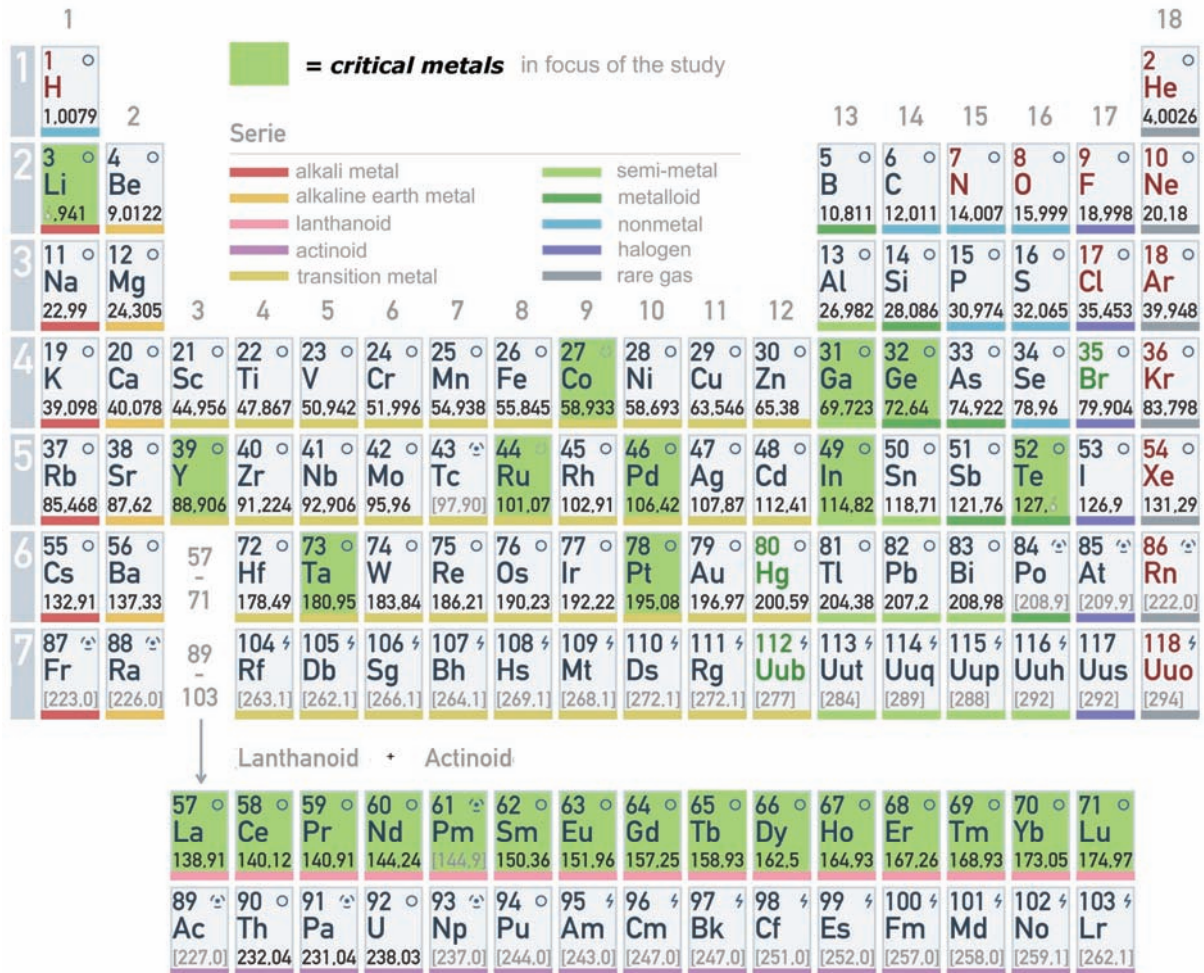


Figure 2.2: Table of the elements with green highlighted metals, which are in focus of this study; illustration by Öko-Institut

Öko-Institut has confirmed UNEP DTIE that an important issue of the study is to work out a prioritization of the different metals concerning the attribute 'critical' (see chapter 0). All collected and in chapter 6 introduced data about the selected metals of this study will provide the basis for this prioritization. Finally, the results from the prioritization will be assessed to a timeline – as critical in a short-term perspective (next 5 years), in a mid-term perspective (until ca. 2020) and in a long-term perspective (2050). This provides an important data source for decision-makers about the temporary exigency of certain critical metals.

### 3 Scientific approach & methodology

#### 3.1 Data Sources

For the fact finding process within this study Öko-Institut assessed different sources of information and collected first-hand data from different experts and institutions. Basic studies regarding critical metals on recommendation of UNEP play an important role in this process:

- 1. Profound analyze of current basic studies (for example):
  - Minerals, Critical Minerals and the US Economy [National Academies 2008]
  - Material security – Ensuring resource availability for the UK economy [Resource Efficiency 2008]
  - Study on global flow of metals – an example of material recycling [NIMS 2008]
  - Technologies innovantes et metaux High-Tech [BRGM 2008]

These recent publications from U.K., France, USA and Japan reflect the high relevance of the critical metal issue despite the different individual national conditions and perspectives. On the one hand side the value of these sources is to deliver data and facts about the green minor metals investigated for this UNEP study. On the other hand side a screening of the different methodical approaches concerning definition and classification/ranking of 'critical metals' is also very fruitful (see below).

Especially to get first hand-information about the current situation and the perspectives of recycling technologies and recycling infrastructures, team members of the Öko-Institut met experts of Umicore Precious Metals Refining in Hoboken, Antwerp.

- 2. Plant visit and intensive personal discussion with representatives from “Umicore Precious Metals Refining” Hoboken, Antwerp, Belgium<sup>11</sup>

Without any doubt, Umicore is a global market leader regarding the recycling and refining of precious and special metals – many of them under the focus of this UNEP study like platinum, palladium, ruthenium, indium, tellurium etc. – and has therefore a tremendous practical competence in these issues. Furthermore Umicore is a manufacturer and/or supplier of special metals or metal-based (semi)-products for catalysts, batteries, applications in the solar industry etc. and has therefore a first-hand market overview for a couple of

---

<sup>11</sup> For more details about the recycling of critical metals and a description of the recycling activities of Umicore and other companies see chapter 5 of this study.

the 'green minor metals'. From this intensive expert interview Öko-Institut received a couple of further important information and additional opinions, regarding criteria for the assessment and ranking of critical metals which are not or not sufficiently addressed in the literature listed above.

Finally Öko-Institut investigates further interesting publications concerning critical metals as well as reliable and comprehensive websites of relevant institutions, enterprises, metal trading places and associations to get a profound data-basis for the results of this study:

- 3. Internet and literature research:
  - [www.metal-pages.com](http://www.metal-pages.com)
  - [www.thebulliondesk.com](http://www.thebulliondesk.com)
  - Website of the International Platinum Group Metals Association
  - Johnson Matthey publications
  - RWI/BGR/ISI study
  - USGS website and publications
  - UNEP/OECD proceedings
  - And many other sources: see chapter 10: Literature
  
- 4. Discussion with UNEP; European Commission and external experts on occasion of the “Second expert meeting on Sustainable Innovation” and incorporation of their comments and feedbacks.

### **3.2 Classification and prioritization of Critical Metals**

Öko-Institut takes the most interesting methodologies regarding the term 'critical metals' into account. Nevertheless, Öko-Institut includes often underestimated but very important issues like minor-product phenomena on the demand side and special challenges like post-consumer recycling of metals in dissipative usages. Furthermore it should be mentioned that some of the criteria published by national bodies are helpful from a national perspective of certain countries (e.g. definition of supply risks for national economies), but not necessarily for an international point of view, which is focus of this study in co-operation with UNEP. For instance the recycling sectors regarding critical metals in Europe and Japan are in a quite different state of the art compared with other regions in the world. Of course, regions with a currently weak performance of recycling industries and infrastructures are – even more – dependent from regions with a very strong mining sector – especially in the case of a high regional concentration regarding the mining of certain metals.

For an overview regarding the classification of 'critical metals', Figure 2 reflects the issues of the UNEP project and helps to communicate the provided facts. All metals under investigation are classified according the three main topics:

- Demand growth
- Supply risks
- Recycling restrictions

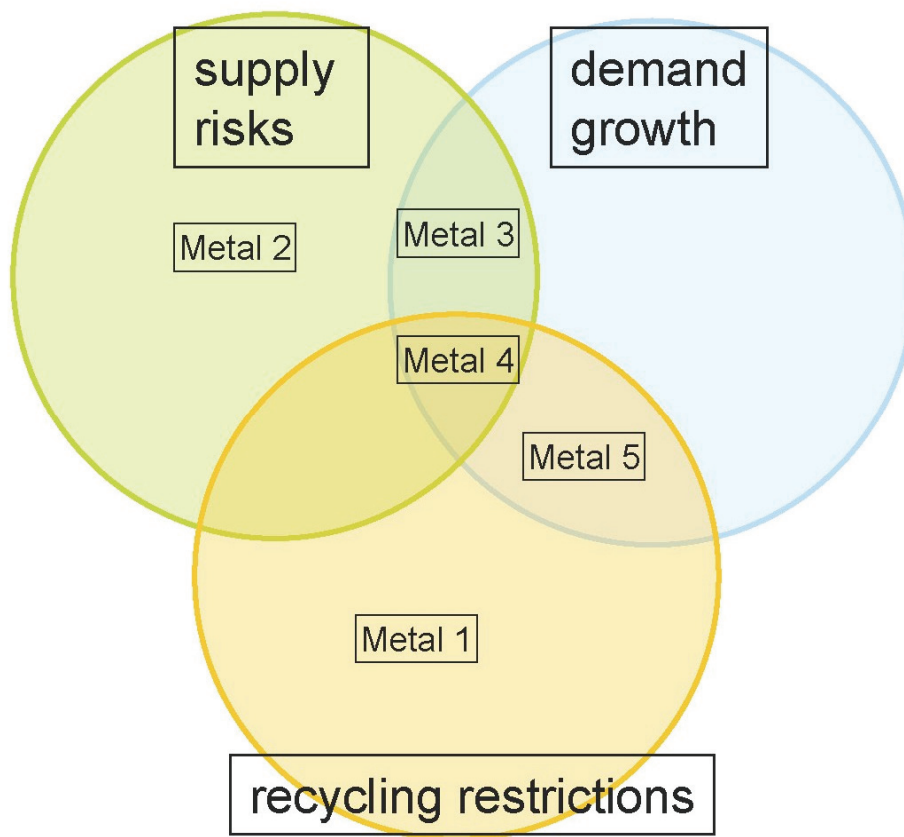


Figure 3.1: Graphical basis of the prioritization process in this study (graphic by Öko-Institut)

Figure 2 shows the graphical basis illustration from the identified results in this study. The fundament of the illustration is three different coloured circles. They represent the three main topics 'demand'; 'supply' and 'recycling' of this report. The database of each investigated metal (see chapter 6) allows the Öko-Institut to assign each metal to a certain position in the restriction circles (see chapter 0). The position indicates which main topic is relevant for the certain metal. As the restriction circles are overlapping each other, this enables to express the importance/relevance of two or three main topics for the metal.



For example, due to its position, Metal 1 shows recycling restrictions. Metal 5 – situated in the overlapping zone between 'demand growth' and 'recycling restrictions' – possesses aspects from both critical topics.

For a profound classification and differentiation of the different metals, the following sub-criteria are taken into account by the Öko-Institut:

- **Demand growth**
  - Rapid demand growth: > 50% increase of total demand until 2020
  - Moderate demand growth > 20% increase of total demand until 2020
- **Supply risks**
  - Regional concentration of mining (> 90% share of the global mining in the major three countries)
  - Physical scarcity (reserves compared to annual demand)
  - Temporary scarcity (time lag between production and demand)
  - Structural or technical scarcity (metal is just a minor product in a coupled production and inefficiencies occur often in the mining process, production and manufacturing)
- **Recycling restrictions**
  - High scale of dissipative applications
  - Physical/chemical limitations for recycling
  - Lack of suitable recycling technologies and/or recycling infrastructures
  - Lack of price incentives for recycling

The different metals under investigation in this study will be screened with the help of the (sub-)criteria and then hereby prioritized. E.g. a metal fulfilling several of the sub-criteria for supply risks will be 'labelled' as 'serious supply risks' (see chapter 0).

The metals will be finally classified regarding the timeline – as critical in a short-term perspective (next 5 years), in a mid-term perspective (until ca. 2020) or in a long-term perspective (2050)<sup>12</sup>. This prioritization and its highlighted facts and arguments have been discussed with UNEP; EU Commission and the external experts on 30 September in Paris for comments and verification.

Regarding future recycling challenges and perspectives (see chapter 0) and necessary policies for progress in resource efficiency (see chapter 0), Öko-Institut has focused mainly in the study on the critical metals under very urgent concern.

---

<sup>12</sup> According to expert statements demand predictions beyond 2020 are to be regarded as very uncertain. Nevertheless, for long-term predictions can be found at [Halada 2008]

## 4 Future sustainable technologies (FST)

Basis for the existent report is a comprehensive analysis of eleven minor metals ('green minor metals'), which are regarded to be important for certain future sustainable technologies (FST). The term 'sustainable technologies' has no official definition; it rather describes an assumption of technologies, their use implicates positive environmental effects. The reduction of environmental impacts can be reached in different ways:

- FST replace an obsolete technology and hereby reduce environmental impacts
- FST lead to emission reductions e.g. automotive catalysts
- FST provide power efficiency during the production or consumption phase (e.g. energy efficient LED lamps)
- FST can be used to monitor political or social behaviour causing negative environmental effects (e.g. electronic devices in satellites for environmental surveillance)

Each of the analyzed metals in this study is used at least in one FST-application. Nevertheless, many of the introduced metals are also used for other applications, which can not directly be regarded as FST. In consideration of possible scarcities of availability among the checked metals, it is exceedingly necessary to describe all demand-driving applications and their predicted development.

To improve the comprehension and readability of the analyzed metals in chapter 6 'Characteristics 'critical metals'', the Öko-Institut decided to appoint major application clusters, building a framework the profound analyse orientates on.

Figure 31 shows the four major application clusters:

- V. EEE Technologies
- VI. Photovoltaic Technologies
- VII. Battery Technologies
- VIII. Catalysts

The four application clusters can be regarded as super ordinate categories for FST Technologies. This means each cluster represents a certain spectrum of single FST-Technologies which can be concentrated in a cluster. The definition of the clusters used in this study was formed during the research phase while it got obvious that all investigated future sustainable technologies can be assumed to a certain super ordinate category.

Figure 31 also shows a box belonging to each cluster and containing several metals which are needed for applications out this sector. Therefore, some metals occur twice (e.g. germanium) due to their adaptability in different application clusters.

It is important to mention that the listed metals represent a selection; it is not to be understood as entire. In the case of photovoltaic, silicon was not included in this study due to its widespread natural deposits.

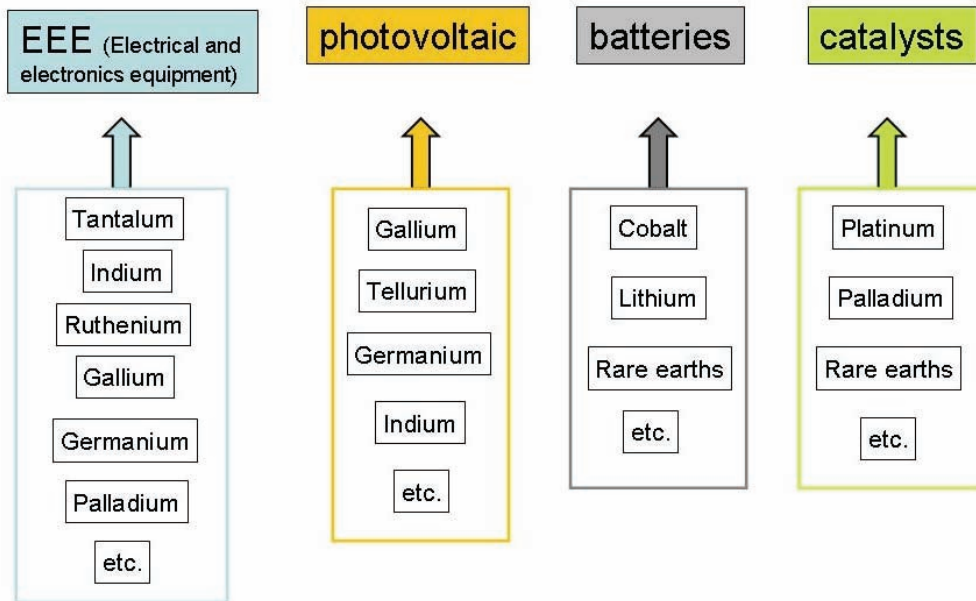


Figure 4.1: Application cluster and exemplary metals belonging to the particular cluster (graphic by Öko-Institut)

Beside the main FST-cluster the Öko-Institut investigation has identified some further innovations/applications, which could be considered as FST and which are associated with critical metals. For example specific alloys of aircraft turbines (see chapter 6.1.1 and 6.1.3) implicating higher security levels and reductions of fuel consumption as well as greenhouse gas emissions.

#### 4.1 Electrical and Electronic Equipment (EEE)

Compared to the other application-clusters of this study, the field of Electrical and Electronic Equipment (EEE) is the widest and therefore most difficult to delimit. As EEE is fairly widespread through all activities of global economy and society, it is even quite hard to define certain industries

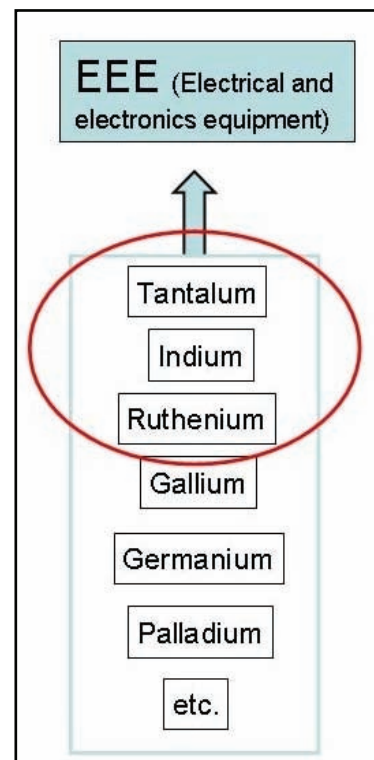


Figure 4.2: Critical metals in EEE applications

or economic sectors in which EEE applications are not being used for. EEE applications can be found in areas like entertainment, military, medicine, consumer goods, navigation etc.

Figure 4.2 shows a selection of critical metals used for EEE applications. The listed metals are to be understood as exemplary. Tantalum, indium and ruthenium represent the metals introduced and characterized in the corresponding chapter 6.1.

EEE applications occur as highly specialized devices, constructed for certain needs like for example night vision goggles for military or private applications, which are also about to become more and more important in the mass market for automotive navigation (see chapter 6.2.3). But EEE can also be multifunctional devices like cell phones, which nowadays tend to be communication unit, organizer, music player and much more, all stuffed into one gadget. At last, EEE occurs in form of very small (even tiny) products like Light Emitting Diodes (LED). In this case (see chapter 6.2.1) EEE's are mass products, constructed of a simple application but in huge numbers.

Respecting the critical metals needed for EEE applications, it can be summarized that generally the amount of therefore needed critical metal in a single EEE unit is rather small. This dissipative usage of the critical metal aggravates technical and economical incentives for recovery and – in some cases – leads to a total loss of the used metal (e.g. tantalum in cell phones, see chapter 6.1.1).

As seen, the problem of delimitation of EEE application is combined with the fact, that a causal reliance between EEE and future sustainable technologies cannot be presumed. Mainly in the field of consumer goods, purchase decisions are being made because of personal preferences and attitudes and not because of economic or environmental reasons. But in some cases reliance between EEE applications and FST can be acknowledged: see chapter 6.1.2 (indium): energy efficient Organic Light Emitting Diodes (OLED).

## 4.2 Photovoltaic Technologies (PV)

The application cluster of photovoltaics (PV) refers entirely to the PV industry sector.

Solar cells are able to transfer sunlight (exactly the electromagnetic spectrum) into electrical energy. Except the production phase, energy recovery takes place without needing fossil fuels or emitting carbon dioxide. Therefore it is obvious why PV technology is to be regarded as FST.

The entire PV-sector can be divided in the two major fields: space and terrestrial applications. While the technology is unrivalled in space applications, capacity improvement and cost reduction in the field of terrestrial applications is essential (and apparent!) to compete successful with other renewable energies like water or wind power.

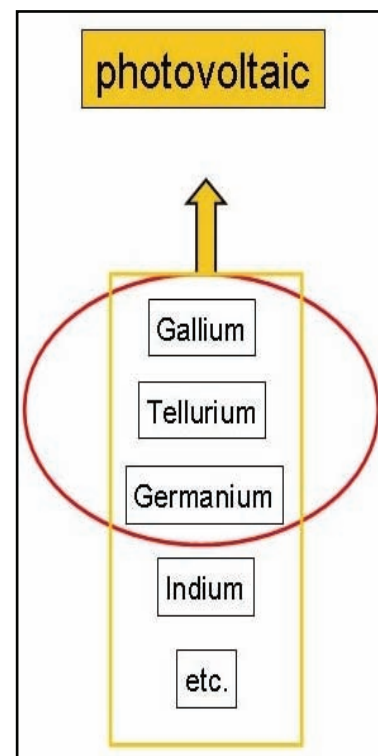


Figure 4.1: Critical metals in PV technology

Critical metals play a major role in the manufacturing process of the new generation of high capacity cells. Figure 4.1 shows a selection of these minor metals needed in the production. As indium is already being introduced in chapter 6.1.2, the study focuses in the PV cluster on the metals gallium, tellurium and germanium.

### 4.3 Battery technologies

Batteries understood as future sustainable technology relate only to rechargeable accumulators and not – as the title may indicate – to primary batteries, which lack of the recharge capability. It is the repeatable capability of storing energy that makes batteries very important for other FST applications like renewable energies and electronic gearing in vehicles. The tremendous debates and developments of rechargeable lithium batteries for energy storage in stationary and mobile applications is a prominent example.

Battery technology is being applied for some decades, but the sector actually experiences a change due to new requirements the branch is facing with. On the one hand side batteries have to store more energy with an increasing capacity (e.g. electric cars). On the other hand side, for lots of applications the batteries have to shrink in size (e.g. EEE devices like cell phones) and the battery producers have to face the problem to reduce the battery size without affecting the capacity.

Due to the relatively long usage of batteries, recycling technologies and collecting infrastructures are fairly widespread and in many countries a common praxis.

Figure 4.2 shows a selection of critical metals used for battery applications. The red circle indicates that chapter 6.3 introduces the metals cobalt and lithium, while rare earths are being introduced in connection with the chapter of catalyst technologies (see chap. 6.4).

### 4.4 Catalyst technologies

The field of catalyst technologies is very manifold and complex. Generally catalysts are being used to accelerate chemical reactions. Furthermore, catalysts are useful because they leave no residue in the solution they fastened up. This aspect makes catalyst materials interesting for recycling. Generally, a huge number of catalysts in different industries (oil industry, chemical industry etc.) are applied. Catalysts in automotives and catalysts

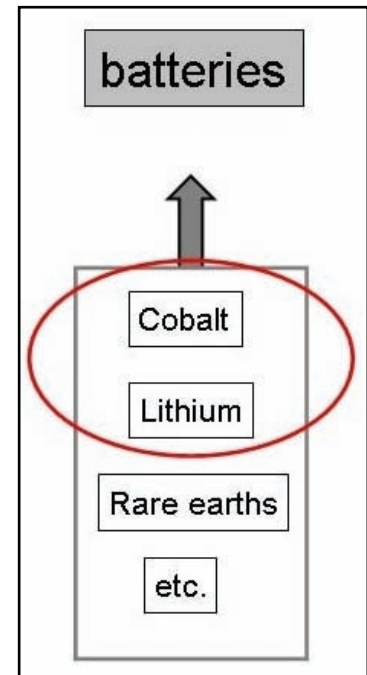


Figure 4.2: Critical metals in battery technologies

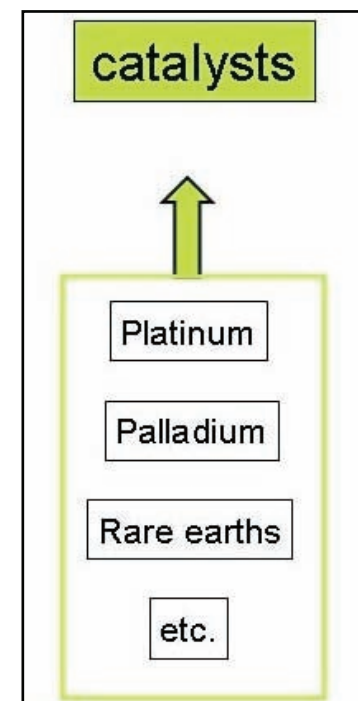


Figure 4.3: Critical metals used for catalysts

in the production of polymers are two major applications in which critical metals are used for. As an automotive catalyst reduces significantly the emission from the engine and improves the efficiency, this technology has definitely to be regarded as FST. A car without a catalyst is unthinkable at present. For automotive catalysts, the so-called Platinum Group Metals (PGM; a group subsuming the precious metals) as well as rare earths play a super ordinate role, as they are represented in each single automotive catalyst.

Concerning catalysts for the polymerization (see chap. 6.2.3: germanium), there is no obvious link to future sustainable technologies. But as the use of germanium for catalysts is a demand-driving application, it has to be regarded as important for the demand development of this particular metal.

Figure 4.3 shows a selection of critical metals in the use as catalysts. Therefore, the corresponding chapter 6.4 introduces the metals platinum, palladium and rare earths. All mentioned other metals belonging to this cluster are already introduced in former chapters.

It should be underlined that all the mentioned FST applications are showing above-average growth rates.

## 5 Current recycling of critical metals

A successful recycling of the critical metals which are under assessment in this study is very important regarding increase of resource efficiency, avoidance of possible scarcities and reduction of the overall environmental impacts<sup>13</sup> linked with the life cycles of the critical metals. Furthermore the positive contribution of the recycling sector to employment and to adding value should be taken into account.

In this chapter an overview about the general situation of the current recycling of critical metals are given. In sub-chapter 5.1 the current technological situation of the recycling is addressed. Beside sophisticated recycling technologies efficient recycling infrastructure systems are essential for successful recycling. Therefore sub-chapter 0 deals with the current situation regarding the recycling infrastructure for critical metals. Success stories as well as current weak points will be shown.

In chapter 6 further specific information about the recycling of the different metals tantalum (Ta), indium (In), ruthenium (Ru), gallium (Ga), tellurium (Te), germanium (Ge), cobalt (Co), lithium (Li), platinum (Pt), palladium (Pd) and rare earths (RE) are presented. Finally in chapter 0 important “Preconditions for an optimized recycling of critical metals” are performed, which are necessary for a further enhancement of critical metals recycling in the future.

### 5.1 Recycling technologies for critical metals

Concerning the recycling of metals two major fields should be differentiated:

- pre-consumer recycling (recycling of new scrap) and
- post-consumer recycling (recycling of old scrap).

In the most cases **pre-consumer recycling**, which means the recycling of production scrap of manufacturing processes ('new scrap') is the easier task compared to post-consumer recycling. Therefore pre-consumer recycling is very common for bulk metals like iron/steel, copper, aluminium etc. as well as for many precious and special metals. The following general advantages could be stated for pre-consumer recycling:

- mostly high concentrations of the distinguished metal in new scrap,
- well-known and definite source of waste generation,
- continuous new scrap formation (logistic friendly),
- very often high volumes of new scrap formation (economy of scale).

---

<sup>13</sup> Besides the entire saving of natural resources the recycling of metals usually shows much lower environmental impacts (lower energy demand, greenhouse gas emissions etc.) compared with the production of primary metals from natural ores: details see for instance [GFMS 2005], [Umicore/ÖI 2008].

In the case of critical metals with a very high specific value like platinum even new scrap streams with very low concentrations are successfully collected and afterwards recycled in special refining plants (see below). For instance in the field of handcrafted jewellery manufacturing, goldsmiths clean their hands with wood wool to keep losses of precious metals to a minimum [Ackermann 2002; Groß-Stahl 2001]. In industrial manufacture of jewellery, large numbers of pieces of jewellery (e.g. wedding rings) are produced. On average, around 40% of the material used is not found in a particular piece of jewellery, but rather in production scrap that is then channelled into recycling. Where pure materials emerge in processing, they are partly re-melted in the plant. Bullion material is collected and – in the case of large companies – delivered on a weekly basis to refiners [Bunz 2002; Kleindrucker 2002; Dornbusch 2002]. This bullion material contains materials occurring in mechanical processing (filing, for example). Sweeps and materials recovered from wastewater are also delivered to refiners [Bunz 2002; Dornbusch 2002].

Exceptions to the rule “pre-consumer recycling is a fast-selling item” could only occur in the cases:

- The critical metal is a quite cheap material (lack of economic incentive);<sup>14</sup>
- The critical metal is just in a low concentration content of a production scrap (and maybe the matrix material is adverse to existing recycling technologies);
- The application of the critical metal is quite new and the overall (global) metal amounts are very low (lack of economy of scale).

Regarding the last exception (new application, low total amount) the example of ruthenium in sputter target processes (for computer hard disk production) is demonstrative. After a dramatic push for the global ruthenium demand in recent years due to the boom of the hard disk production the related industry has now reacted and built up the necessary infrastructures for the appropriate collection and refining of the enormous percentages of 'ruthenium new scrap' in this manufacturing processes (see also chapter 6.1.3). The high ruthenium prices and the remarkable amounts of 'ruthenium waste' have triggered this recent development. [JM 2008a]

On the other hand side **post-consumer recycling** of critical metals is often a much more difficult task – even in the case of valuable precious metals. The main reasons are:

- low metal concentrations in waste flows: dissipative applications;
- The critical metal is a minor composition in a complex material matrix (many other metals, plastics etc.);

---

<sup>14</sup> The price of Lithium for instance is about 1,000 times lower compared with platinum (for details see chapter 6).



- Regarding consumer applications like automotives or electrical and electronic equipment (EEE): e.g. just about hundred tons of a metal like platinum are sold in many million single product units per year worldwide. The final end-use for an increasing share of these million units takes place in emerging or developing countries without sufficient take-back and collection systems for secondary materials.

Despite these restrictions today the post-consumer recycling of many critical metals is in a ripe status due to sophisticated and continuously improved recycling technologies. The next figure shows a post-consumer automotive catalyst. Typically a range between 2g and 5g per unit is the content of Platinum Group Metals (PGM) like platinum, palladium and rhodium in automotive catalysts. [GFMS 2005] This means a PGM concentration of > 1000 ppm – more than 100 times higher compared to natural ores.



Figure 5.1: Post consumer scrap - automotive catalyst (photo by courtesy of Umicore Precious Metals Refining)

Therefore automotive catalysts are interesting secondary materials for the recycling of critical metals like PGM and special refining plants are working with very high recovery rates (> 90% for the PGM). This good recycling situation for automotive catalysts does not indicate that generally all metals used in catalysts can be recycled. For some applications of catalyst-metals, e.g. used for the polymerization of plastics, like germanium described in 6.2.3, a total loss of the catalyst-metal is observed because the metal remains in the polymer products. This means, the usage of germanium in this process leads to a total loss of this metal.

A more detailed technical insight is given below in this sub-chapter and a description of the necessary recycling infrastructure – the related success stories and the weak points – are discussed in sub-chapter 0.

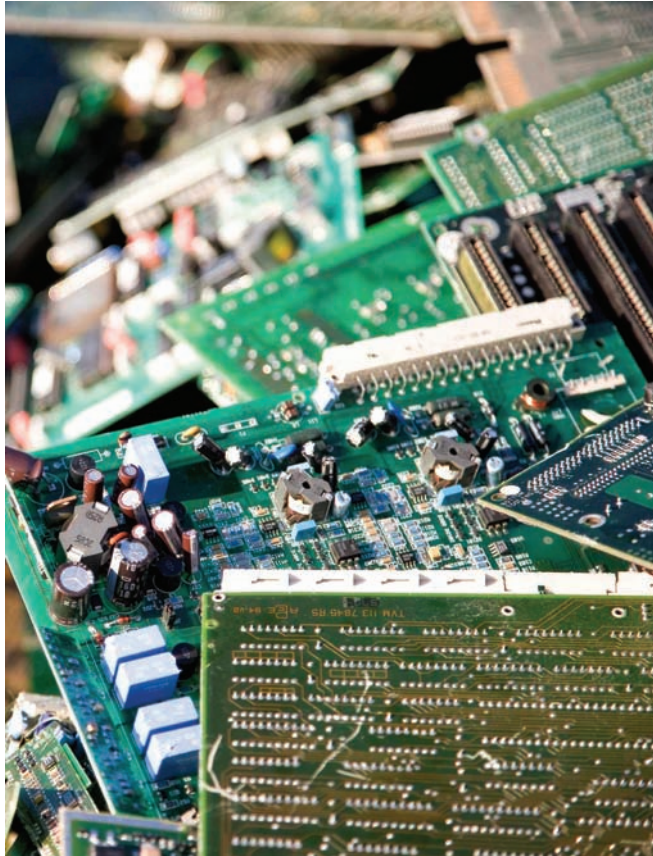


Figure 5.2: E-scrap - circuit boards (photo by courtesy of Umicore Precious Metals Refining)

A very relevant secondary material in a global scale is waste of EEE (WEEE<sup>15</sup>) which fulfilled the criteria of a complex matrix material with dissipative concentrations of critical metals like palladium and indium<sup>16</sup>. But besides the mentioned disadvantages e-scrap (WEEE) has also interesting characteristics regarding recycling. Typical e-scrap like circuit boards (see next figure) contains a spectrum of interesting metals like copper, tin, cobalt, gold, silver, indium, palladium, platinum etc. That means e-scrap is a really challenging task for recycling technologies due to its complexity. But on the other hand side the appropriate recycling of e-scrap

---

<sup>15</sup> Directive 2002/96/EC on waste electrical and electronic equipment (WEEE) of the European Parliament and of the Council -January 2003

<sup>16</sup> The following description of recycling technologies and processes doesn't focus on large EEE consumer goods like washing machines, refrigerators etc. Their different material composition compared to smaller IT and consumer goods like notebooks and cell phones etc. causes a different recycling process chain. The recycling of these large EEE consumer goods focuses on their main components steel and plastics.

promises the parallel recovery of several interesting and valuable metals – EEE could be regarded as 'mine above ground'. [Umicore/ÖI 2008]

In the next figure a flow sheet with an overview about Umicore's integrated metals smelter and associated metals separation units at Hoboken/Antwerp is given. This plant with a clear focus on end-of-life materials and by-products is able to recover 17 different metals – many of them under focus in this UNEP study: the critical metals indium, tellurium, platinum, palladium and ruthenium. Typical end-of-life products as input in Hoboken are e-scrap, spent industrial catalysts, spent automotive catalysts etc. The plant has an input capacity of about 350,000 tons. Umicore announces the following yearly output capacities for the bulk metals lead (125,000 t), copper (30,000 t), nickel (2,000 t), tin (1,000 t), antimony (3,000 t) and for the special and precious metals silver (2,400 t), gold (100 t), platinum (18 t), palladium (24 t), rhodium (5 t), bismuth (400 t), indium (50 t), tellurium (150 t), selenium (600 t). [Umicore 2008]. For the output metals ruthenium, iridium and arsenic no capacity figures are published by Umicore. Furthermore 140,000 t is the output capacity of the side-product slag, which is used as aggregate for concrete. The slag still contains metals like tantalum (as oxide) in very low concentrations, which are problematic for recovery. Due to its chemical characteristics metals like tantalum tend to oxidize easily. Therefore Umicore does not recover tantalum [Umicore 2008] in the current refining process.

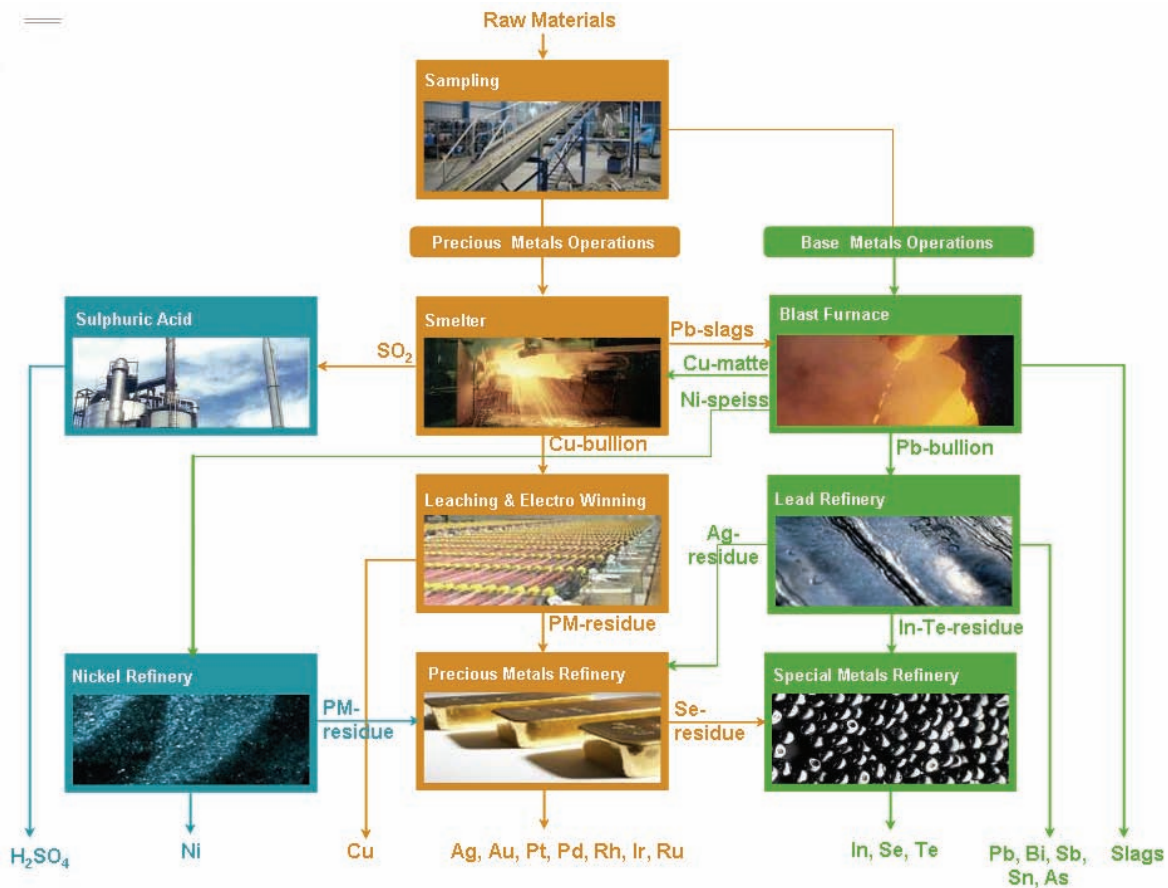


Figure 5.3: Material flows and main process units at Hoboken plant (by courtesy of Umicore Precious Metals Refining)

In the flow sheet above the material flows and main process units around Umicore’s integrated smelter are performed. After sampling and (depending on the end-of-life material) pre-treatment operations the input materials are transferred into the large smelter. Plastic components (circuit boards) are used as reducing agents and fuel substitutes. The obtained copper bullion (copper has the function of a so-called collector-metal) is transferred into a leaching and electro-winning process to separate copper from the precious metals. The precious metals are separated from themselves and purified in the precious metals refinery by complex hydro-metallurgical operations. Silver, gold, platinum, palladium, rhodium, ruthenium and iridium are recovered in this operation unit and get ready for the use in jewellery, automotive and industrial catalysts, electronic industry etc.

The lead slag phase (lead worked as collector metal for special metals) is transferred from the smelter into a special blast furnace. In this process unit, lead bullion is separated from a copper matte phase (back into integrated smelter) and a nickel speiss phase. From the last one, nickel is recovered in the nickel refinery (separated precious metals are transferred into the precious metals refinery). The lead bullion, which contains silver, indium, tellurium, selenium, bismuth, antimony, arsenic and tin is purified via different steps to lead and the eight different other metals are separated as high purity metals.

It should be underscored that the Hoboken plant of Umicore is unique regarding the flexibility of very different input materials (very different by-product and post-consumer materials). Regarding the most critical metals under concern in this UNEP study it is important to say that worldwide just 5-10 different plants are in a technological performance to refine e.g. indium, tellurium, ruthenium etc. from different pre- and post-consumer materials. Regional focus for these special refining plants is mainly Europe and Japan. Examples are the Norddeutsche Raffinerie AG in Germany (Europe's largest copper producer) for precious and some special metals from e-scrap via the copper refining process, Boliden in Sweden/Finland [Boliden 2008], Johnson Matthey in USA/UK [JM 2008b] and DOWA [DOWA 2008] in Japan.

For some metals like tantalum in dissipative applications (cell phones), lithium (e.g. batteries), rare earths (broad spectrum of applications), gallium and germanium (up-to-date just very small and dissipative amounts in post-consumer materials) there are until today none recycling technologies in commercial scales running or at most first steps in small (pilot) plants are initiated (see chapter 6 for recycling details of the single metals).

Furthermore some applications of critical metals are so new, that relevant mass flows of post-consumer materials will reach the waste management sector not until in a few years. A prominent field are solar cells for photovoltaic. Depending on the solar cell type indium, tellurium gallium and/or germanium are used in growing amount in this future sustainable technology. Compared to the rapidly growing installation of many million square meters of solar cells per year there are still no appropriate capacities and technologies installed.<sup>17</sup>

An appropriate recycling technology is recently established in Germany for the recycling of tellurium from CdTe thin-film solar cells. [Euwid 2008] [First Solar 2008b]

In the case of battery applications the European Battery Directive is a driver for action due to soon mandatory collection and recycling rates for different battery types. Umicore is running a special plant for the common smelting of lithium ion and Ni-metal hydrid batteries in Sweden (for more detailed information about the Umicore Val'Eas® process of battery recycling see [Meskers et al 2009]). In the next figure a flow sheet about the battery recycling process of Umicore is given. The shown recovery process refers as well to rechargeable as to non-rechargeable batteries. The main products of the overall recycling steps are cobalt oxides and nickel hydroxide, which are used for the manufacturing of new batteries. Copper is an important side-product within the process. Nevertheless the recycling of lithium compounds is not purpose of this process (lithium moves as slag component out of the process and is not being recovered as metal or metal component).

---

<sup>17</sup> It should be mentioned, that the expected lifetimes of solar cells should be at least one or two decades.

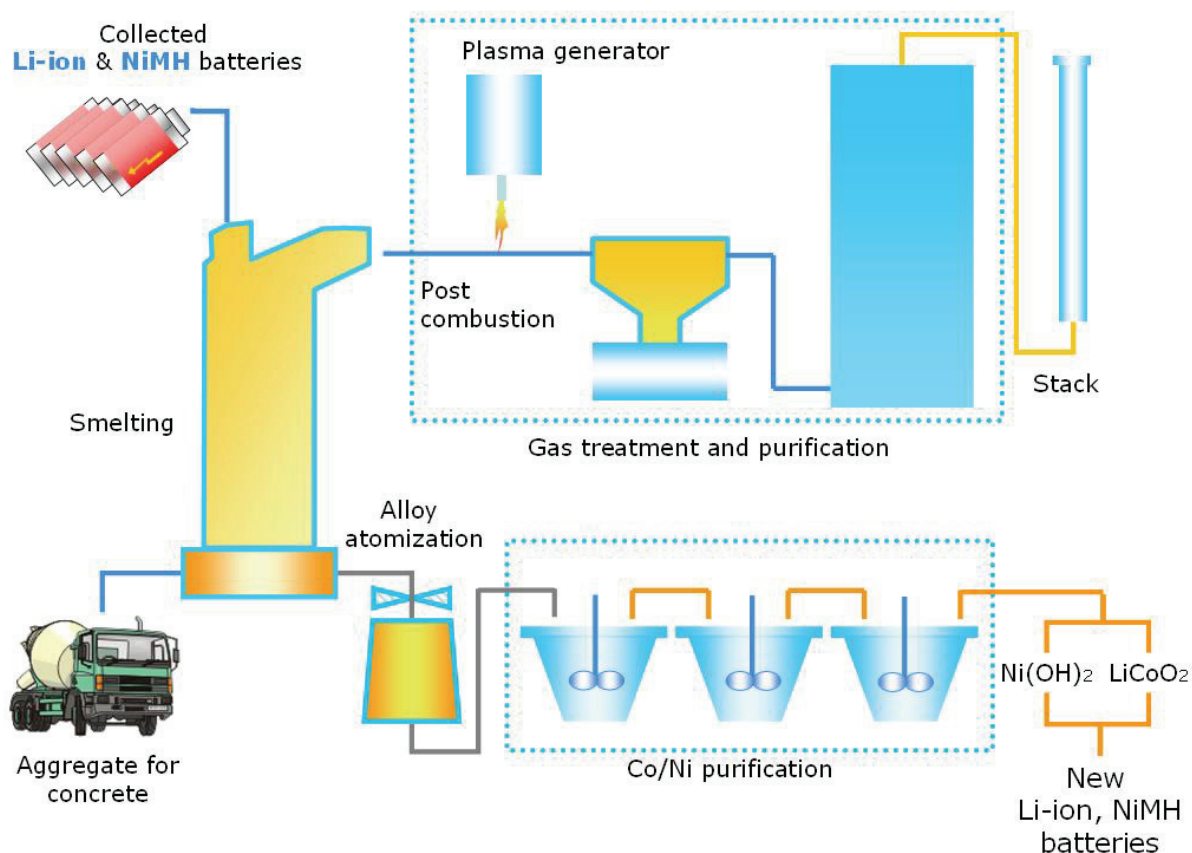


Figure 5.4: Material flows and main process units of Umicore’s battery recycling process (by courtesy of Umicore Precious Metals Refining)

Applications of critical metals in the chemical industry like organic catalyst residues – for example, spent rhodium homogeneous catalysts from oxo synthesis – were previously burned. In the process, considerable rhodium losses frequently occurred, so that modern processes precipitate PGMs from the organic suspension by means of certain metals, thus producing a PGM concentrate. [Karch 2001]. Another new development is the treatment of such residues with supercritical water [Collard 2001].

Diluted aqueous solutions of platinum group metals – for example, spent electroplating baths – are concentrated by evaporation and then channelled into the separation process or, if unwanted materials are present, processed in an alkaline solution by way of ion exchange, cementation or reduction.

With oil refining catalysts containing platinum, platinum/iridium and platinum/rhenium – for example, from reforming or isomerization processes – the supporting material mostly consists of  $\gamma$ -alumina, which can be dissolved in special reactors by means of NaOH or  $H_2SO_4$ . Besides inert impurities, platinum and iridium remain in the form of slimy concentrates. If rhenium is present, this is dissolved with the aluminium oxide and is recovered by means of anion exchangers [Grehl 2002, Hagelüken 1999]. The next figure

shows the very efficient recycling situation for oil refining catalysts in Germany [GFMS 2005]. Recycling quotas (blue streams) of about 97% could be achieved. These excellent results are not limited to developed countries like Germany. It is a good example that the recycling of precious metals from large industrial applications like oil refineries is much easier compared to consumer applications like EEE goods (dissipative applications).

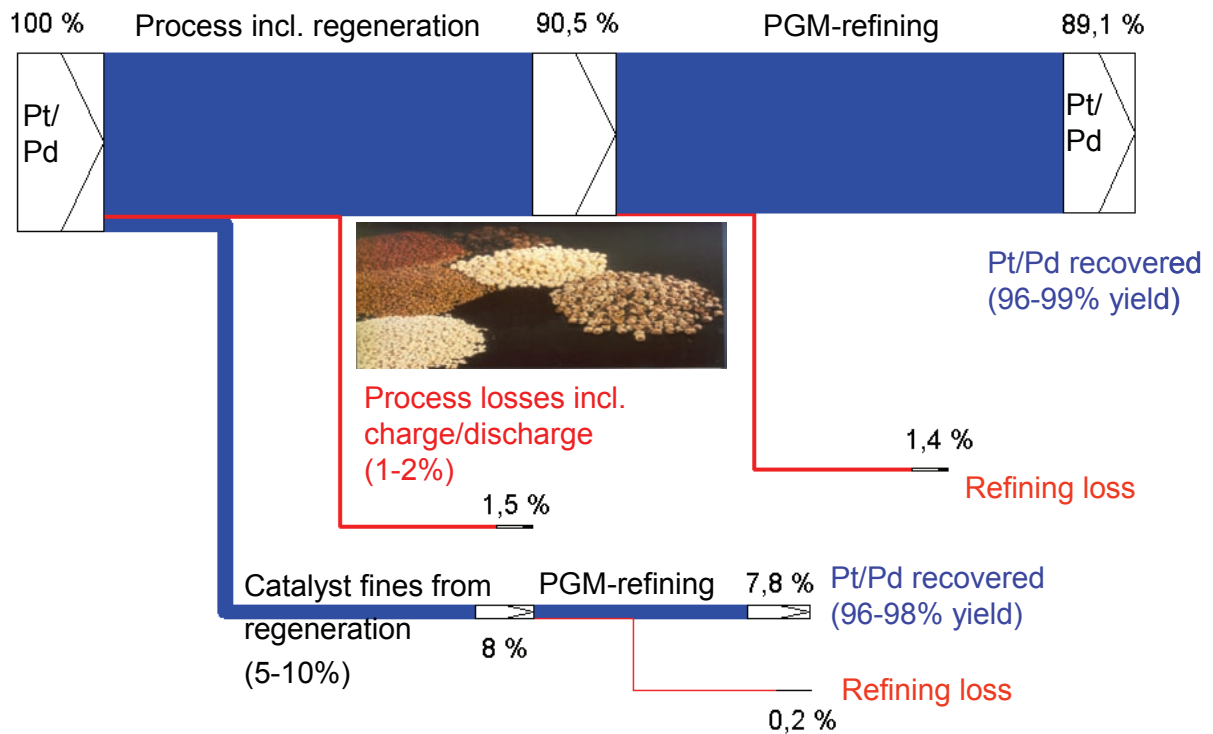


Figure 5.5: Materials flow of platinum/palladium in refinery catalysts in Germany (all percentage data relates to 100% input flow)

Platinum group metals, and alloys of such that are recycled, are frequently treated directly in a dissolving process, with larger elements being first crushed to speed up dissolution. These include catalyst gauzes, plungers, stirrers and bushings from the glass industry, thermo-electric couples, laboratory equipment etc. With shares of more than 20% iridium or 30% rhodium, the rate of dissolution is very slow. If expensive dissolution in fused salt is to be avoided, highly refractory PGM bullion material can be melted down together with non-precious metals such as copper, aluminium, iron and zinc, and the non-precious metals subsequently can be dissolved out of the alloy with acids. There remains a residue of finely dispersive precious metal ("blacks"), which generally dissolves easily. In the processing of common platinum/rhodium alloys, final separation of both metals is in some cases not necessary. In the case of scrap material with just surface contamination, surface leaching with acids can suffice, with complicated hydrometallurgical refining being avoided [Renner 1992, EM TB 2001].

In the glass industry, with the exception of fibreglass nozzles, an alloy consisting of 95% platinum and 5% rhodium is generally used [Gölitzer 2001]. Glass furnaces are built of

ceramic refractory bricks. Extremely high temperatures and, in part, highly aggressive liquid glass require the use of stirrers made of PGM alloys. To protect the brick lining of the furnace, and to protect glass from impurities from the brick lining, furnaces are partly or wholly lined with thin sheets of PGM alloys. Glass passes through several furnaces during its manufacture. Respective feeder systems, as well as plungers, draw-off funnels and drip rings are made of platinum or platinum-rhodium alloys [EM TB 1995]. It has to be mentioned that the mass products of sheet glass and container glass have no relevance for PGMs.

Companies offer the global glass industry a complete service from planning to the recycling of PGM elements, which is commonly utilized by glass manufacturers. For instance, manufacturers such as Heraeus and Umicore offer this service under the term "Precious metal Management" [Heraeus 2002] and "Life Cycle Management" [Gölitzer 2001]. In glass production processes, PGMs are worn off the materials. A proportion of these PGMs passes into the product, leaving the rest to concentrate in the brick lining of the furnace. Through direct product recycling (for example, the removal of a stirrer) and PGM recovery from the brick lining of the furnace, around 98% of inputted quantities of PGMs are recovered (see next figure).

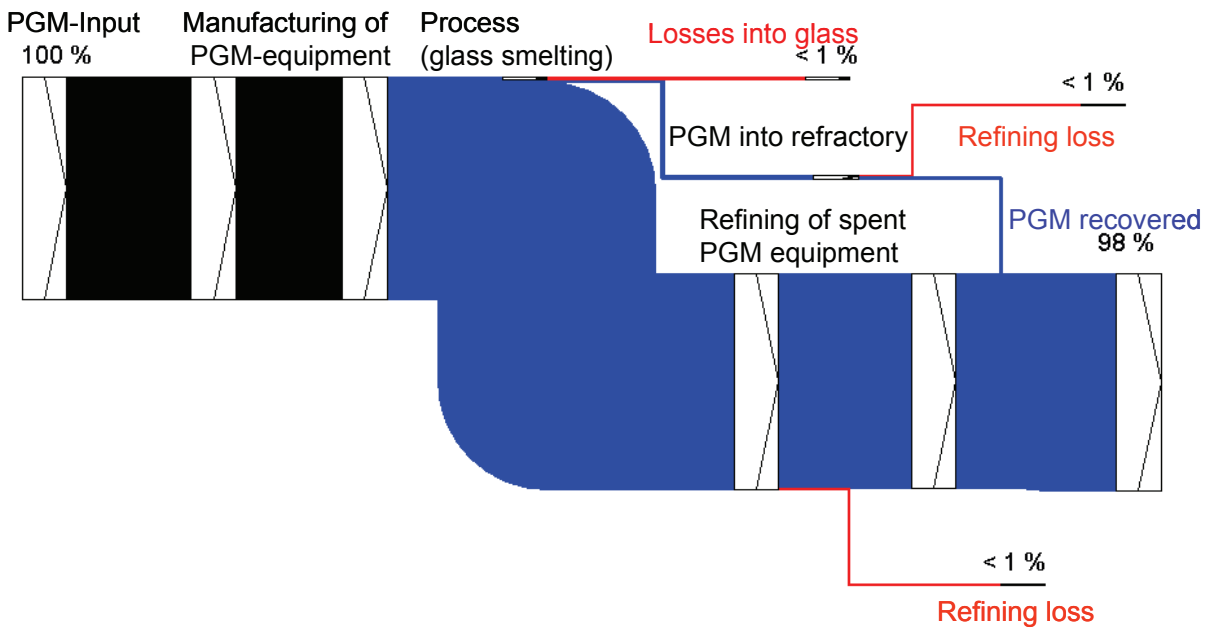


Figure 5.6: Materials flow of PGMs in the glass industry [GFMS 2005]

The short overview about current recycling technologies has shown that a couple of interesting technologies and real working plants are already available for the recycling of many critical metals. In some cases the developments are quite or even brand new and there is a need for further developments in this field in the near future in order to reduce the dependencies and the risks from primary metals production.

Nevertheless in the next sub-chapter the important issue of recycling infrastructure is addressed. This issue is very crucial, because the recycling plant with the best technology is almost useless if the plant suffers from an underemployed capacity.



## 5.2 Recycling infrastructure for critical metals

As an example in the next figure the recycling chain for automotive catalysts is performed. As mentioned above these post-consumer materials are important regarding the critical metals platinum, palladium and rhodium. Furthermore it could be stated that post-consumer automotive catalysts are quite uncomplicated materials compared with others like e-scrap, rechargeable batteries etc. Nevertheless the illustrated recycling chain gives an idea about possible weak points, which could cause severe total losses of platinum group metals.

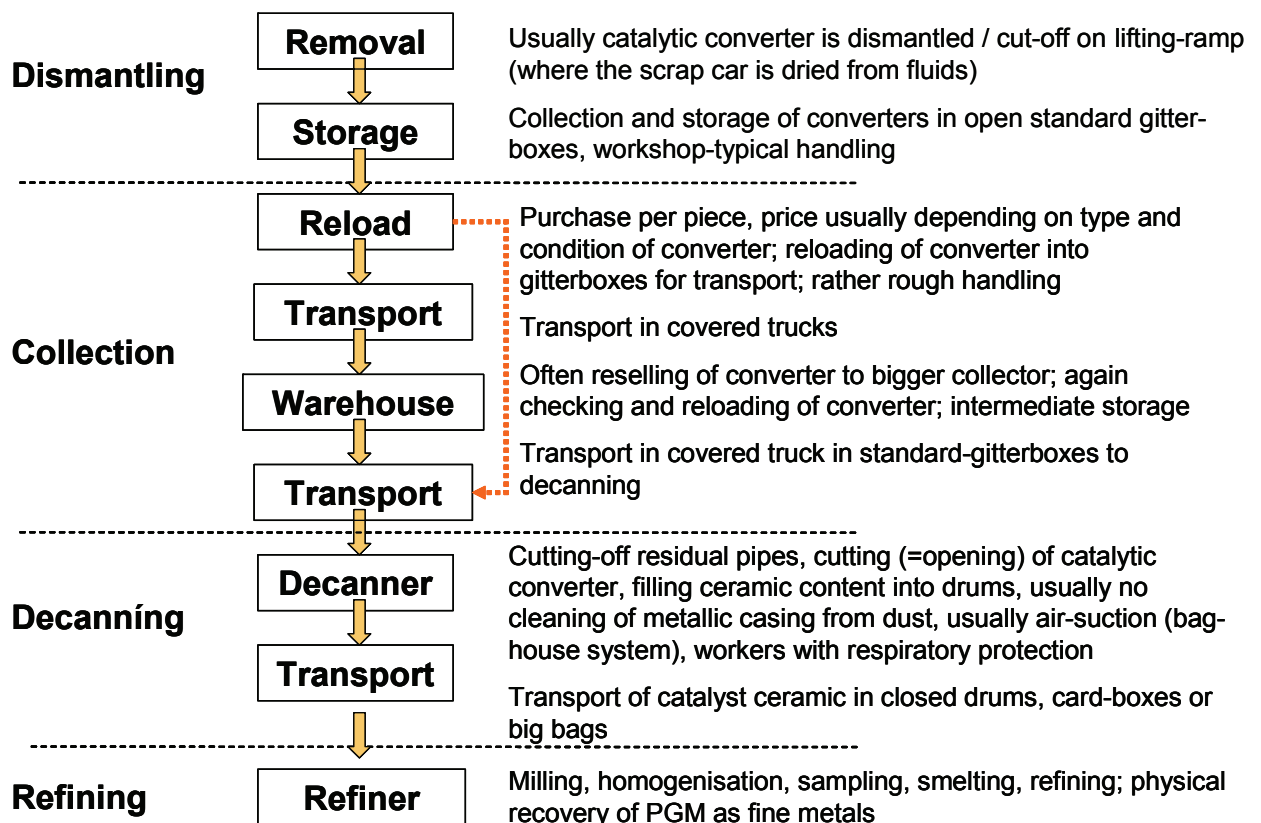


Figure 5.7: Recycling chain for automotive catalysts from scrapped cars [GFMS 2005]

One problem could be the non-appropriate handling during transport (open boxes) and transfers steps. The valuable precious metals are located on the surface of the shock-sensitive ceramic. So, diffuse losses could occur in the case of non-sensitive handling by non-professional actors. Furthermore the de-canning step (separation of the metallic casing from the ceramic which contents the precious metals) needs appropriate facilities equipped with modern dust collection systems to avoid total losses of the precious metals through the air. If good housekeeping rules are violated or dismantling takes place in 'backyards' in the grey market zones, serious losses of the desired critical metals are very probably. [GFMS

2005]. The ELV<sup>18</sup> has set clear rules for the handling of automotive catalysts in the EU and in 2007 28 t platinum and 31 t palladium are recovered from automotive catalysts in a global scale (almost 15% of the global mining production). [JM 2008a] But despite this pleasant development it has to be underlined that even in the EU (especially in the new member states) the collection systems are not perfect at all. But far more concern has to be taken on to the fact, that via used vehicles (transport via seaports or highways) serious amounts of automotive catalysts leave developed countries with legislation systems like in the EU. In Germany, for instance, about 80% of the de-registered passenger cars leave the country. Many of them to other EU states like Poland. But a large number of cars have the destination Africa, Middle East etc. Because of the fundamental lack of take-back and collection systems for post-consumer materials like automotive catalysts in many of the destination countries, bad road conditions and lack of technical maintenance (damage of the catalysts), the total loss of increasing amount of platinum group metals is likely. [Buchert et al. 2007] This is backed by field studies in Africa. According to an investigation carried out by staff of the Massachusetts Institute of Technology together with Swedish and Ghanaian researchers, increased concentrations of platinum were measured in road dust in Accra, Ghana. [Kylander 2003]

Concerning the current recycling infrastructure for other types of pre- and post-consumer scraps which are relevant within the focus of the study, the following short statements can be made:

- Industrial catalysts: mature recycling infrastructure systems all over the world realized; the suppliers of the catalysts are very often also the institutions for the recycling of the containing special and precious metals,
- Photovoltaic: recycling infrastructure for pre-consumer recycling are initiated or improved in the last years; post-consumer recycling has to be developed in the next years in Europe and world wide
- Batteries: collection systems are initiated since a couple of years in Europe, further improvements could be expected due to the collection and recycling quotas of the European Battery Directive<sup>19</sup>; serious lack of recycling infrastructure in developing countries has to be addressed in the future,
- EEE applications: recycling infrastructure in Europe was developed in the last years, but further progress is necessary to address an optimized recycling of the metals despite the very heterogeneous applications (cell phones, TVs, note books, etc.); recycling infrastructure in emerging economies and developing countries are a very crucial challenge due to an almost total lack of basic collection and infrastructure systems.

---

<sup>18</sup> ELV = End of life vehicles, Directive 2000/53/EC of the European Parliament and of the Council - September 2000

<sup>19</sup> Directive 91/157/EEC on batteries and accumulators and waste batteries and accumulators and repealing of the European Parliament and of the Council – June 2006

The details of the required recycling infrastructure depend mainly on the types of products and the applications. In the case of batteries for instance separations steps before entering the metallurgical processes are not necessary (except large batteries for hybrid electric vehicles for which a dismantling of the casing makes sense). In the case of EEE, a separation of the different main types of EEE (large consumer goods etc.) are common as well as manual first separation steps of main components (e.g. separation of cathode ray tubes from TVs).

In chapter 0 “Preconditions for an optimized recycling of critical metals” important steps for further improvements of the international recycling chains are listed in order to optimize the recycling of critical metals.

## 6 Characteristics 'critical metals'

### 6.1 Selected metals in EEE technologies

#### 6.1.1 Tantalum (Ta) – characteristics

**Global reserves:** The U.S. Geological Survey estimates the worldwide reserves of tantalum to be around 130,000 t in 2007.

**Global mining and regional concentration:** The annual production of primary tantalum is at about 1,400 t [USGS 2008]. Australian mines deliver approximately 60% of the global raw tantalum material on world markets; followed by Brazil (17%) and Canada (5%) [USGS 2008 and Schwela 2007]<sup>20</sup>.

**Resource base:** Tantalum occurs as oxides in different ratios coupled with Niobium oxides in earth crust. Examples for tantalum and niobium containing minerals are tantalite, microlite, wodginite and coltan (or columbite, see footnote).

**Global current demand:** The current demand for tantalum can be regarded as slightly lower to the magnitude of supply. Even a growing demand can be satisfied through supply [Hagelüken 2008 and Meskers 2008]

**Current applications:** With about 60% of all applications the leading use of tantalum is in form of metal powder and wire in electronic capacitors [Wickens 2004 and Cunningham 2004]. All of these applications use the ability of tantalum to store and release electrical energy with high capacity-grades even in small sizes. 16% of total tantalum consumption refers to industrial applications using tantalum carbide's hardness for e.g. cutting-tools. Third mayor application (14%) of tantalum is in the air- and space technology in form of alloys. Turbines with tantalum-containing coatings (up to 15% Ta-containing) are extremely high-temperature resistant and durable [RWI 2007]. Super alloys for airplane turbines cause less fuel demand and less greenhouse gas emissions accordingly. Therefore they are to be regarded as future sustainable technologies.

**Price development:** Prices for tantalum materials are not traded openly. Most raw materials are sold in long-term contracts. Estimations of prices occur through interviews with market trades [Schwela 2007 and Papp 2006]. Tantalum prices slightly grew from 72 USD/kg in

---

<sup>20</sup> Excursion Coltan: Beside the mentioned mayor mining countries, further tantalum mining sites are located in Central Africa (e.g. D.R. Congo, Mozambique and Rwanda). Especially the Democratic Republic of Congo (DRC) used to be the source of significant tonnages, but civil war between 1996 and 2008 dropped mining dramatically. The country gained notoriety in the media because of illegal Coltan mining under the control of opposing parties during the civil war [Behrendt 2007]. Coltan ores contain niobium and tantalum. The illegal Coltan mining lead also to social and environmental problems like for example deforestation and dangerous threat for the domestic gorilla population. Compared to the world scale of tantalum production, the mining capacities are less significant nowadays (D.R. Congo: about 5% of world production).

1989 during the last decade of the twentieth century. Then prices reached a dramatic peak in 2001, when 1 kilogram of tantalum cost 600 USD. Afterwards prices dropped again far below the mark of 100 USD/kg and returned increasing slightly till around 100 USD/kg [USGS 2007].

**Global demand development:** Consumption of tantalum grew beside two peaks in 2000 and 2006 more or less continuously. Increasing demand for EEE technologies can be seen as the mayor driving force for this process. For example the introduction of completely new applications like cell phones pushed the need for electronic capacitors in huge numbers – in the year 2006 1,000 Mio cell phones were sold worldwide [Hagelüken 2007]

**Forecast demand growth rates:** The RWI study [RWI 2007] forecasts an ongoing growth in tantalum demand. This will lead to a total plus in demand of 200% from 2004 until 2025. The total growth rate of 200% is similar to an annual growth rate of 5.3% in the same period. These rates include an increasing recycling rate from today 10% to 20% in 2025 (mainly from pre-consumer scrap).

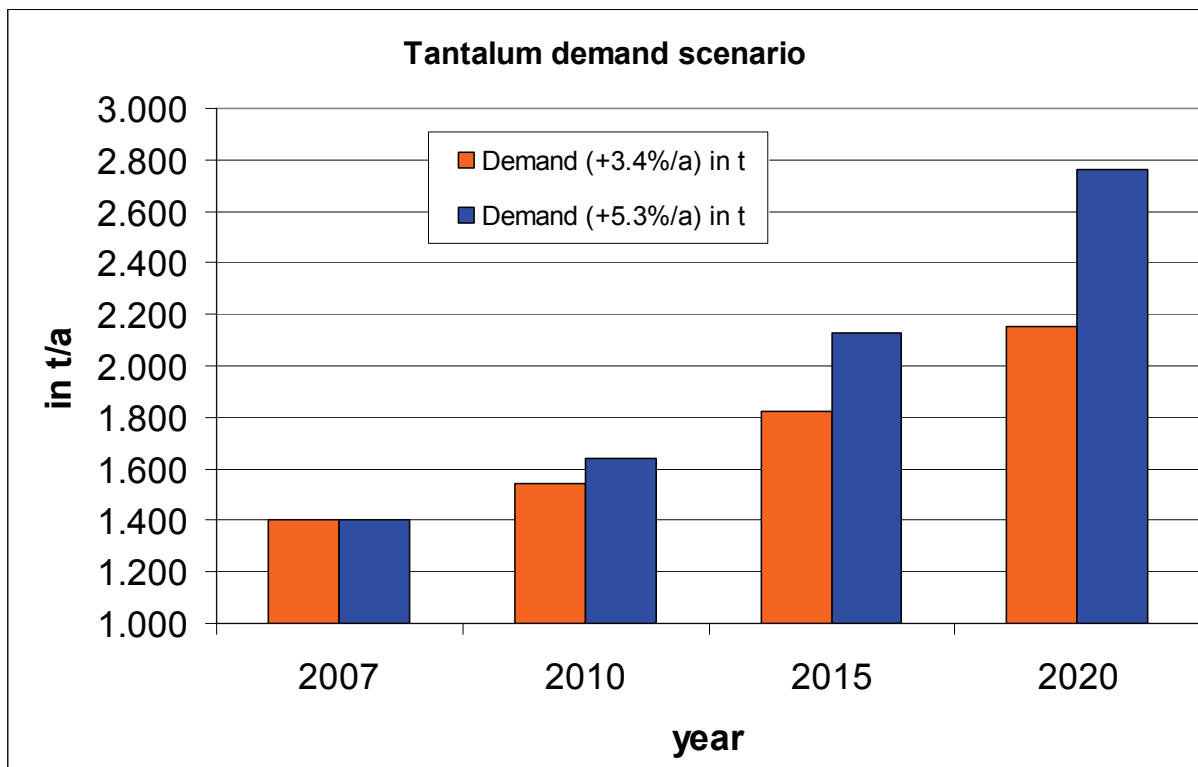


Figure 6.1: Tantalum demand scenarios, calculation Öko-Institut based on RWI growth forecast

Figure 6.1 shows the future tantalum demand adjusted to the regarded time line of this report. The blue column shows the total annual tantalum demand until 2020 based on a growth rate of 5.3%/a, like RWI suggests. The orange column gives a comparison for a more moderate development in Ta-demand from 3.4%/a. Both scenarios deliver a remarkable increase of the upcoming global tantalum demand until 2020.

**Forecast upcoming applications:** In the field of space and aircraft industry no mayor technical substitutes are seen. The engineering, testing and implementing of alloy types in airplanes lasts for years. Once a material is established it is economically worthwhile to proceed with it. The introduction of new materials in this field demands at lot of time and money.

Particularly EEE applications will be the main driver in the field of upcoming application. Still the trend towards smaller and high-performing applications is widely exhibited. Substitutes for tantalum in electronic devices do exist, but they come along with a lower performance.

**Current pre-consumer recycling:** Tantalum recycling in the pre-consumer phase during manufacture of Ta-containing electronic components, cemented carbide and super alloy is common. New scrap materials reclaimed at manufacturing plants producing tantalum-related electronic components are a major source of tantalum supply and delivered back to tantalum processors for recycling. Scrap recycling generated within the various segments of the tantalum industry accounts for about 20 to 25% of the total input each year [TIC 2008].

**Current post-consumer recycling:** Most of old scrap is recycled in the form of tantalum-bearing cemented carbide and super alloys. Jet engines are estimated to have a 20 year life span; discarded or obsolete parts can be recycled to the same alloy type or downgraded to applications with lower requirements [Cunningham 2004]. Recycling from discarded tantalum-containing electronic equipment has not been developed to a significant degree. Ongoing miniaturization of electrical conductors in electronic devices leads to dissipative problems. Each conductor contains less tantalum, but the whole number of produced conductors increases constantly. A major source for old tantalum-bearing scrap is seen in here, collection and recovery is economically difficult.

Technically it's problematic to recover tantalum from old scrap (low Tantalum concentrations). Due to chemical characteristics Ta oxidizes easily and moves during pyro-metallurgical processes into the slag phases [Hagelüken 2008].

**Potential pre-consumer recycling:** Beside efficiency enhancements, no further potentials are actually seen.

**Potential post-consumer recycling:** Improvements regarding the above-mentioned technical problems would open up new resources. The dissipative problem regarding tantalum in post-consumer e-scrap and its chemical nature remains a crucial challenge for further research and development.

**Specific conclusion for Tantalum:**

- I. Recycling technical problem concerning post-consumer e-scrap (cell-phones etc.), tantalum oxidizes easily and moves into slag phases.
- II. Applications in EEE devices very dissipative, recovery therefore technically and economically difficult.
- III. With a short and mid term perspective, tantalum supply will be able to satisfy demand [Hagelüken 2008]



Figure 6.2: Indium pearls (photo by courtesy of Umicore Precious Metals Refining)

### 6.1.2 Indium (In) - characteristics

**Global reserves:** The U.S. Geological Survey estimates the world indium reserves to be at 11,000 t in 2007.

**Global mining and regional concentration:** The world mining production adds up to 610 t of primary Indium [Tolcin 2008 and Metal Pages 2008]. Chinese mines convey 50 % of world's primary indium, followed by Canada (15%) and Japan (18%); which has no natural indium reserves but a well developed recycling system [Jorgenson 2005 and Tolcin 2008].

**Resource base:** Indium does not occur reclusively but as a minor metal in combination with other minerals like sphalerite, tin ores and zinc ores. The most widespread application to recover indium is during the zinc production process [Felix 2005]. Around 0,028 kg by-product indium can be recovered from 1 t zinc ore [Jorgenson 2005].

**Global current demand:** The current indium demand is comparable with the indium supply: 610 t primary indium plus ~600 t secondary indium from recycling [Metal Pages 2008]

**Current applications:** By far, the most important application of indium is in the consumer industry (85%). Thin films made out of Indium-Tin-Oxide (ITO) are mainly used for liquid crystal displays (LCD) how they are applied in monitors, televisions, notebooks and cell phone displays. Secondly with a percentage of 8% indium is applied for alloys and solders.

Indium containing alloys show a low melting-point and are therefore used to as fuses and temperature indicators. Solders which contain indium have low crack propagation and improve resistance to tiredness. Thirdly (5%) intermetallic compounds of indium find application as semiconductors [Metal Pages 2008, Tolcin 2006, Felix 2005 and Jorgenson 2005]. Indium in solar cells is a relatively new application with strong growth potential.

**Price development:** Till end of 2002 indium prices slightly decreased (around 100 USD/kg) due to the expansion of production in China. During the following strong growth of ITO demand attributed to the technical changeover towards LCD applications, indium prices rose between 2003 and 2006 to 900 USD/kg and remain actually at high level of about 500 USD/kg [Van den Broeck 2008, Metal Pages 2008 and O'Neill 2004].

**Global demand development:** End use of indium grew continuously over the last 20 years

**Forecast demand growth rates:** The market for LCD applications is still growing rapidly. Alone the television market is expected to grow 24% between 2007 and 2012 and will then contain LCD shipments from 106.2 million units [Metal Pages 2008 and Tolcin 2006]. Here ITO demand is also driven through the tendency towards bigger screen sizes which causes the need for more ITO per unit.

As mentioned above, indium-containing thin film applications in the photovoltaic industry is about to push demand further on. Traditionally, solar cell modules use wafer-based crystalline silicon technology. Beside this, new technologies are entering the market, enabling cost reduction in the production process [Jäger-Waldau 2007]. One of the new technologies is CIGS (copper indium gallium selenide) thin film modules. Installed global solar capacity is estimated to grow at the rate of 30 – 35% each year which will lead to 120–130 t annual consumption of primary indium in 2010 [Metal Pages 2008].



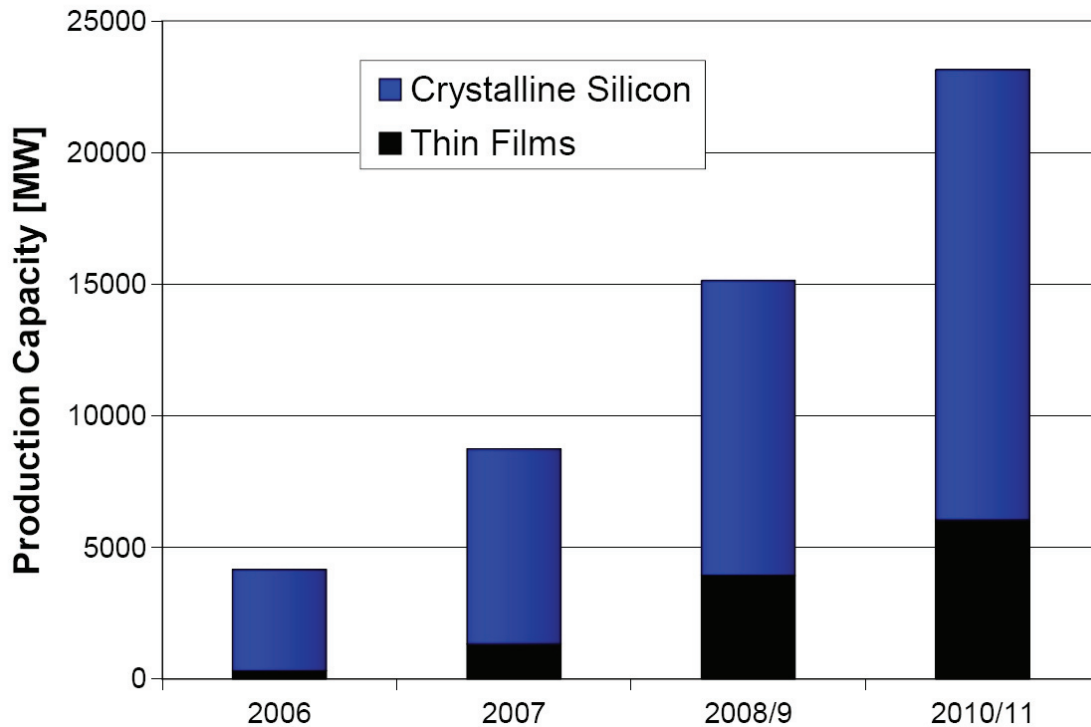


Figure 6.3: PV Production Capacities 2006 and forecast (Source: Jäger-Waldau 2007)

Figure 6.3 shows the actual and planned production capacities for the worldwide photovoltaic industry. Clearly visible is the growing use of thin film cells in the PV industry. It must be pointed out that Indium is not the only compound thin films are made of. Therefore, the use of other minor metals like e.g. tellurium (see Chap. 6.2.2) is also displayed in the black column of Figure 6.3.

Figure 6.4 shows the future indium demand adjusted to the regarded time line of this report. The orange column shows the total annual indium demand until 2020 based on a growth rate of 2.5%/a. The blue (+5%/a), green (+10%/a) and brown (+20%/a) columns give a comparison for an even stronger development in In-demand. Taken the recent developments and innovative applications for Indium into account, Öko-Institut suggests the range between the blue (+5 %/a) and green scenario (+10 %/a) to be the most realistic scenarios.

**Forecast upcoming applications:** In the field of display technologies new applications could push further demand for ITO products. So-called Organic Light Emitting Diodes (OLED) are regarded as highly innovative and mark the next generation of flat panel displays. Simplified, it is an indium-containing thin film applied on a polymer substance. Advantages of this technology are a higher flexibility and the missing of background illumination (power efficiency).

But not only techniques to increase In-demand are in discussion, possible substitutes for indium is also circulating. Japanese electronics material makers consider zinc oxide as an alternative for indium. This would reduce production of thin film coating used for flat panel displays and solar cells [Platts 2008].

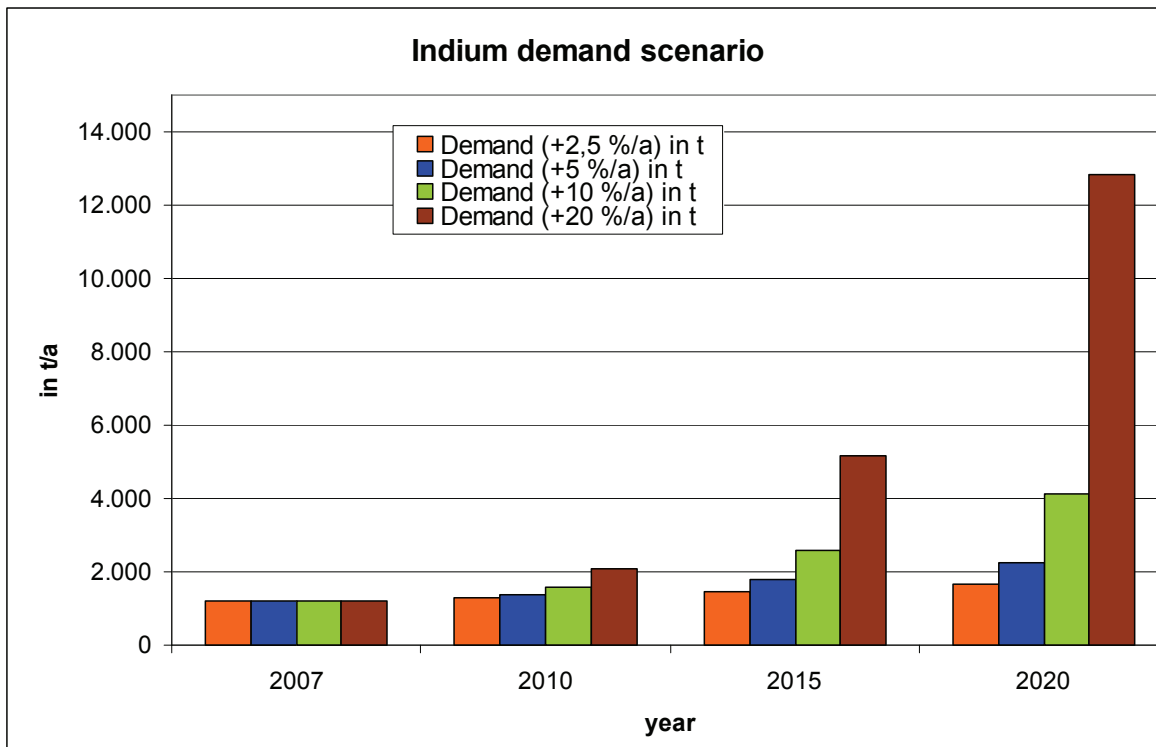


Figure 6.4: Indium demand scenarios, calculation Öko-Institut

**Current pre-consumer recycling:** The process how ITO is put as a thin-film coating onto a substrate is called ‘sputtering’. It is a highly inefficient method; only approx. 15% of an ITO sputtering target is deposited onto the substrate, the remainder is scrap. This indicates the potential amount of pre-consumer scrap accumulating at the production sites. Japan and South Korea as the major producers of LCD monitors and televisions dispose of well-developed recycling systems for new ITO scrap [Tolcin 2008].

**Current post-consumer recycling:** Recycling facilities for In-containing old scrap are only partly installed and initiated (e.g. in Belgium by Umicore). [Hagelüken 2008] The US Economy for instance runs without any recycling facilities for indium currently [National Academies 2008]. One problematic aspect is the lack of a focused collection and reconditioning of indium-containing products in many regions of the world. The dissipative and widespread applications of indium in EEE and solar cells mean a challenge regarding recycling logistics and the development of a suitable legal framework.

**Potential pre-consumer recycling:** Beside possible increments of recycling facilities, the amount of accrued new scrap will rise due to higher production figures.

**Potential post-consumer recycling:** Depending on worldwide collection systems and the extension of suitable recycling facilities, further potentials could be opened up. From a technical point of view the post-consumer recycling of indium from mixed scraps is less difficult compared with tantalum for instance.

### Specific conclusion for indium:

- I. The critical issue on the demand side is seen through increasing demand rates in all fields of application.
- II. Extraction of Indium on the mining side is dependent on development in zinc mining sector: could be a bottleneck.
- III. Currently recycling of indium from LCD and solar cells not sufficiently economic, but nevertheless important: e.g. funding systems (fee on new solar cells) or specific legal frameworks should be an issue for the future.
- IV. Short-term volatility of indium supply is considered as critical [National Academies 2008]

### 6.1.3 Ruthenium (Ru) – characteristics

**Global reserves:** The global reserves of ruthenium are estimated to 5,000 t<sup>21</sup>: Following Andersson the global reserves of ruthenium are mainly concentrated in South Africa with more than 95%. [Andersson 2001]

**Global mining and regional concentration:** Detailed figures about the mining of ruthenium are not available. [JM 2008a]. Nevertheless the figures of the global mining should be comparable with the global net demand (36 t in 2007). Due to lack of information about the mining figures exclusive data for the regional concentration of ruthenium mining are not available. In 2006 South Africa accounted for 71% of the 'other PGM' world production (sum of ruthenium, rhodium, osmium, iridium), followed by Russia with a 21% global share of the other PGM production. [George 2007] These figures give an idea about the regional concentration of the ruthenium mining, too.

**Resource base:** In natural deposits ruthenium is strictly coupled with other PGM (Pt, Pd, Rh, Ir) or as a by-product of nickel mining (in Russia and Canada). Typical PGM concentrations in ores range between 5 and 10 ppm. [GFMS 2005]

**Global current demand:** In 2007 the net demand (without recycling flows) of ruthenium amounts to 36 t. [JM 2008a]

**Share of current applications:** The most relevant applications for ruthenium could be stated for electronics (particularly for the manufacturing of perpendicular magnetic recording – PMR – hard disks) with a share of 75% of the global net demand in 2007. Further fields for ruthenium are the electrochemical (10%) and the chemical (10%) sector. [JM 2008a]

**Price development (USD/kg):** In the years 2000-2005 the ruthenium price showed an up - and - down course between 1,600-6,400 USD/kg. In the years 2006/2007 the ruthenium price raised until 28,000 USD/kg, triggered by heavy purchasing of ruthenium by the

---

<sup>21</sup> <http://www.lenntech.com/Periodic-chart-elements/Ru-en.htm> The sum of the global reserves for the six platinum group metals (PGM) platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os) are estimated to 71,000 t. [George 2008]

electronics industry and then dropped to 13,300 USD/kg in December 2007, caused by huge amounts of recycling ruthenium on the market from sputtering targets. [JM 2008a]

**Global demand development (net):** The global ruthenium demand (net) has shown a dramatic increase since 2002 (13 t). After 21 t in 2004 the ruthenium demand has been more than tripled until 2006 (52 t). The sharp increase of the global ruthenium demand was mainly occurred by the recent success story of computer hard disks based on perpendicular magnetic recording – PMR – technology. Thin ruthenium layers are essential for this new technology with rapid growing market shares. [JM 2007] In 2007 the global ruthenium (net) demand dropped to 36 t due to a push for new scrap recycling activities (recycling of new scrap from the sputter target and hard disk production). This shows that ruthenium recycling flows - pre-consumer flows - begin to play a role on the markets.

**Forecast demand growth rates:** Despite the recent drop in ruthenium net demand (without recycling flows) experts expect a demand increase in the future. [Loferski 2008]

As external forecasts for ruthenium demand are not available, Öko-Institut has calculated two demand scenarios (net) for ruthenium. The conservative scenario (orange bar) is based on a moderate annual growth of 3%. Increase in existing and slight increase in up-coming applications are assumed for this scenario as well as an increasing influence of per-consumer and post-consumer recycling. In 2020 the top level net demand figure of 2006 (52t) would be achieved again. In the other scenario (blue bar) a more dramatic increase of the demand of ruthenium in existing and upcoming applications is supposed. Despite the increasing relevance of recycling flows the net demand of ruthenium would increase with an annual rate of 6% until 2020. This would lead to a doubling of the ruthenium net demand until 2020 and could be considered as a serious challenge for the PGM mining industry.

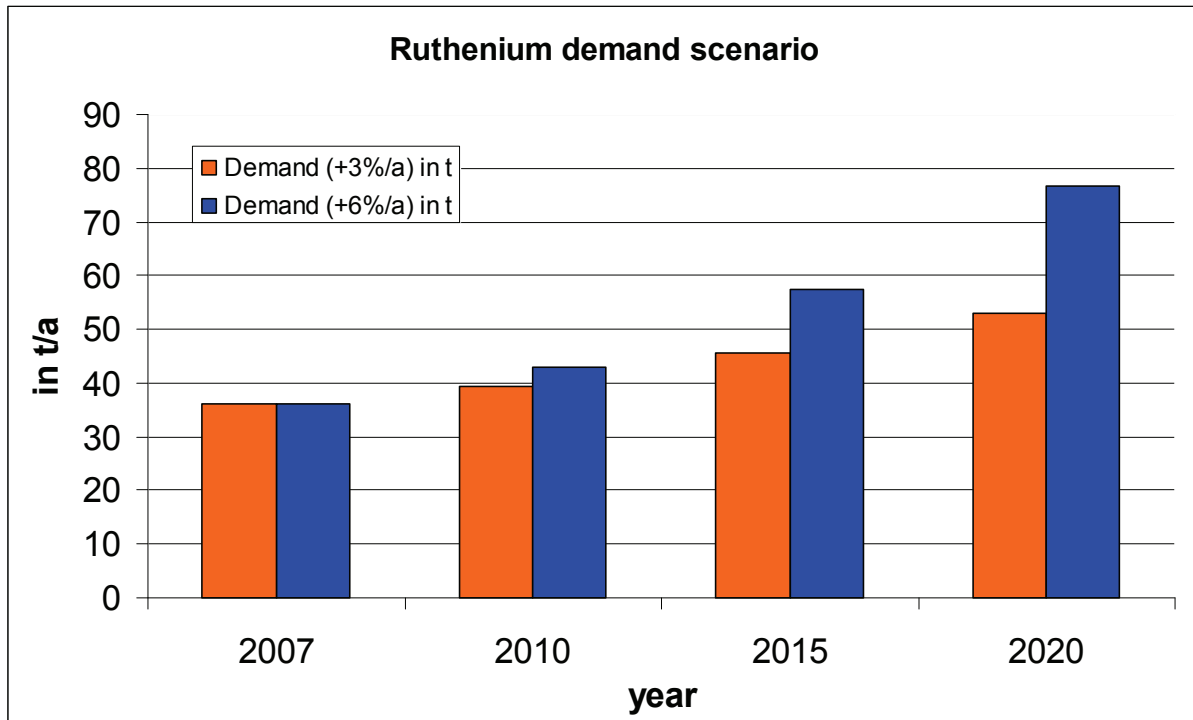


Figure 6.5: Ruthenium demand (net) scenarios based on Öko-Institut calculations.

**Forecast upcoming applications:** For ruthenium two new potential applications are discussed. [IPA 2008]. The use of ruthenium in alloys for aircraft turbine blades is in a prototype state (reduction of fuel demand and CO<sub>2</sub> emissions!). Due to the high melting points and high temperature stability of these alloys the efficiency rate regarding the demand on aircraft fuels could be enhanced. Another interesting example is the use of ruthenium in certain catalysts applications in modern gas-to-liquid technology to generate various sulphur-free, high quality fuels. [IPA 2008]

**Current pre-consumer recycling:** Pre-consumer recycling of ruthenium is becoming common since about two years. As an answer on the rapid growing meaning of ruthenium in the hard disk sector which is combined with large volumes of production scrap in manufacturing of the sputter targets (large amount of ruthenium containing production scraps) as well as the hard disks themselves the industry has now installed important capacities for the refining of ruthenium from these pre-consumer sources. [JM 2008a]

**Current post-consumer recycling:** Post-consumer recycling of ruthenium is already initiated, but has just played a minor role in the past due to small total amounts of ruthenium in products like EEE applications and catalysts. Therefore figures about post-consumer ruthenium are not available yet. Nevertheless Umicore in Belgium announces capacities to the refining of five PGM including ruthenium. The ruthenium is isolated in the Umicore plant in Hoboken from post-consumer scrap after passing a smelting process (integrated smelter) from which the ruthenium and other precious metals are concentrated in the copper-bullion. The precious metals are concentrated as a residue by a leaching process of the copper and then further separated in different steps in the precious metals refinery. [Umicore 2008]

The Norddeutsche Raffinerie AG in Germany (Europe's largest copper producer) has capacities for the winning of precious metals from secondary products like e-scrap in Lünen (copper and precious metals production from secondary materials only) and Hamburg (scrap as well as primary copper materials) as valuable by-products of the cathode copper production. [NA 2008]

**Potential pre-consumer recycling:** Further potentials of ruthenium pre-consumer recycling are expectable due to high ruthenium prices and large new scrap volumes.

**Potential post-consumer recycling:** Also further potentials of secondary ruthenium from post-consumer electronic applications could be expected for the future. Ruthenium is very suitable for recycling and different refining plants are equipped these days with the process installations to separate precious metals like ruthenium from copper. So from a technological point of view the situation for ruthenium recycling is satisfying, but due to the dissipative applications of ruthenium and the tremendous drain of e-scrap into developing countries the global take-back infrastructures will be the crucial challenges.

**Specific conclusion for ruthenium:**

- I. The critical issue on the supply is obviously the tremendous regional concentration of mining. The power supply problems in S.A. (most important primary ruthenium producer) will be an ongoing problem, but not a knock-out issue in the future.
- II. Ruthenium demand will probably increase remarkably until 2020 due to huge driving forces in the major application: electronics; new applications in aircraft turbines and catalyst sector could give the ruthenium demand a further push in the future.
- III. The appropriate collection and delivery of ruthenium containing post-consumer materials (e-scrap from computers etc.) to suitable refining plants (e.g. in Europe, Japan) from all over the world including developing countries remains a serious challenge.

## 6.2 Selected metals in photovoltaic technologies

### 6.2.1 Gallium (Ga) - characteristics

**Global reserves:** The U.S. Geological Survey estimates the worldwide reserves of gallium in bauxite to be more than 1 Mio t [Kramer 2008]<sup>22</sup>. The reserves in zinc ores are estimated at 6.500 t [Greber 2002]. However, the largest reserves of several million tons are in phosphate ores and coal with a low Ga-content of 0.01-0.1%.

**Global production and regional concentration:** The global production of primary gallium was about 80 t in 2006 [Kramer 2008]. The refinery was mainly done in China, Germany, Japan and Ukraine. The upstream processes mainly took place in other regions: The bauxite mining is concentrated in Australia (34%), Brazil (12%) and Guinea (11%) [BGR 2006]. The

---

<sup>22</sup> [Greber 2002] estimates 1.6 Mio t in bauxite reserves.

aluminium production is concentrated in China (32%), Russia (11%) and Canada (8%) [Bray 2008].

**Resource base:** Presently, almost all primary gallium is a by-product of bauxite processing, the remainder is produced from zinc processing residues [Kramer 2008]. The theoretical annual production of gallium is estimated at 4.000 t/a, if all bauxite from mining would also be used for the gallium production<sup>23</sup>.

**Global current demand:** There are no data on the current demand. However, the global production of refined gallium from primary production and recycling was about 103 t in 2006 [Kramer 2008]

**Share of current applications:** The U.S. Geological survey estimates for the U.S. market that more than 98% of the gallium is used in electronic components. Hereby, the major applications are integrated circuits (IC) in computers, telecommunication etc. (66%), optoelectronic devices (particularly LED, diodes and solar cells) (20%) and others (special alloys, high temperature applications, etc.) (14 %) [Kramer 2008].

**Price development:** After a decrease of the prices from the 1960's until the mid of the 1990's, the prices slightly rose again - with fluctuations and a peak in 2007 - from about 325 USD/kg in 1994 to 400-600 USD/kg in 2008. [Di Francesco Kramer 2007] [Asian metal 2008]

**Global demand development:** There are no figures for the worldwide demand, but there are data on the refined gallium production. The production almost continuously increased from 16 t in 1973 to 103 t (primary production and recycling) in 2007 [Di Francesco Kramer 2007] [Kramer 2008]

**Forecast demand growth rates:** The market for GaAs (Gallium-Arsenide) containing devices is estimated to increase annually about 7% within the next years [Kramer 2008]. For some major applications of gallium, there are even higher forecasts: The applications of LED's in lighting applications is expected to grow with 37% per year, and the LED in cell phone camera flashes is expected to have an annual growth rate of 23% within the next years [Kramer 2007]. The installed global solar capacity is estimated to grow at the rate of 30 - 35% each year [Metal Pages 2008] and should enhance the gallium demand accordingly. The demand for GaAs-devices in the U.S. defense sector is expected to increase by 9%/a. [Kramer 2007]

Based on these forecasts, two scenarios are shown in Figure 6.10. They show the range of the development of the Gallium demand for an annual growth rate of 5% (left bar in orange) and alternatively for a high growth rate of 10% (right bar in blue). The overall increase of the gallium demand until 2020 will be almost 100% (lower growth scenario) or even 250% in the case of the rapid growth scenario.

---

<sup>23</sup> Estimation of [Greber 2002] for 1986 and extrapolation by Öko-Institut for 2006

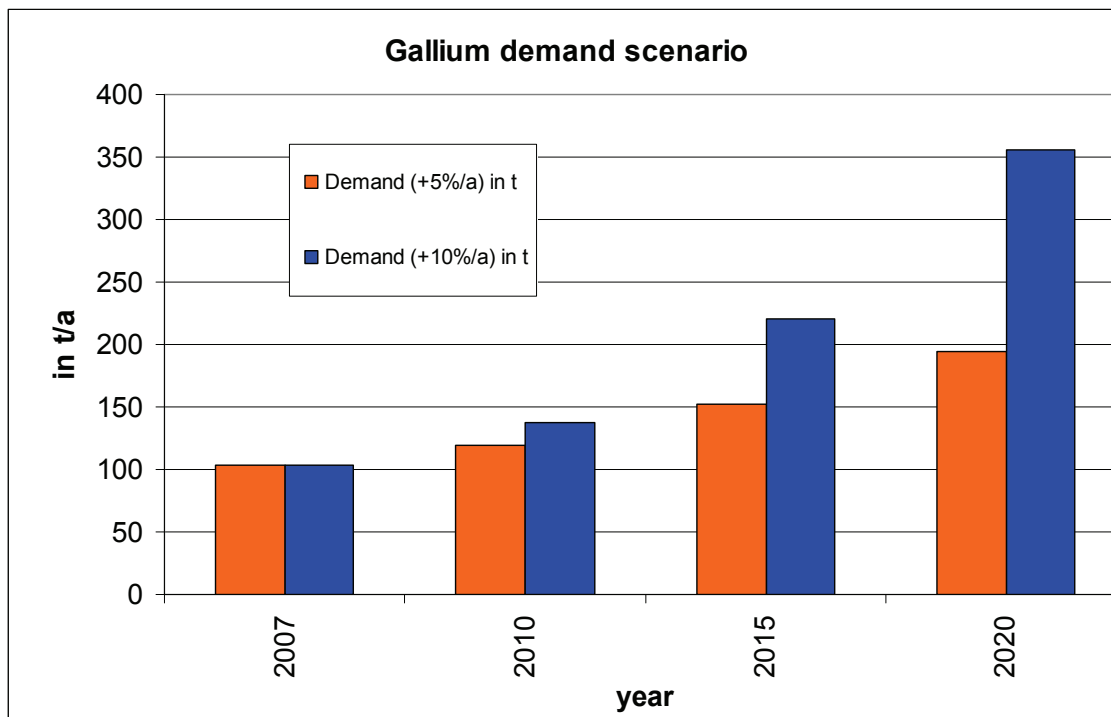


Figure 6.6: Gallium demand scenarios based on calculations from the Öko-Institut

**Forecast upcoming applications:** The main drivers of the future demand increase until 2020 will probably be the applications described above. The replacement of gallium in some applications, e.g. LED's, solar cells and transistors by other materials is also discussed. However, the U.S. National Research Council estimates that for around 40% of the gallium-applications, a substitution by other materials is difficult or impossible [National Academies 2008].

**Current pre-consumer recycling:** There are already high recycling capacities for gallium from production. The total recycling capacity worldwide is 78 t. This is quite high compared to a total primary production capacity of 184 t [Kramer 2008]. The recycling plants in Germany, Japan, UK and USA mainly recover gallium from new scrap from production [Kramer 2008] [Kramer 2007] [DOWA 2008] [RM 2008].

**Current post-consumer recycling:** Currently, no common post-consumer recycling is known.

**Potential pre-consumer recycling:** There might be an additional potential for a pre-consumer recycling, but there is already a very high pre-consumer recycling rate.

**Potential post-consumer recycling:** Potentials for a post-consumer recycling might be realized when the gallium input in recycling plants will rise and when gallium prices will deliver economic incentives. As almost all gallium applications are in the field of electronics the mostly promising recycling technology is the recovery of gallium in WEEE smelting plants, if they are able to extend their output range by gallium.



Hereby, it is to consider that gallium is mostly used in a very high dilution rate, which sets clear limits to high post-consumer recycling rates [Christen 2005].

**Special conclusion for Gallium:**

- I. Gallium belongs to the minor metals due to the small market and the small production capacities. The future demand will be determined by its use in electronics and photovoltaic. An accurate demand forecast is difficult due to the manifold applications, but an annual growth rate between 5 and 10% seems to be realistic.
- II. The main supply restrictions do not arise from the total reserves, but from the time span which is necessary to install further gallium production technologies at the bauxite and zinc processing plants.
- III. There are already large capacities for a pre-consumer recycling (about 40 % of the capacities for the primary production!).
- IV. The wide use of Gallium applications at high dilution rates impedes the installation of post-consumer recycling technologies. The recycling will only be possible in sophisticated WEEE smelting plants and requires an efficient electronic scrap collection system.

## 6.2.2 Tellurium (Te) - characteristics

**Global reserves:** The U.S Geological Survey estimates the reserves in copper deposits to be about 21,000 t [George 2008]. Beside this, there are primary tellurium deposits (known in China and Mexico), and the development of further tellurium resources from mining of associated minerals or sulfides might be possible<sup>24</sup> [NREL 1999].

**Global production and regional concentration:** Due to secrecy official data on the tellurium production are only available for few states. However, tellurium producers are situated in Belgium, Canada, China, Japan, the United States, the Commonwealth of Independent States, the former Soviet Union, Germany, Peru and the Philippines [Porter et al. 2007] [George 2007] [Knockaert 2005]. Experts estimate the current global production in 2007 at approximately 450 t/a [Van den Broeck 2008]. The theoretical maximum global production coupled with the actual copper production is estimated at 1.500 t<sup>25</sup> plus about 130 t from lead refining [NREL 1999].

More than half of the copper ore arises from Chile (39%), Peru (8%) and the USA (8%). A third of the global primary production of refined copper is coming from China, Chile and Japan.

---

<sup>24</sup> [NREL 1999] gives an extensive overview on potential worldwide tellurium deposits (solitary and coupled with other minerals or metals).

<sup>25</sup> Calculation by Öko-Institut for Te-production coupled with copper electrolysis. Basic assumptions: Cu-production by electrolytic refineries 17.4 Mio. t [ICGS 2007]; 0.085 kg Te per t Cu; equivalent to 0.4 pound Te per t refined Cu at a recovery rate of 50% according to [NREL 1999].

**Resource base:** About 90 % of all tellurium is produced from anode slimes collected from electrolytic copper refining together with selenium. The remainder is derived from lead processing and smelting of bismuth, copper and lead ores [George 2008].

**Global current demand:** There are no statistical data on the current demand available. However, the global demand of tellurium is estimated at around 450 t/a in 2007 [Van den Broeck 2008].

**Share of current applications:** The main applications are the use as alloying element in iron and nonferrous alloys (40%), the use in photovoltaic and electronics (in sum 40%) and the use in chemicals and catalysts (20%) [Van den Broeck 2008, Matos et al. 2005].

**Price development:** The price rose continuously over the last 30 years, however with partly high fluctuations. In 2008 the prices increased stronger than in the previous years and rose from 130 USD/kg in January up to 280 USD/kg in October [Crystal 2008].

**Global demand development:** There are no accurate data on the global demand development as some countries publish no data due to secrecy. The demand development in the United States shows a decrease in tellurium demand since the 1970's until 2001. The main reason is that the use of tellurium as metallurgical alloying element declined continuously over the last 30 years due to rising prices [George 2007]. Since 2006 the tellurium demand is increasing strongly because of high growth rates for tellurium in flash memory and in thin film cadmium-tellurium solar cells<sup>26</sup>. The flash memory based on tellurium can be rewritten and will not erase once power is turned off. The potential for this end-use could be dramatic despite the low tellurium concentration per unit, since almost all electronics have this type of memory [George 2007].

**Forecast demand growth rates:** The demand development is mainly influenced

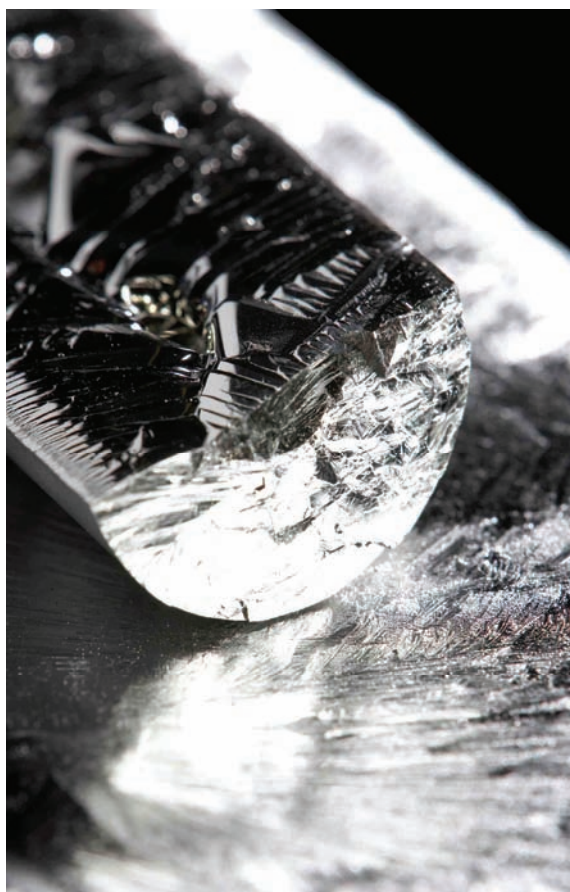


Figure 6.7: Tellurium (photo by courtesy of Umicore Precious Metals Refining)

---

<sup>26</sup> According to [Van den Broek 2008] and [Jäger-Waldau 2007] the growth rates for CdTe solar cells were tremendously high in the last two years, probably more than 50%/a.

by two contrary developments: Firstly, the decrease in traditional applications, such as alloys due to rising tellurium prices which caused a shift to substitutes, and secondly the high growth rates in tellurium consumption in solar cells (see footnote 18) and flash memories. The next figure shows two scenarios: One scenario (left bar in orange) shows a conservative estimation with a growth rate of 5%/a. The second scenario (right bar in blue) shows a scenario which has taken the high growth rates of the new tellurium applications into account. It is even thinkable that the growth rates will be much higher. But in this case, the demand will exceed the existing production capacities as well as the current theoretical production capacities within a few years.

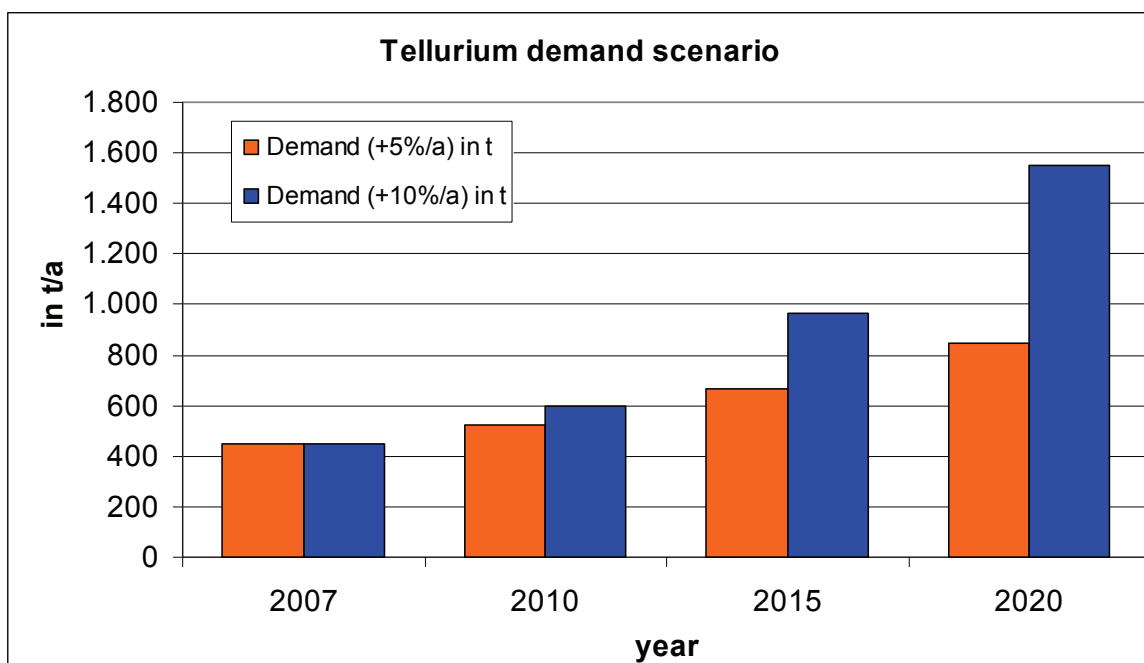


Figure 6.8: Tellurium demand scenarios based on calculations from the Öko-Institut

In the scenario with an annual growth of 10% the demand in 2020 exceeds the theoretical maximum tellurium supply, which is estimated for the case that all electrolytic refineries for copper also produce as by-product tellurium (see above).

**Forecast upcoming applications:** There are many smaller fields of applications, e.g. cooling, magnets, opto- and thermo-electronics et al. New applications might arise in these fields. However, it is to expect that the main demand-driving applications will remain the solar cells and the flash memories.

**Current pre-consumer recycling:** According to a life cycle analysis on the production of CdTe solar cells the material utilization rates of the deposition of CdS and CdTe range from 35-90%. The material loss is collected by filter systems. The recycling of the filter residues is feasible and economical and shall be practiced in large-scale production [Fthenakis 2004]. At the production of CdTe solar cells at First Solar, the waste streams are recycled [First Solar

2008a]. Furthermore there are recycling capacities for complete solar cells (see next paragraph).

**Current post-consumer recycling:** The company First Solar installed the first recycling plant for used thin film solar cells based on cadmium telluride in Germany [Euwid 2008] [First Solar 2008b]. There are also recycling capacities for tellurium from electronic scrap at UMICORE/Belgium and Dowa/Japan, which might be used if the plant input will actually contain tellurium, e.g. from flash memories now starting to enter the markets.

**Potential pre-consumer recycling:** There is probably a high potential for tellurium in electronics and solar cell production, which might be opened up soon due to supply restrictions and rising prices.

**Potential post-consumer recycling:** There is almost no potential for tellurium recovery from dissipative applications (e.g. alloys). However, there is a potential for tellurium recovery from electronic scrap, if the scrap is processed in appropriate smelting plants already having the ability to recover tellurium (see above). Precondition for this recycling route is an efficient electronic scrap collection.

**Special conclusion for tellurium:**

- I. A supply shortage might occur in the short term. The current production is estimated at 450 t/a. The theoretical production capacity from Cu- and Pb refining is estimated around 1.600 t [NREL 1999 and own calculations]. The demand might exceed the theoretical production capacities in a few years, if the current high demand growth will continue. The main driver for the high demand is the rapid market growth of cadmium telluride solar cells and telluride based flash memories.
- II. Options on the supply side for an increase in production are:
  - an increase of the recovery rate from Cu- and Pb-refining and other material flows,
  - the development of primary Te-deposits (known in China and Mexico) and
  - the development of new Te-resources, e.g. from mining of associated minerals or sulfides.
- III. In view of short-term supply restrictions and the environmental burden related to the opening of new mining activities the recycling plays a very important role. There are already recycling technologies for the recovery of tellurium from solar cells and electronic scrap available. However, their application requires an enhanced global electronic scrap and solar cell collection and treatment.
- IV. In view of the expected bottlenecks in the tellurium supply the research on adequate substitutes which are abundantly available is also a necessary task.

### 6.2.3 Germanium (Ge) - characteristics

**Global reserves:** Due to the fact that many Ge-related mining facts are proprietary, there is no authoritative forecast about the worldwide reserves of germanium available. U.S. Geological Survey estimates the U.S. germanium reserves to be at around 450t. The world

production of germanium is about 100-110t, including 35t secondary germanium from recycling processes. [Feltrin et al. 2008 and Smith 2008]

**Regional concentration of mining:** Corresponding to the uncertain database concerning global reserves, data about the current share of major producers are also to be regarded as uncertain. Major producers are: China, Canada, Chile and Belgium (due to recycling) [Butterman et al. 2005]. Some sources point out that China produces 80% of the global germanium supply [Rosenberg 2008]

**Resource base:** Germanium is classical by-product which can be extracted during the zinc/copper production through in form of flue dust. In some countries germanium was and still is recovered from the coal ash of electrical power plants [Lifton 2007].

**Global current demand:** The actual world demand for germanium is estimated to be at around 120-130t, which indicates that demand outstrips supply moderately [Bi 2006 and Rosenberg 2008]

**Share of current applications:** By far, the major use of germanium is in optical materials, representing about 50% of the world Ge-consumption. This branch can further be divided into the two sub-categories 'infrared optics' and 'fiber optics'. The allocation of Ge-demand among these categories changed repeatedly over the last 20 years. Actually infrared applications like night vision lenses - for e.g. luxury automotives - are taking with 30% of total demand the lead. Fiber optics – mainly fiber glass cables - played until 2000 a dominating role in the use of germanium. Since then, the use of the applications decreased to actually ca. 20% from the total Ge-consumption. Second major use of germanium is as a catalyst in the industrial production of polymers (mainly PET). This use requires about 30% of the world Ge-consumption [Scoyer et al. 2005; Butterman et al. 2005 and Bi 2006].

Germanium is also being applied in the photovoltaic industry in form of so called multi-junction solar cells. Compared to conventional single-junction silicon solar cells, higher efficiencies (up to twice as efficient) are performed through different thin film layers of photovoltaic materials based on a germanium substrate. Each layer captures a different part of the solar spectrum. Originally designed for the space industry, these cells also have a large potential for earthbound applications [Metal Pages 2008b]. Actually not among the major use of germanium, the solar applications segment represents a fast growing end-use market.

**Price development:** During the 1980's germanium prices have been more or less stable. Prices first set in motion during the 1990's: strong increase with a peak at around 2,000 USD/kg was followed by times of strongly decreasing prices. Since 2004, continuous growths lead to an actual price at around 1,500 USD/kg [Jorgenson 2001; [www.thebulliondesk.com](http://www.thebulliondesk.com)].

**Global demand development:** Germanium demand was driven through different tendencies over the last decades. At first, Ge-containing infrared devices have been a serious issue for the military sector (the U.S. built up strategic stockpiles of germanium). During the 1990's these kinds of applications decreased, but actually experience a renaissance. Similar with the demand for fiber optic cables; a peak in the mid 1990's was followed by a phase of decreasing demand. Summarizing, demand for germanium grew steadily.

**Forecast demand growth rates:** The RWI study [RWI 2007] forecasts an ongoing growth in germanium demand between 22% and 49%. Figure 6.9 shows the two estimated growth rates adjusted to the timeline of this report. A total growth rate of 22% is similar to an annual growth rate of 1.0% and is illustrated in the orange column of Figure 6.9. The blue column represents a total growth rate of 49% respectively 1.9% per annum. Both scenarios deliver an increase of the upcoming global demand until 2020 but remain - compared with metals like tantalum- in a moderate range. Although, in many fields new germanium containing applications are being described (see below).

On the supply side, the results of the growing Ge-demand can already been seen through increasing capacities on productions sites like the construction of new mines (e.g. in Tennessee USA), Ge-extraction from zinc slags in the Republic of Namibia or capacity enlargements in recycling plants (e.g. Umicore site in Oklahoma, USA) [Metal Pages 2008b]

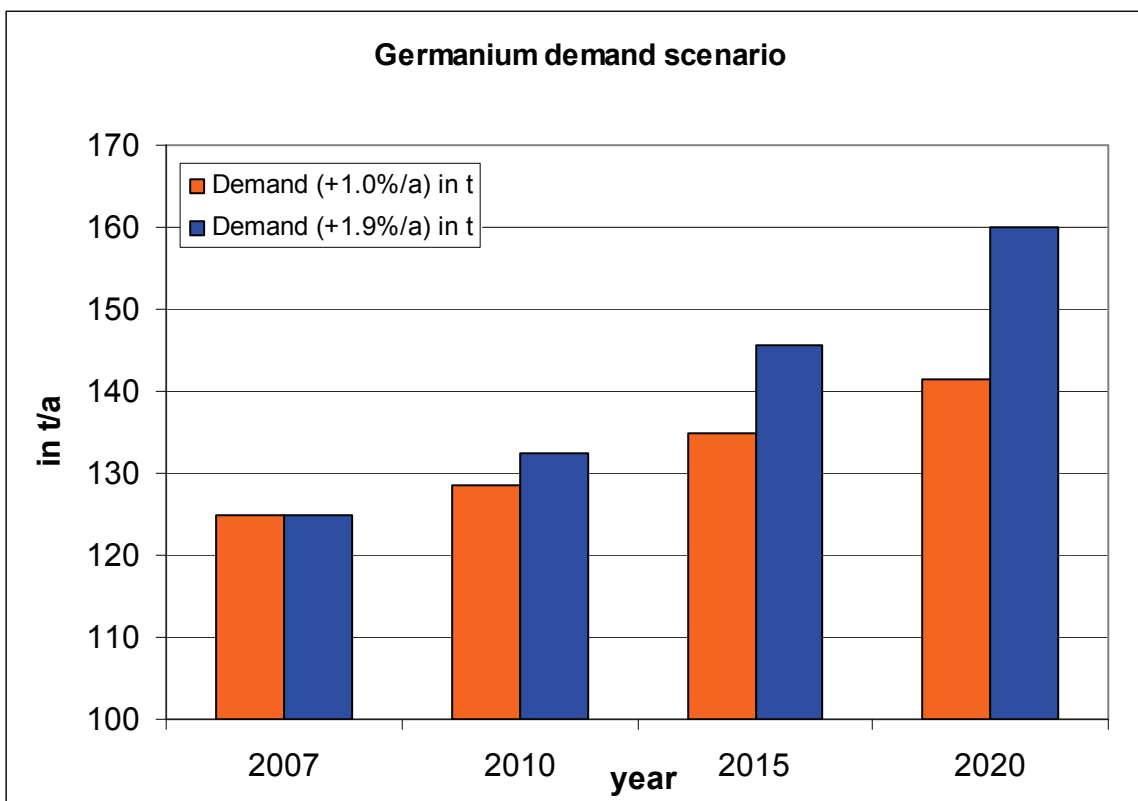


Figure 6.9: Germanium demand scenarios, calculation Öko-Institut based on RWI growth forecast

**Forecast upcoming applications:** Many industrial sectors show potential Ge-containing applications: The fiber optic benefits from the U.S. program FTTH (fiber-to-the-home), which aims to deliver fiber optic cables to every U.S. home. The electronic branch is developing germanium, tellurium and antimony containing phase-change memory, which is able to retain its memory even in the event of a power failure [Lifton 2007]. A major growth area for

germanium stays the infrared-based security and surveillance equipment and in the automobile market [Butterman et al. 2005].

**Current pre-consumer recycling:** Common (solar cells, fiber optics, infrared devices)

**Current post-consumer recycling:** As most Ge-products and devices contain very small amounts of the metal, it is technical and economical difficult and complex to recovery secondary germanium from this type of scrap. In the case of polymerization no germanium at all can be recovered (total Ge loss) [Butterman et al. 2005 and Hagelüken 2008].

**Potential pre-consumer recycling:** Increasing potential due to increasing production figures

**Potential post-consumer recycling:** Fiber-optics cables in form of a long term sink. The access to this source would bear a large potential for recycling [Hagelüken 2008]. The introduction of new EU Directives on Waste Electrical and Electronic Equipment (WEEE) is expected to result in more germanium availability from old scrap. Generally, the lack of data concerning global reserves could boost the necessary for enhanced recycling technologies.

**Specific conclusion for Germanium:**

- I. Critical issue on the demand side by increasing demand rates in all fields of application.
- II. Recycling potential is low because of miniaturization in applications, fiber optic cables which a currently used are a potential source for recycling.
- III. Global collection of Ge containing consumer goods remains a serious challenge

## 6.3 Selected metals in battery technologies

### 6.3.1 Cobalt (Co) - characteristics

**Global reserves:** Estimations implicate the worldwide cobalt reserves to be at around 7,000,000 t in 2007.

**Global mining and regional concentration:** In the year 2007, the world mining production of cobalt was around 62,000 t [Shedd 2008]. With 48% of the annual cobalt mining, the Democratic Republic of Congo is the world's leading Co-producer. Further major producers of cobalt are Australia (20%), followed by Cuba (14%) [Shedd 2008].

**Resource base:** Due to its low concentrations in earth's crust, cobalt usually is produced as a by-product element of other metals like copper or nickel

**Global current demand:** The global cobalt demand refers to 55,500 t in 2006.

**Share of current applications:** Pure metallic cobalt has few applications; it is mostly used in combination with other metals. During the last 10 years a significant switch in the share of cobalt applications took place. Based on a boost for battery applications, cobalt demand by end use in this field grew from 3% in 1995 to actual 23%. Second most common use for cobalt is in the field of super alloys (21%), where cobalt improves the strength, wear, and

corrosion-resistance of the processed material. Third often use of cobalt is for cemented carbides (11%) like e.g. cutting tools; using cobalt's important properties like the high melting point and the high temperature strengths. The same percentage (11%) appears for cobalt in the use as catalyst material in plastics and textiles industries [Kapusta 2006, CDI 2007 and Donaldson et al. 2005]. The two major applications of cobalt-batteries and super alloys can be regarded as future sustainable technologies. Batteries (cobalt is an important component in Li-ion batteries) have the potential to progressively replace combustion engines in vehicles. Alloys and super alloys play an important role in the aircraft industry, because their use leads to reductions of emissions and fuel consumption.

**Price development:** The year 2002 marked a significant change in cobalt price development. Till then Co-prices continuously decreased until they reached the bottom at around 17 USD/kg. From this point markets experience a rapid growth of Cobalt prices to around 66 USD/kg [USGS 2007a and CDI 2006].

**Global demand development:** Growth in cobalt consumption by the battery industry has been a key driver to the increase in demand for cobalt regarded over the past few years. According to a doubling of mining capacities over the last 10 years, the mentioned increase of demand was able to be satisfied.

**Forecast demand growth rates:** Long-term supply side forecasts suggest an annual growth of 2.8% till 2025 [Resource Efficiency 2008 and Kapusta 2006].

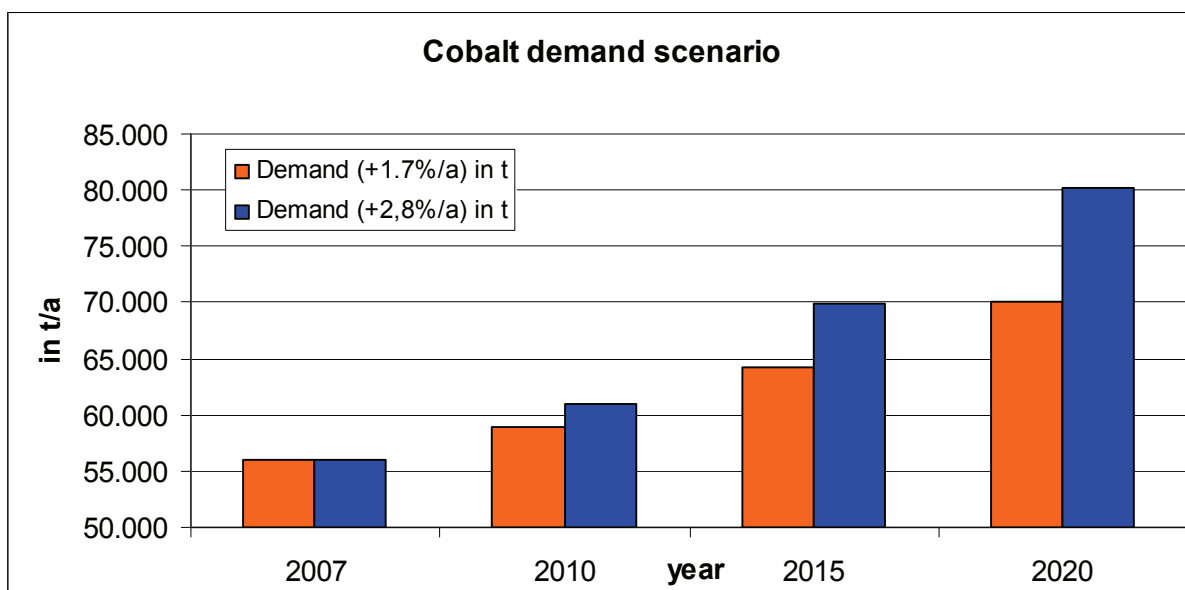


Figure 6.10: Cobalt demand scenarios based on Kapusta growth forecasts

Figure 6.10 shows the future cobalt demand adjusted to the regarded time line of this report. The blue column shows the total annual cobalt demand until 2020 based on a growth rate of 2.8%/a, like Kapusta and Resource Efficiency suggest. The orange column gives a comparison for a more conservative scenario (own estimation Öko-Institut) in Co-demand from 1.7%/a. Exact forecasts are crucial currently due to several parallel developments in battery technologies (see below).



**Forecast upcoming applications:** An upcoming shift in the use of cathode material in batteries may cause change in the demand for cobalt significantly. The current cathode material Lithium Cobalt Oxide (LCO) could be gradually replaced through Lithium Nickel Cobalt Manganese Oxide (NMC), Lithium Iron Phosphate (LFP) and Lithium Nickel Cobalt Aluminium Oxide (NCA). LCO contains 60% cobalt, NMC 10-20% cobalt, NCA 9% cobalt and LFP no cobalt at all. As a result the demand growth of cobalt could be significantly reduced through this switch in material [Metal Pages 2008a].

**Current pre-consumer recycling:** Cobalt recycling of new scrap can be regarded as common.

**Current post-consumer recycling:** Cobalt post-consumer recycling is widely common. It focuses on rechargeable batteries (for information about the Umicore Val'Eas® process of battery recycling see [Meskers et al 2009]), spent catalysts but also on alloys. The global recycling rate grew from 4,200t (1995 18%) to 10,000t (2005 20%) [Kapusta 2006].

**Potential pre-consumer recycling:** Potentials are seen in an increasing of efficiency in the recycling process.

**Potential post-consumer recycling:** Enhanced recycling flows are quiet possible. The quotas of the European Battery Directive will lead to an increasing number of collected and for recycling re-circulated batteries.

**Specific conclusion for Cobalt:**

- I. Current demand is partly based on environmental applications (rechargeable batteries, alloys for turbines in gas power plants)
- II. Overall moderate growth rates expected
- III. On the part of the supply side no natural scarcities are noticeable.
- IV. Enhanced recycling could help to foster satisfaction of Co demand in the future and therefore help to stabilize prices

### 6.3.2 Lithium (Li) - characteristics

**Global reserves:** The world reserves for lithium are estimated to 4,100,000 t with a major share in Chile (73%), followed by China (13%), Brazil (5%), Canada (4%), Australia (4%) and others (1%). [USGS 2008]

**Global mining and regional concentration:** Global mining of lithium amounts to 25,000 t (data in metric t of lithium content) in 2007 with a share of 38% from Chile, 22% from Australia, 12% from China, 12% from Argentina and 16% from a couple of further countries. [USGS 2008]

**Resource base:** Approximately 150 lithium minerals are known. Important examples are petalite and spodumene ( $\text{LiAlSi}_2\text{O}_6$ ). Spodumene concentrate for instance is used in the production of lithium carbonate. Furthermore natural brines (e.g. in the Atacama desert in Chile) with high lithium chloride contents are important sources for the lithium industry. [Wietelmann et al. 2005]

**Global current demand:** The current global demand (2007) is estimated to 17,500 t lithium. [Jaskula 2008]

**Share of current applications:** The current share of lithium amounts to 25% for batteries, 18% for ceramics/glass, 12% for lubricating grease, 7% for pharmaceutical/polymers and 38% for a couple of other applications. Worldwide Li-batteries power more than 60% of the cell phones and 90% of the laptop computers. [Meskers 2008]

**Price development (USD/kg Lithium carbonate):** The price development of lithium carbonate shows an increase from 1 USD/kg in the early 1970's to 4.5 USD/kg in 2000. Then a drop to a range 2-2.5 USD/kg follows. [Meskers 2008] Lithium is a low-priced metal which is under concern in this UNEP study.

**Global demand development:** Driven mainly by a boom in different battery applications (rechargeable batteries) the lithium demand has shown annual growth rates of 7.5% over the last 10 years. The strong impact of the battery sector for the overall lithium demand is demonstrated by the increase of the battery share from 12% in 2003 to 25% in 2007. [Jaskula 2008]

**Forecast demand growth rates:** Recent statistical data, the growing global markets for rechargeable batteries and tremendous research and development efforts regarding hybrid electrical vehicle (HEV) batteries and other energy storage applications [BMBF 2008] [Claus 2008] allows the anticipation of further growth of the global lithium demand. External forecast figures are not available (and exact predictions due to the R&D of very different types of lithium batteries are very difficult). Therefore Öko-Institut has calculated two scenarios based on own assumptions. The scenario with the 5% growth rate (orange bars) could be considered as a conservative one. The more offensive lithium demand scenario (blue bars) is based on a 10% growth rate until 2020. This would deliver more than a triplication compared to the current figure. But this scenario would be possible if lithium battery technologies will conquer the mass market for hybrid electrical vehicles or even all-electric vehicles.

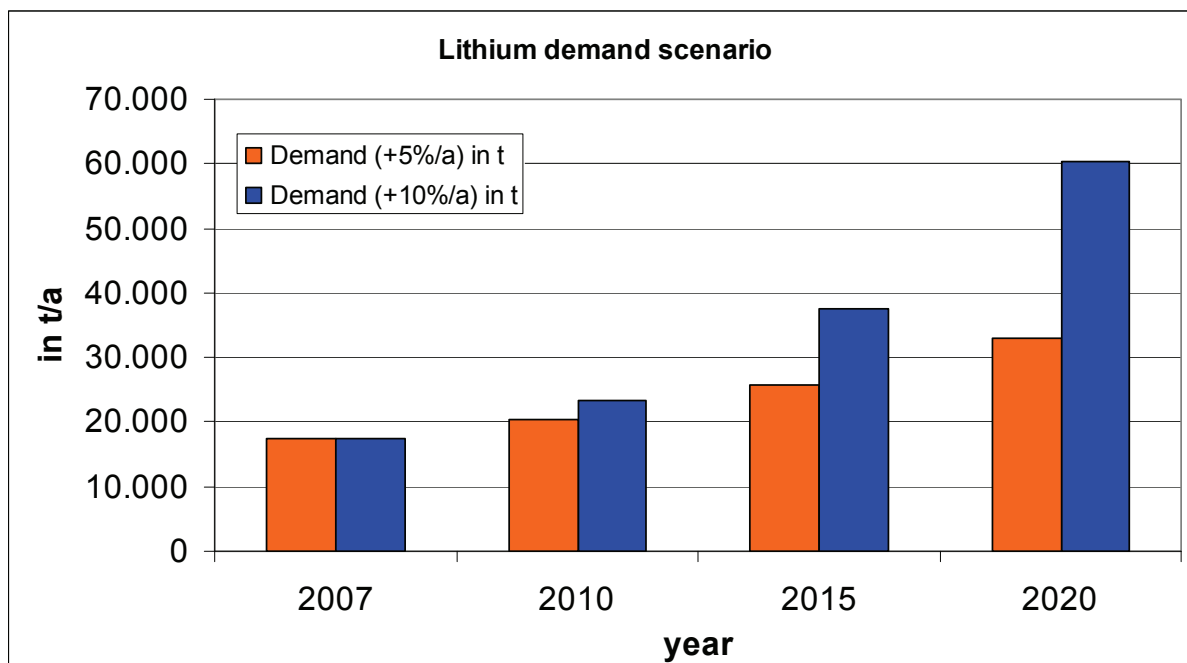


Figure 6.11: Lithium demand (net) scenarios based on Öko-Institut calculations

Öko-Institut has made an own rough calculation to get an impression of the impact of HEV batteries for the overall lithium demand. For the example of an average Li-ion battery with a lithium cobalt oxide (LCO) cathode for a full-hybrid vehicle the followings assumptions are made: 40 kg total weight of the battery [JRC 2005] and 25-27 weight%  $\text{LiCoO}_2$  [Meskers et al. 2009]. In this case the lithium content of the HEV battery would be about 1.8 weight% or about 0.7 kg. For the production of 20,000,000 HEV cars – maybe in the year 2020 – 14,400 t lithium would be necessary. This rough calculation<sup>27</sup> demonstrates that the overall lithium market would be seriously influenced in the case of a tremendous break-through of Li-ion batteries for HEV.

**Forecast upcoming applications:** The growth of the lithium demand will be driven by a total increase of current battery applications (in lap-tops etc.), but also by the start in hybrid electric vehicles (HEV) batteries [Continental 2008], which would have a tremendous effect - a HEV battery needs ca. 100 times more lithium compared with a portable computer battery.

**Current pre-consumer recycling:** Following market overviews of Umicore pre-consumer-recycling of lithium is insignificant. [Meskers 2008]

**Current post-consumer recycling:** Post-consumer recycling is not common and until today just a kind of niche activity. One reason is the quite low price of lithium and the often quite low lithium concentrations in products and compounds due to the low atomic weight of

<sup>27</sup> There are different Li-Ion battery systems under research & development. The lithium content could be lower as well as the total weight of the battery. On the other hand all-electric vehicles with lithium batteries are under current discussion as well as for stationary energy storage purposes. Therefore the growth of lithium demand could be triggered by different important applications. [Claus 2008]

lithium. Nevertheless one company in the United States is mentioned which produces small amount of lithium carbonate from solutions recovered during the recycling of lithium batteries. [USGS 2008] Furthermore RECUPYL (France) has announced the recent start (April 2007) of a lithium battery recycling plant in Singapore in partnership with TES-AMM Singapore Pte Ltd. According to RECUPYL the plant has a capacity of 320 t lithium batteries per year. The company claims, that after a hydrometallurgical treatment process, metal oxides and lithium salts are recovered. [RECUPYL 2008]

Umicore owns a battery recycling plant in Sweden which is running with a mixed input of different batteries (nickel-metalhydride and lithium batteries). This pyro-metallurgical process is designed for the production of an alloy (containing copper, iron, manganese, nickel and cobalt), which is further treated for the recovery of the main products  $\text{NiSO}_4$  and  $\text{Co}_3\text{O}_4$  and the other metals as side products. The lithium and aluminium contents of the batteries move into the slag phase as oxides. The recycling of lithium itself is not the purpose of this Umicore plant. [Meskers et al. 2009]

**Potential pre-consumer recycling:** Statements about a serious pre-consumer recycling potential are difficult. Perspectives should depend on the production developments of lithium batteries and the price developments of lithium.

**Potential post-consumer recycling:** The potential for lithium post-consumer recycling could not be seriously predicted in this study. As mentioned the economic incentive for lithium recycling is much lower compared with many other metals. On the other side a larger stream of down-stream lithium material will occur – especially from batteries. Collection rates for batteries will also rise in the future due to appropriate directives like the EU Battery Directive. So, there could be a further potential for lithium recycling, but the perspectives should not be overestimated by economic reasons (depending on the lithium prices!).

**Specific conclusion for lithium:**

- I. The reserve base is not a critical issue in the case of lithium – even if scenarios with high growth rates will be fulfilled.
- II. The lithium demand will probably increase remarkably until 2020 due to battery applications (HEV would give lithium demand a further huge push).
- III. The recycling of lithium to new lithium products is still a niche. Nevertheless huge growth rates in battery applications, development of recycling legislations in many countries and further technical improvements could deliver moderately higher recycling rates for lithium – depending mainly on more attractive lithium prices as incentive for recycling.

## 6.4 Selected metals in catalyst technologies

### 6.4.1 Platinum (Pt) - characteristics

**Global reserves:** The sum of the global reserves for the six platinum group metals (PGM) platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os) are

estimated to 71,000 t [George 2008] and for platinum only about 27,000 t with a tremendous share in South Africa [Hagelüken 2007].

**Global mining and regional concentration:** The global mining of platinum amounts to 204 t in 2007 with a 77% share of South Africa, followed by Russia with 14% share and others (Canada, USA, Zimbabwe etc.). [JM 2008a]

**Resource base:** Platinum is strictly coupled with the other PGM (Pd, Rh, Ru, Ir, Os) in mineral deposits and partly coupled with nickel ores (in Russia and Canada). The typical PGM concentrations in ores range between 5 and 10 ppm (parts per million). These low natural concentrations mean a huge operating expense for the platinum mining. [GFMS 2005]

**Global current demand:** Johnson Matthey refers a global Platinum demand of 219 t for 2007. This figure means the net demand without recycling flows. [JM 2008a] The global gross demand for platinum could be calculated to about 400 t per year due to in-depth analysis of Umicore and Öko-Institut concerning the PGM recycling flows in Germany [GFMS 2005] and global market background of Umicore. [Hagelüken 2008]

**Current applications:** The global net demand is divided mainly in automotive catalysts (47%), industrial applications like industrial catalysts, glass industry, dental applications (in sum 28%) and jewellery (23%). [JM 2008a] Due to very high recycling quotas in most of the industrial applications the share of this sector regarding the gross demand is higher compared to the net demand figure. [Hagelüken 2008]

**Price development (USD/kg):** Platinum price has shown an almost continuous increase in the last ten years. From 11,960 USD/kg in 1998 to 22,216 in 2003 and to a very high level of 41,925 USD in 2007, due to an almost continuous increase of the global platinum demand.<sup>28</sup> [JM 2008a]

**Global demand development (net):** Platinum has shown an almost continuous increase of the global net demand (without secondary platinum) since 1980. In this year the platinum net demand refers to 73 t, in 2000 174 t and in 2007 219 t. This means an overall increase of 200% between 1980 and 2008. This ongoing platinum boom was mainly driven by the success story of the automotive catalysts. [JM 2008a]

**Forecast demand growth rates:** A further growth of platinum demand could be expected due to the increasing global demand for cars and the growing number of nations (emerging economies etc.) with ambitious vehicle emissions standards which could be fulfilled by automotive catalysts only. The RWI has announced a range for the platinum demand increase of 63-99% between 2004 and 2025. Due to further progress regarding platinum recycling the increase of the platinum mining has been expected in a range of 54-88% between 2004 and 2025. [RWI 2007] In the next figure two scenarios are shown based on the RWI forecast and adapted for the period 2007-2020.

---

<sup>28</sup> From this price level the platinum price has dropped to a level of about 22,000 USD until October 2008 due to the turbulences of the international financial markets.

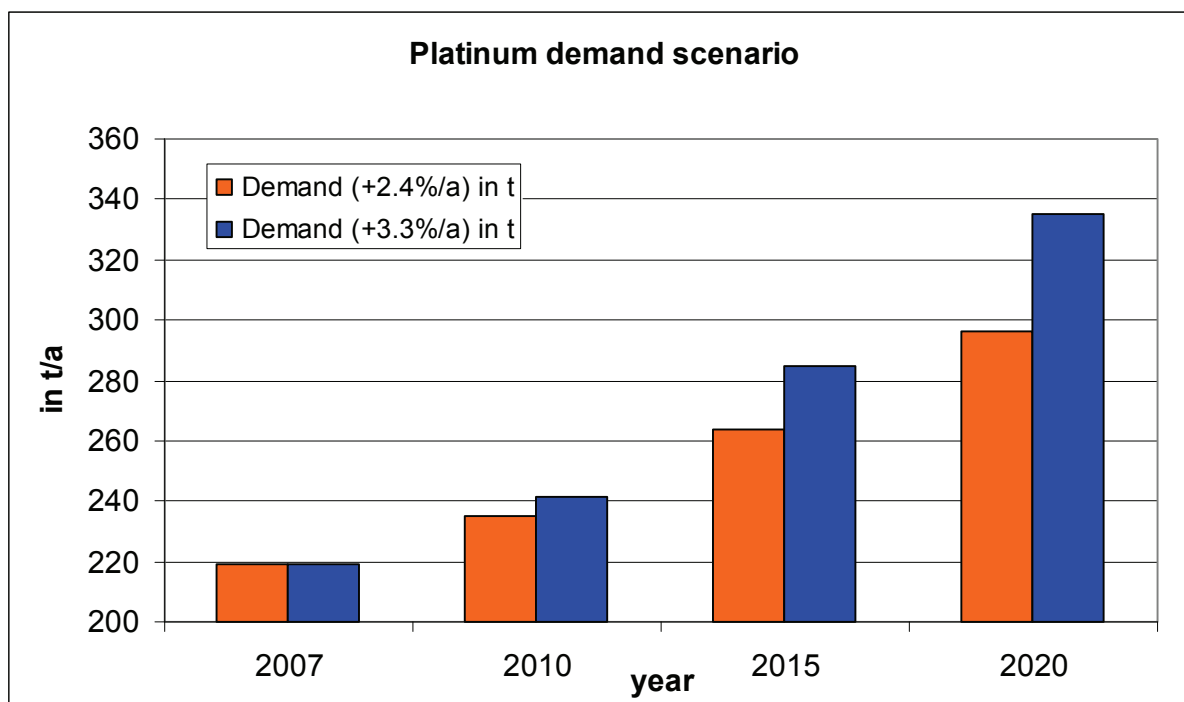


Figure 6.12: Platinum demand (net) scenarios based on RWI growth forecasts

**Forecast upcoming applications:** The further growth of the global platinum demand is mainly driven by existing applications like automotive catalysts and enhanced production of special glass types like LCD glass and fibre glass.

**Current pre-consumer recycling:** Pre-consumer recycling is very common for platinum since many years due to the high economic value of platinum and the fact that the platinum concentrations in new scrap amounts in higher magnitudes compared to the platinum concentrations in natural ores. [GFMS 2005]

**Current post-consumer recycling:** Post-consumer recycling of platinum is very common in many applications due to the advantageous chemical characteristics of platinum and its high value. Umicore, for instance has refined in its Antwerp plant 12 t platinum in 2007 from automotive catalysts, e-scrap and other recyclables and by-products. [Umicore 2008]

In the case of industrial applications like glass industry and industrial catalysts (e.g. nitric acid production, powder catalysts, fixed-bed and fluidized-bed catalysts) the overall recycling quotas for platinum amounts 90-95%. [GFMS 2005] In the case of consumer applications the overall recycling quotas are much lower currently. The reason is not due to technical recycling problems but due to difficulties in the collection systems for dissipative applications like EEE and used vehicles. There is a huge drain of secondary material from developed countries to developing countries, which do not yet have the necessary infrastructure and know-how to treat end-of-life vehicles or WEEE in a proper way to collect and to re-refine precious metals like platinum. [Buchert et al]. Nevertheless secondary platinum supplies currently about 180 t on a global scale by very high recycling rates of industrial applications (catalysts, glass industry) and increasing amounts from automotive catalysts and jewellery. [Hagelüken 2008]

**Potential pre-consumer recycling:** No further potentials could be expected by enhanced new scrap recycling, because these activities are in a ripe status since many years.

**Potential post-consumer recycling:** Öko-Institut states remarkable further potentials for post-consumer recycling from consumer applications for platinum. The key for success will be an enhanced collection of automotive catalysts and e-scrap in industrial and especially developing countries and a progress in international co-operations regarding recycling chains. An overall global recycling quota for platinum of 70% (currently about 45%) should be the minimum target for 2020. [GFMS 2005], [Buchert et al. 2007] [Hagelüken 2008]

**Specific conclusion for platinum:**

- I. The critical issue on the supply is obviously the tremendous regional concentration of mining. The power supply and other problems in South Africa (most important primary platinum producing country) will be an ongoing problem, but not a knock-out issue in the future. Nevertheless 'Lonmin', the world's third biggest platinum producer, has confirmed in its latest results that annual platinum output fell by 16%." [Platinum Today 2008]
- II. The platinum demand will probably increase remarkably until 2020 and beyond due to huge driving forces in the major applications: further development of emission legislation in the automotive sector incl. light and heavy duty diesel vehicles will be a kind of a mega trend.
- III. The proper collection of Pt-containing consumer goods in developing countries as a precondition for recycling remains a serious challenge, as well as legal (as used goods) or illegal exports of WEEE and ELV from industrial countries in regions without appropriate recycling systems.

#### 6.4.2 Palladium (Pd) - characteristics

**Global reserves:** The total amount of the palladium reserves ranges with ca. 26,000 t in the same magnitude compared with platinum. Again South Africa is the leading country regarding the share of the world reserves (about 60-70%), followed by Russia. [Hagelüken 2007]

**Global mining and regional concentration:** Johnson Matthey announces in 2007 a global mining of 221 t palladium plus 46 t Russian state sales. Russia counts for 53%, South Africa for 32% and Canada/USA in sum for 12% of the primary palladium production, including the Russian state sales. [JM 2008a]

**Resource base:** Palladium occurs in natural ores strictly coupled with other PGM (Pt, Rh, Ru, Ir), or it is coupled with Nickel mining (in Russia and Canada). The typical PGM concentrations in ores range between 5 and 10 ppm.

**Global current demand:** The net demand of palladium amounts to 213 t in 2007. [JM 2008a]. The global gross demand for palladium including all recycling flows could be estimated like for platinum to about 400 t per year. [GFMS 2005] [Hagelüken 2008]

**Share of current applications:** The global net demand of palladium is focused with 50% on automotive catalysts, followed with 19% for electronics and 11% for jewellery. Further applications are industrial catalysts (chemical industry), dental and investment. [JM 2008a] It should be mentioned that regarding the gross demand of palladium (including recycling flows) the industrial catalysts has a high share due to palladium recycling rates of about 90 % in this sector. [GFMS 2005]

**Price development (USD/kg):** The palladium price has shown a dramatic peak at the beginning of the century due to a 'substitution hype' (substitution of platinum by palladium for automotive catalysts caused by higher platinum prices) and restricted Russian exports at this time. Therefore the palladium price rose from 9,131 USD in 1998 up to 21,895 USD in 2000. In the following years the price dropped to 6,462 USD until 2003 and rose again due to increasing demand to 11,414 in 2007.<sup>29</sup>

**Global demand development (net):** The figures of the palladium demand development is appropriate to the price course of palladium. Starting from a net demand of 63 t in 1980 the mentioned substitution hype in the automotive sector pushed the global net demand to 291 t in 1999. After a normalization period the palladium net demand dropped to 151 t in 2002. Since 2002 the palladium net demand increased to 213 t in 2007. In a long term perspective (from 1980-2007) the net palladium demand has been more than tripled. [JM 2008a]

**Forecast demand growth rates:** A further growth of the net palladium demand is likely due to a strong position of this metal in its main applications (automotive catalysts and electronics). [Loferski 2008] In the automotive sector for countries like Russia, China, India etc. a huge increase of vehicle purchases are expected in the next years – all of them equipped with automotive catalysts – and palladium is the cheaper PGM with about half of the price per unit compared to platinum. This fact makes palladium very attractive for the production of automotive catalysts. Because individual forecast figures for palladium are not available, Öko-Institut has considered the same range of increase for palladium like the estimated platinum demand increase of 63-99% between 2004 and 2025. [RWI 2007]. The next figure shows two scenarios, based on the RWI forecast for platinum and adapted for palladium for the period 2007-2020. It should be mentioned that recycling flows of palladium (automotive catalysts, dental, electronics etc.) will have an increasing relevance to moderate the increase of the palladium net demand, which has to be satisfied by mining production.

---

<sup>29</sup> Caused by the turbulences in the international financial markets palladium prices were halved from summer to October 2008 to a level of about 5,000 USD per kg.



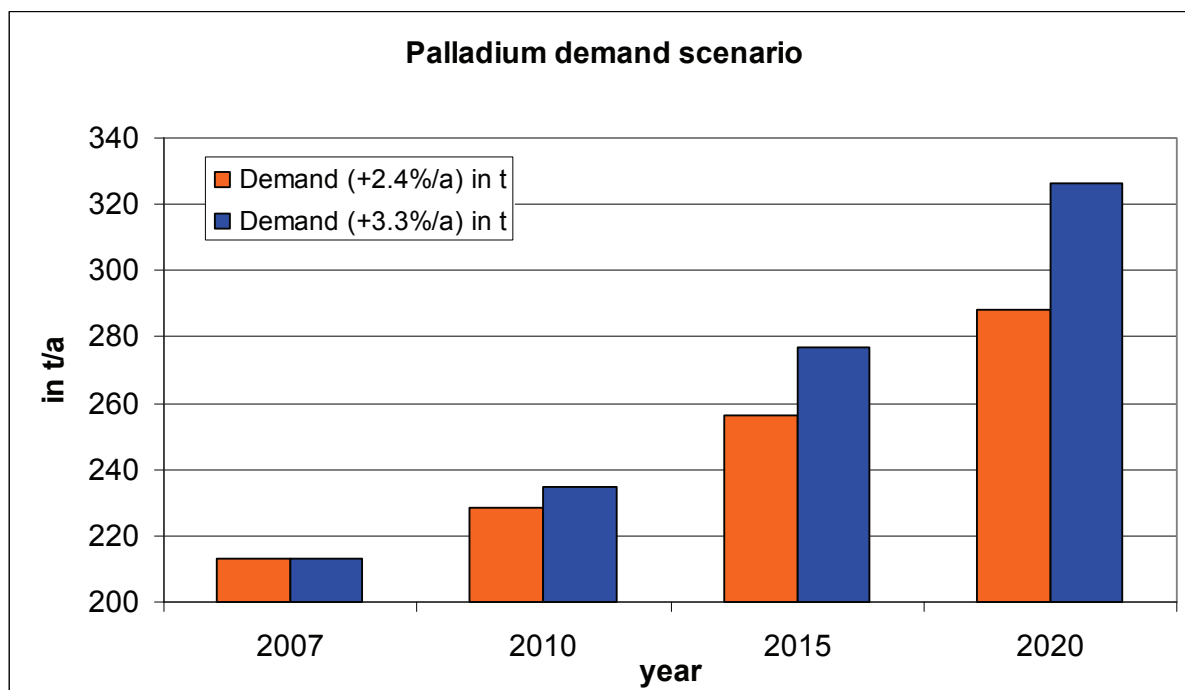


Figure 6.13: Palladium demand (net) scenarios based on RWI growth forecasts

**Forecast upcoming applications:** The growth of the palladium demand is mainly driven by existing applications. But further automotive catalyst applications (light duty diesel vehicles, large trucks) could further enhance the demand for palladium in the future. [JM 2007] [JM 2008a]

**Current pre-consumer recycling:** Like for platinum pre-consumer recycling is very common for palladium since many years due to its high economic value and its recycling-friendly chemical characteristics. [GFMS 2005]

**Current post-consumer recycling:** The post-consumer recycling of palladium is in a ripe status and common. Umicore for instance has announced the recycling of 15 t palladium in Hoboken/Antwerp in Belgium as well as a total recycling palladium capacity of 24 t. [Umicore 2008]. Further important examples for companies with experiences and different installations for palladium post-consumer recycling from different sources are Norddeutsche Affinerie in Germany [NA 2008], Boliden in Sweden/Finland [Boliden 2008], Johnson Matthey in USA/UK [JM 2008b] and DOWA [DOWA 2008] in Japan. Secondary palladium supplies about 180 t in 2007 due very high recycling rates of industrial applications (catalysts), quite high recycling rates from dental and increasing amounts from automotive catalysts and electronics. [GFMS 2005] [Hagelüken 2008]

**Potential pre-consumer recycling:** The pre-consumer recycling of palladium is common since many years. So, remarkable further potentials are not expected.

**Potential post-consumer recycling:** Remarkable further potentials from consumer applications could be expected from dental post-consumer material and first of all from used automotive catalysts and e-scrap in industrial and developing countries. [GFMS 2005] [Buchert et al. 2008]

### Specific conclusion for palladium:

- I. A critical issue on the supply side is given by a quite regional concentration of mining (South Africa and Russia). Power supply problems etc. in S.A. will be an ongoing issue. Furthermore parts of the Russian plant infrastructures need serious investments for modernization activities.
- II. Palladium demand will probably increase remarkably until 2020 due to huge driving forces in the major applications: automotives and electronics.
- III. The appropriate collection and delivery of palladium containing post-consumer materials (e-scrap from computers, automotive catalysts from old cars in developing countries etc.) to suitable refining plants (e.g. in Europe, USA, Japan) from all over the world including developing countries remains a serious challenge.

### 6.4.3 Rare earths (RE) - characteristics

**Global reserves:** The U.S. Geological Survey<sup>30</sup> estimates the total rare earth oxides reserves to be at 88 Mio. t in 2007 [Hedrick 2008a].

**Global production and regional concentration:** The global mining amounted to 124,000 t rare earth oxides in 2007. Hereby, more than 95 % are mined in China [Hedrick 2008]. China is also the leader in the processing of rare earth oxides and rare earth technology [Haxel et al. 2002] [Hedrick 2008a]. The major reserves are in China, in the Commonwealth States and in the USA [Hedrick 2008a].

**Resource base:** The rare earths are mined from deposits with different compositions of rare earths. There is no coupling with none rare earths elements.

**Global current demand:** The current global demand amounts to 132,500 t rare oxides (forecast) in 2008 and a rating from Roskill and IMCOA<sup>31</sup> forecasts the demand in 2013 for some elements [Kingsnorth 2008] (figures as rare earth oxides are rounded): cerium 76.000 t, lanthanum 58.000 t, neodymium 42.000 t, yttrium 15.000 t, praseodymium 9.000 t, dysprosium 3.000 t, samarium 2.000 t and europium 1.000 t. A consumption of 100 to 1.000 t is estimated for erbium, terbium, gadolinium and the sum of holmium, thulium, ytterbium and lutetium.

**Share of current applications:** The consumption of the 16 different rare earths covers manifold sectors from glass polishing up to high-tech applications [Behrendt 2007]. The U.S. Geological survey estimates the following shares of applications for the U.S. market:

1. automotive catalysts: 25%
2. petroleum refining catalysts: 22%

---

<sup>30</sup> The data of the U.S. Geological Survey refer to 16 elements (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y)

<sup>31</sup> IMCOA: Industrial Minerals Company of Australia; Roskill Information Service is a provider of information on international metals markets.

3. metallurgical additives and alloys: 20 %
4. glass polishing and ceramics: 11%
5. lighting, TV, monitors etc. 10% [Hedrick 2008a]

**Price development:** There was no uniform trend since the 70ies which represents the whole spectrum of the elements. There are high variations between the elements. The prices varied in 2006 from 30 USD/kg rare earth oxides for abundant elements up to 3.500 USD/kg oxide for scarce elements [Hedrick 2008c].

**Global demand development:** In [Kingsnorth 2008] the following figures on the demand development of rare oxides are announced. Starting from about 1,000 t in 1953 the global demand increased to 85,000 t in 2003 to 132,500 t in 2008..

**Forecast demand growth rates:** The average annual growth rates in the past were 4.4 % over the last twelve years and 4.8 % over the last five years [Di Francesco Hedrick 2007]. It is to assume that this trend will go on as the rare earths are part of many high tech applications in growing markets. The National Institute for Material Science assesses for the rare earths a slightly lower average annual growth rate in the range of 3 to 4 % [NIMS 2008]. The following figure shows two scenarios. There is one scenario with an average annual growth rate of 4.5 % (left bar in orange), which is seen as a moderate scenario extrapolating the previous trend. The other scenario (right bar in blue) with a growth rate of 9 % growth is seen as the upper limit. It considers the upcoming markets for manifold new applications. This scenario is supported by evaluations of specific applications with high growth rates. The growth rate for the use as catalysts is estimated at 6 to 8 %/a [Hedrick 2008a], and the use as magnet is expected to increase by 10 to 25 % per year [Hedrick 2008a] [Kingsnorth 2008]. Australian companies estimate an average annual growth rate between 8 and 11 % [James 2008] [Kingsnorth 2008].

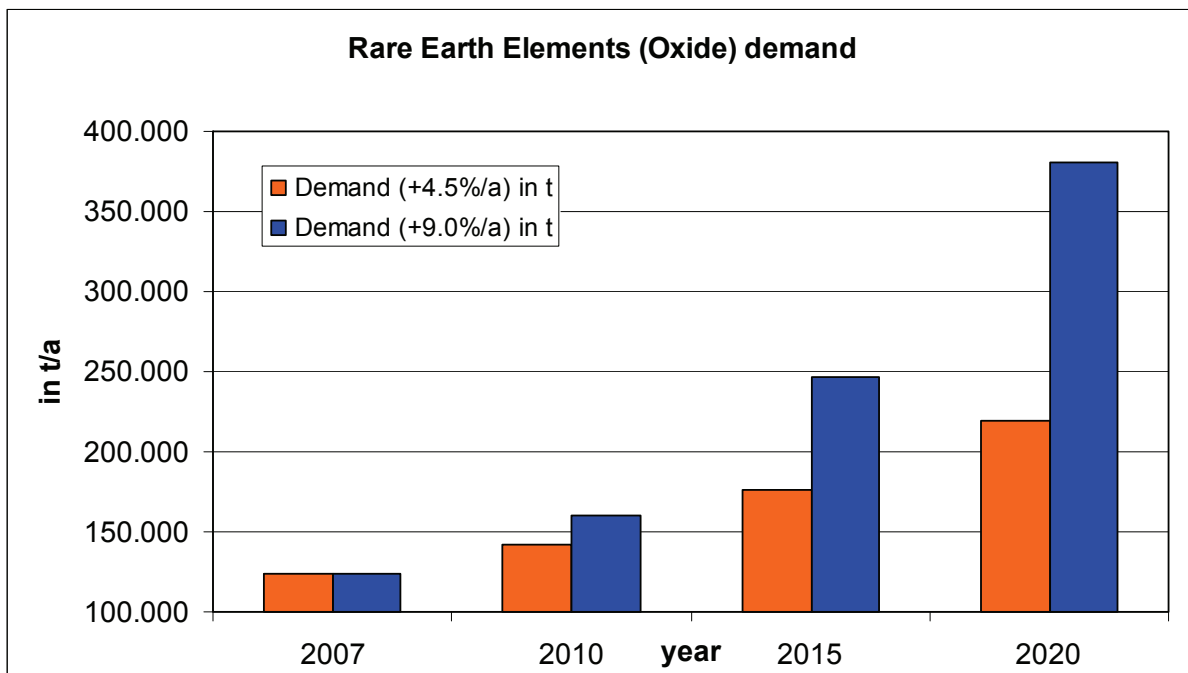


Figure 6.14: Rare earths oxides demand scenarios based on calculations from the Öko-Institut

**Forecast upcoming applications:** There are manifold research activities, and it is estimated that there will be new applications for magnetic devices, catalysts, batteries, electronics, fibre optics and medical applications [Hedrick 2008c]. One promising technology is the magnetic refrigeration, which could eventually substitute conventional gas-compression refrigeration, as it is more efficient and requires no refrigerant [Haxel et al. 2002]. Substitutes are available for many applications, but generally they are less effective [Hedrick 2008a].

**Current pre-consumer recycling:** In the USA small quantities of rare earths, mostly from permanent magnet scrap, are recycled.

**Current post-consumer recycling:** There is no information on any current activities in the post-consumer recycling.

**Potential pre-consumer recycling:** The rare earths applications comprise a wide variety, mostly with a very fine dispersion. Therefore, potentials can only be identified on basis of a detailed analysis for each element and its applications.

**Potential post-consumer recycling:** There is probably only a low potential in post-consumer recycling due to the widespread use in low concentrations and the frequent use in alloys. Furthermore, the rare earths hold a disposition to slag (as oxides) in smelter plants. This impedes the recycling in WEEE smelting plants.

**Special conclusion for rare earths:**

- I. There are widespread resources in all continents. However, currently there is a global imbalance in mining and processing due to the very high regional concentration in China.
- II. Further in-depth investigations should not address the rare earths in total, because the different elements have manifold different applications, prices, properties and resources.
- III. Concerning the environment, the rare earth mining from monazite containing radioactive thorium should be avoided, particularly as the world's largest resources are from other rocks.
- IV. Research in new recycling technologies which address the different rare earths regarding their chemical characteristics and specific value is a necessary task for the future.

## 7 Prioritization of critical metals

### 7.1 General prioritization (1<sup>st</sup> step)

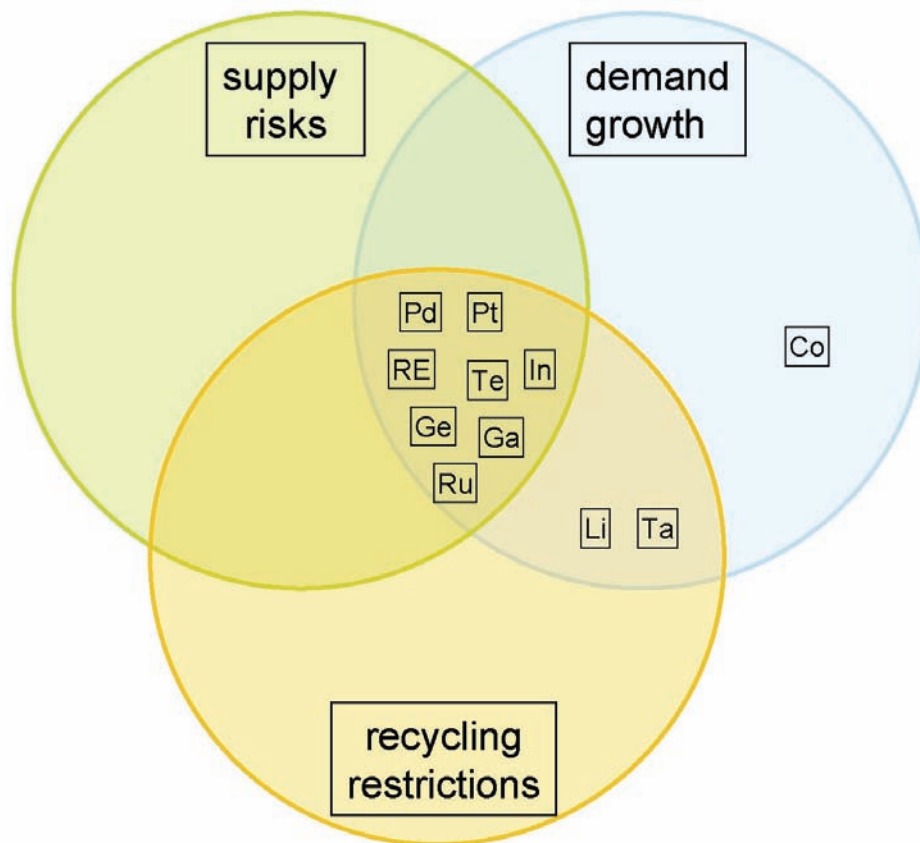


Figure 7.1: Prioritization step 1: general assignment of critical metals

Figure 7.1 shows the first step of the prioritization process of this study. The results from the individual characterization of each critical metal in chapter 6 provide the data base for this first step. Due to the facts of the data base, Öko-Institut assigns every metal to a certain point in the three restriction circles. The overlapping design of the restriction circles is therefore essential. Through the positioning of a certain metal-sign (e.g. tantalum = 'Ta') in the overlapping zone between two restriction circles, the belonging to both restriction issues is being expressed. Regarding the example 'Ta', all listed facts from the individual characterization lead to the positioning of tantalum as well in the circle 'recycling restrictions' as in the 'demand growth' circle. Simultaneously the graphic provides the information, that no supply risks are being forecasted (seen) for tantalum.

Figure 7.1 reveals that – beside cobalt, lithium and tantalum - all analyzed critical metals are situated in the overlapping zone of all 3 restriction circles. This fact underlines the general importance of these critical metals for the future sustainable technologies and shows the

exigency of a cooperative international struggle to maintain global availability of these metals – also through efficient recycling techniques and infrastructures.

## 7.2 Focused prioritization regarding demand (2<sup>nd</sup> step)

	<b>Rapid demand growth</b> > 50% increase of total demand until 2020	<b>Moderate demand growth</b> > 20% increase of total demand until 2020
✓ Tantalum	+	
✓ Indium	+	
✓ Ruthenium	+	
✓ Palladium	+	
✓ Platinum	+	
✓ Rare earths	+	
✓ Gallium	+	
✓ Tellurium	+	
Germanium		+
Cobalt		+
✓ Lithium	+	

Figure 7.2 Prioritization step 2: Distinction of rapid/moderate demand growth

Figure 7.2 illustrates the next step of the prioritization process accomplished in this study. Step 2 intends to give a closer differentiation of the demand side. Öko-Institut decided therefore to focus on the amplitude of given demand growth rates for each analyzed critical metal. A two-stage distinction has been realized by concerning either an estimated rapid demand growth (> 50% increase of total demand since 2007 until 2020) or an estimated moderate demand growth (> 20% increase demand growth until 2020).<sup>32</sup>

As Figure 7.2 shows clearly - except the metals germanium and cobalt - all other metals demonstrate a rapid demand growth estimated until 2020.

<sup>32</sup> A more distinguished differentiation regarding the total demand growth seems to be not useful due to the uncertainties in the scenarios.

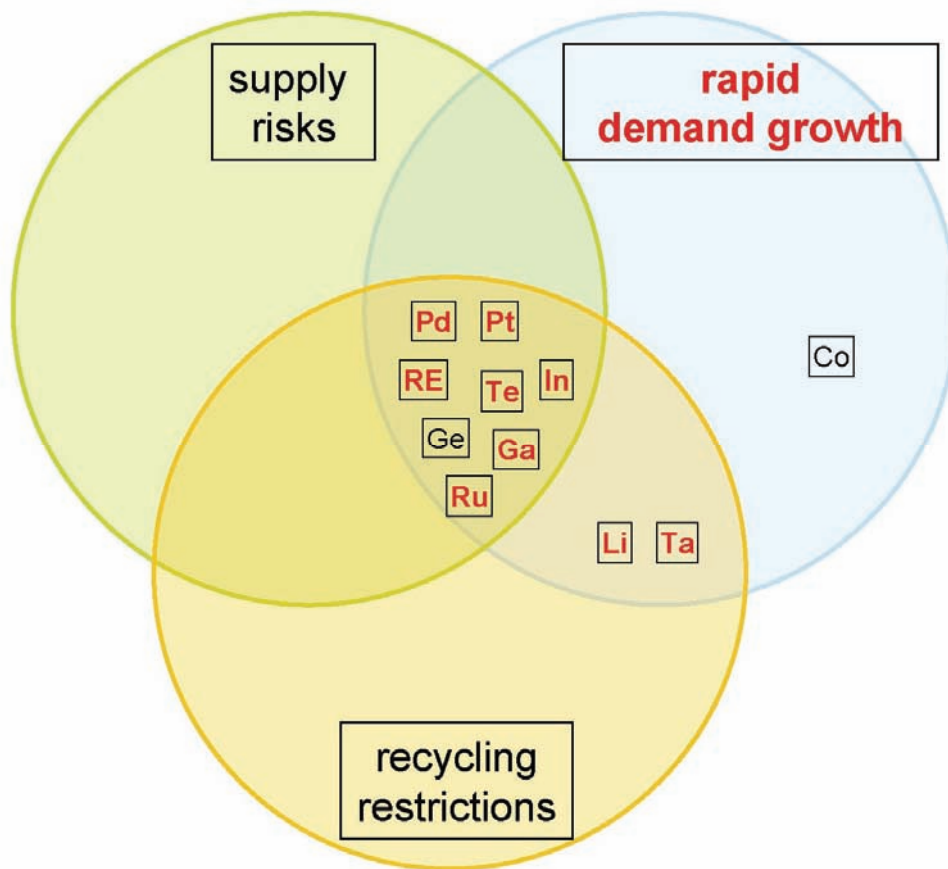


Figure 7.3: Visual transfer of differentiated growth rates for demand

The visualization seen in Figure 7.3 adapts the above-given results of different demand growth rates to the graphic illustration of restriction circles and therein appointed critical metals. A visible distinction is being achieved through a red coloured highlighting of the metals showing a rapid demand growth. In contrast, the remaining metals germanium and cobalt – with a moderate growth rate – remain without any modification of the colour.



### 7.3 Focused prioritization regarding supply (3<sup>rd</sup> step)

	<b>Regional concentration of mining</b> >90% share of global mining in the 3 mayor countries	<b>Physical scarcities</b> reserves compared to annual demand	<b>Temporary scarcity</b> Time lag between production and demand	<b>Structural or technical scarcity</b> Metal just a minor or by-product
	Tantalum	-	+ -	-
✓	Indium	-	+	+ -
	Ruthenium	+	-	+ -
	Palladium	+	-	+ -
	Platinum	+	-	+ -
	Rare earths	+	-	-
✓	Gallium	-	-	+
✓	Tellurium	-	+ -	+
	Germanium	-	+ - (?)	+ - (?)
	Cobalt	-	-	+
	Lithium	-	-	+ -

Figure 7.4: Prioritization step 3: Focused distinction of supply restriction

Consequently, prioritization step 3 now focuses on the supply side risks of the critical metals. Like already seen for the demand side, a two-stage distinction of critical metals has been accomplished, showing serious supply risks and critical metals showing moderate supply risks. To achieve the individual classification into the two stages serious/moderate, four specific sub-criteria were worked out by the Öko-Institut. Figure 7.4 shows the four specification questions corresponding to single aspects and possible scarcities for the supply side. As a result, all critical metals are labelled with a red check mark, which shows two or more positive responses on the specification questions. It is visible that indium, gallium and tellurium are to be classified as handicapped with serious supply risks. The critical metal germanium is at the edge of being also classified with serious supply risks. As the database about physical and temporary scarcities is uncertain, these questions can not be responded undoubtedly and are therefore marked separately.

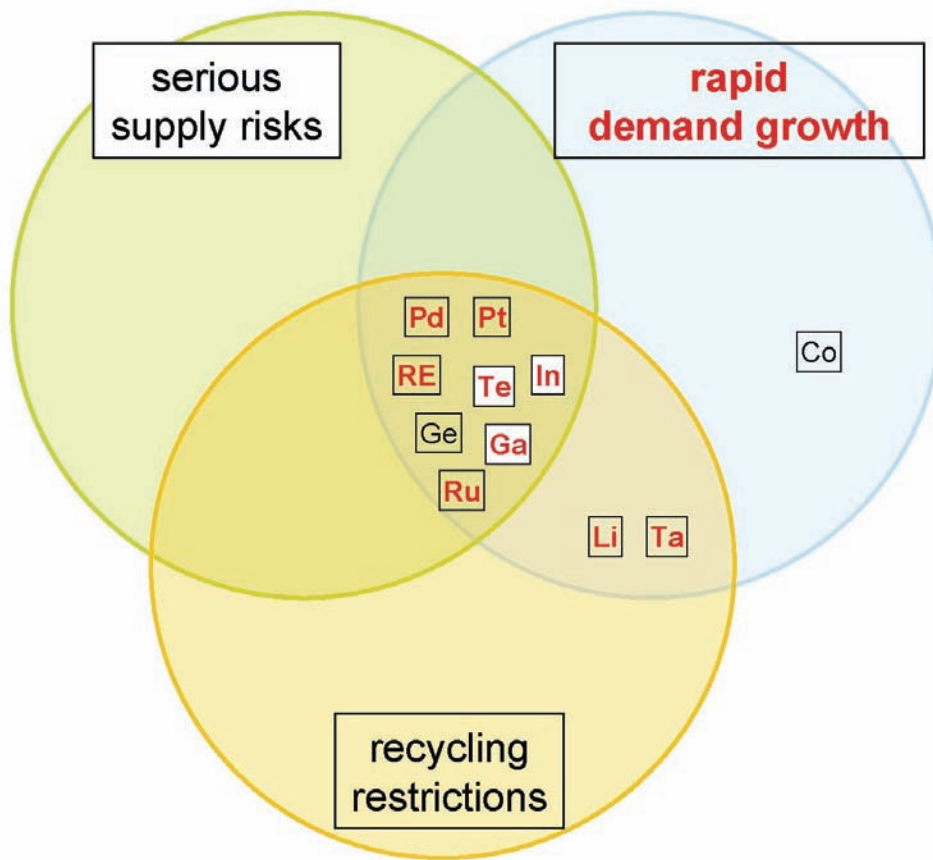


Figure 7.5: Visual transfer of differentiated supply restrictions

As already seen for the demand side, a visualization for the above-given results of the distinction in serious and moderate supply risks is adapted through Figure 7.5. The graphic illustration builds up on Figure 7.3 , maintaining the information of rapid/moderate demand growth. To visualize the supply-side differentiation, it was decided to dye the background in white colour as far as a critical metal is classified with serious supply risks. In contrast, the all critical metals showing a moderate supply risk remain without any background colour.

#### 7.4 Focused prioritization regarding recycling (4<sup>th</sup> step)

	High scale of dissipative applications	Physical/chemical limitations for recycling	Lack of suitable recycling technologies and/or recycling infrastructure	Lack of price incentives for recycling
✓ Tantalum	+	+	+	-
Indium	+	-	+ -	-
Ruthenium	+	-	+ -	-
Palladium	+ -	-	+ -	-
Platinum	+ -	-	+ -	-
✓ Rare earths	+ -	+	+	-
Gallium	+	-	+ -	-
Tellurium	+	-	-	-
Germanium	+	-	+ -	-
Cobalt	+ -	-	-	-
✓ Lithium	+ -	+	+	+

Figure 7.6: Prioritization step 4: Focused distinction of recycling restrictions

Similar to the preceding differentiation for the demand and supply side, it is finally necessary to accomplish the same proceeding for the recycling side. Again, a two-stage distinction has been chosen to either classify the recycling restrictions of a critical metal as serious or moderate. Like Figure 7.6 shows, the response to four specification questions concerning different aspects of recycling restrictions lead to the individual assessment of each critical metal in this field. It is visible that tantalum, rare earths and lithium stand out from the rest of the critical metals and show serious recycling restrictions.

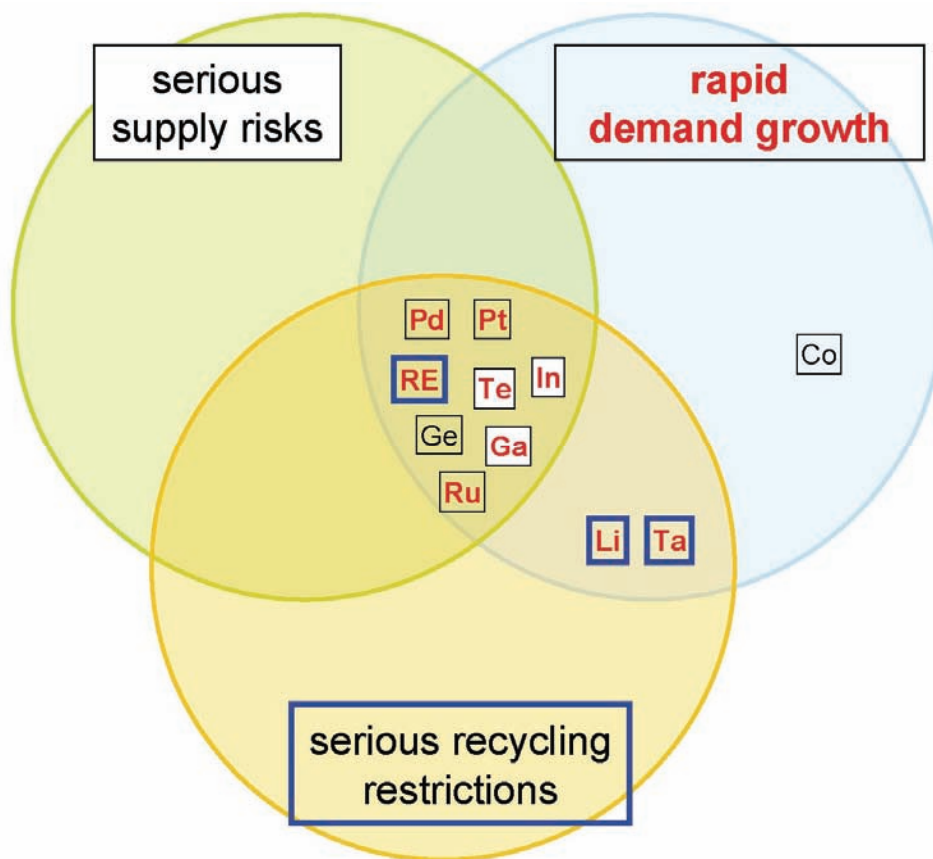


Figure 7.7: Visual transfer of differentiated recycling restrictions

The last visual transfer now adapts the results of the specific recycling-classification, accomplished in Figure 7.6. As seen in the previous illustrations, Figure 7.7 maintains the differentiated information about demand growth & supply restrictions and adds up the recycling-side distinction. The information is added by bolding and highlighting the frame of the specific critical metal in blue colour.

Figure 7.7 now summarizes all information of the prioritization process of this study and allows a differentiated view on the critical metals and their specific properties regarding each restriction circle.

## 7.5 Summarized prioritization and urgency regarding timeline

timeline	Metal
<b>short-term (within next 5 years)</b> + <b>rapid</b> demand growth + <b>serious</b> supply risks + moderate recycling restrictions	Tellurium Indium Gallium
<b>mid-term (till 2020)</b> + <b>rapid</b> demand growth and + <b>serious</b> recycling restrictions  <u>or:</u> + moderate supply risks + moderate recycling restrictions	Rare earths Lithium Tantalum  Palladium Platinum Ruthenium
<b>long-term (till 2050)</b> + moderate demand growth + moderate supply risks + moderate recycling restrictions	Germanium Cobalt

Figure 7.8: Summarized prioritization regarding timeline of this study

Final step of the prioritization process is to interpret the conclusions from the detailed restriction-analyse and bring them together with a short-, mid- and long-term timeline. Figure 6 shows the results of this time-regarding classification. Each time category is composed of a criteria-setting with the above-explained distinguishing in rapid or moderate demand growth and serious or moderate risks.

Within the next five years (short-term perspective), Öko-Institut estimates that the metals tellurium, indium and gallium to be regarded as most critical. In a mid-term perspective, the metals: rare earths, lithium, tantalum, palladium, platinum and ruthenium are becoming crucial. Finally, in a long-term perspective till 2050, only germanium and cobalt are regarded to become critical.

Need for coordinated action is necessary for all of the investigated critical metals to reduce environmental burden of the primary production (enhanced production share of secondary metals) and ensure the resource base for important sustainable future technologies like solar cells, catalysts etc. Nevertheless in the case of tellurium, indium and gallium special activities of UNEP and other international and regional bodies are recommended due to the urgency of possible critical supply situations etc.

## 8 Preconditions for an optimized recycling of critical metals

Taken the current situation and upcoming developments into account (see chapters 0-0) Öko-Institut identifies three different spheres of activities to promote the recycling of critical metals in the future decisively and insure the supply base for future sustainable technologies:

- The enlargement of recycling capacities,
- the development and realization of new recycling technologies and
- the accelerated improvement of international recycling infrastructures.

### Enlargement of recycling capacities

As punctuated on important examples successful technologies for the recycling of many critical metals are already realized in a couple of special plants worldwide (mainly in Europe and Japan). But it is obvious that the existing capacities of these very particular plants will not be sufficient in the near future for the rapidly growing pre-consumer and more important post-consumer material flows, which will contain increasing total amounts of very valuable and important metals. This statement is backed by three different examples.

#### Platinum group metals from automotive catalysts

In chapter 0 of this UNEP study it is noted that in 2007 28 t platinum and 31 t palladium were recovered from automotive catalysts worldwide. In the same year the global gross-demand for the production of new automotive catalysts was 131 t platinum<sup>33</sup> and 138 t palladium. [JM 2008a] The Umicore plant at Hoboken/Antwerp – one of the world largest sites for the recycling of precious metals in the world – has current capacities for 18 t platinum and 24 t palladium – from different waste inputs. [Umicore 2008] That means in a about 10-15 years (average lifetimes of cars) a global capacity which is about six times higher than the total current capacity in Hoboken will be necessary for optimized global recycling capacities of platinum and palladium from spent automotive catalysts only. Furthermore optimized collection infrastructure for spent automotive catalysts will be required in the emerging economies and developing countries.

#### Indium

The second example is the important critical metal indium, which shows special urgency regarding the timeline (see chapter 0) due to rapid demand growth in different applications (LCD, solar cells). Umicore again announces for Indium a current recycling capacity of 50 t in its large Hoboken plant. [Umicore 2007]

---

<sup>33</sup> For instance, the platinum demand for automotive catalysts has shown a strong growth in the last 20 years. E.g. in 1998 the global platinum demand for this application was just 69 t [JM 2008a]



Figure 8.1: Indium bullion (photo by courtesy of Umicore Precious Metals Refining)

But starting from a current net demand of about 610 t indium<sup>34</sup> (and additionally 600 t indium delivered from mainly new-scrap recycling) and taking the expected strong increase rates for indium into account the amount of indium in post-consumer waste flows will be at least 3 times higher in 2015 compared with 2007. That means capacities for pre-treatment and refining of indium have to be enhanced remarkably in the next 5 years to address the upcoming post-consumer indium flows from applications with often quite low life-times like computer notebooks.

#### Tellurium from photovoltaic applications

As demonstrated in the chapter 6 the tellurium demand is rapidly growing triggered by a boom of Cd-Te thin film solar cells. This could double or even triple the global tellurium demand in the next years and tellurium recycling will get a key role to ensure a satisfying tellurium demand in the future due to serious supply restrictions from natural resources (see chapter 0). Therefore the global recycling infrastructures and capacities for the recycling of solar cells, new scrap and as well for post-consumer solar cells have to be built up. In this context the expansion of the current EU WEEE Directive on solar cells for photovoltaic should be focused seriously in the next years.

---

<sup>34</sup> Furthermore 600 t indium are delivered from mainly new-scrap recycling (see chapter 6).

The demonstrated enormous demand for an expansion of the recycling capacities in the EU and worldwide respectively means a tremendous need for investments in particular technical installations (several billions of USD investment costs). Furthermore there is a continuous need for knowledge transfer and education of more skilled people, who have to plan and run further recycling plants in the future.

### **Development and realization of new recycling technologies**

Taken the given facts in chapter 0 and 6 into account, there is urgent need for further improvements and optimizations of existing recycling technologies – especially on the interface of suitable pre-treatment steps with core refinery plant performances. For instance further improvements for gallium, indium and tellurium which focus on quite new LCD and solar cell applications are necessary and should be back-bond by national, EU and international research programs. The growth of photovoltaic for example demands on a secure supply base of these important critical metals.

Need for research and development of total new technical procedures and recycling and refining concepts could be stated for:

- tantalum in dissipative EEE applications like cell phones,
- distinguished rare earth metals like europium etc. and
- lithium applications (current problem: missing economic incentives)

### **Accelerated improvement of international recycling infrastructures**

In several cooperative research activities with Umicore Öko-Institut has proved the fact that the main problems of the current recycling of critical metals are the lack of suitable take-back and collecting systems for post-consumer waste flows in largest parts of the world. [GFMS 2005, Buchert et al. 2008, Umicore/ÖI 2008] It should be underscored that practices like shown in the following figure are the reality for the recycling of critical metals today in most parts of the world. This means serious health risks for the people and tremendous losses of valuable critical metals.

Therefore there is an enormous need for know-how and technology transfer from the developed countries to the emerging economies in Asia, Africa and Latin America and to the developing countries, too. The global recycling for critical metals will fail in a large scale if a decisive improvement of the basic recycling infrastructure (first step: appropriate local and regional take-back and collecting systems; second step: appropriate pre-treatment steps → no open use of fire and chemicals in backyards!) in these countries will not succeed in the next 5-10 years. Especially Europe has the experiences and premises (leading level of technical, legal and logistical know-how to build up circular economies!) to contribute to these global target decisively. This means a serious responsibility for the EU and also Japan, USA etc. But on the other hand side the leading countries in the recycling of critical metals will get also in an economic, technological and political pole position.





Figure 8.2: “Low –tech” gold recycling in Bangalore/India (photo by courtesy of EMPA, Switzerland)

In the next five to ten years the following potentials for critical metals could be achieved if the above - performed measures will be realized consequently:

- For platinum and palladium 70% share of the gross demand could be satisfied through recycling until 2020 (today about 45%).
- In case of cobalt further moderate increase of the recycling percentage of at least 30% is regarded as realistic until 2020 (depending on applications with long-term lifetime).
- Concerning the “new” critical metals indium, gallium, germanium, tellurium and ruthenium in the next five years appropriate post-consumer recycling infrastructures and well shaped pre-treatment and refining technologies will be essential. By achieving these tasks, remarkable recycling quotas for these important critical metals for FST are possible.
- Regarding tantalum, lithium and the rare earths basic research in suitable recycling processes are required due to their crucial chemical behaviour in actual recycling processes.

## 9 Conclusions and recommendations

Öko-Institut likes to give the following conclusions and recommendations concerning the investigated critical metals within this short term study:

- The expected demand growth for the investigated critical metals could indicate different developments:
  - Growth of environmental-friendly technologies (e.g. photovoltaic, energy storage devices, catalysts for emission reductions etc.);
  - growth of overall mining production combined with related environmental stress;
  - enormous increase of the meaning of recycling technologies and related infrastructures in the next 5-10 years,
  - Investments of several billions USD will be essential for an enhanced circular economy regarding critical metals to satisfy demand growth and to reduce overall environmental impacts!
  - A further successful development concerning the recycling of critical metals will create additional employment in the developed countries as well in the emerging economies and the developing countries.
- We would like to recommend UNEP and its Resource Panel as well as the EU (on the occasion of their new strategy to address EU critical needs for raw materials) to give the investigated critical metals with short term risks (gallium, tellurium, indium: see chapter 0) a special focus in their work and policies during the next years; furthermore the tremendous resource efficiency potentials of the other metals should also be targeted.
- We would like to suggest profound research and development regarding to single metals of the rare earth elements due to their demand growth, supply risks (regional concentration) and their identified serious recycling restrictions. Also basic research on metals with serious technical recycling problems like tantalum in dissipative applications is very important.
- Furthermore research, development and initiation of recycling technologies corresponding to specific fields of applications (e.g. solar panels & indium containing LCD-monitors) is an urgent task, as well as legislation measurements (WEEE etc.)
- We would like to support regional (EU) as well as international organizations (UNEP, OECD) to multiply their engagement for the monitoring and controlling of illegal scrap-exports usually containing critical metals (e.g. WEEE, ELV etc.)
- Finally we would like to underscore that enhanced know-how transfer and international cooperation regarding the increasing stocks of used products in developing countries (e.g. old cars containing auto catalysts, electronic devices etc., used consumer electronics, batteries etc.) is crucial in order to avoid serious supply restrictions regarding valuable critical metals for future sustainable technologies.

The most important framework conditions that could help to foster technologies for the implementation of closed-loop recycling systems for critical metals are summarized as results of the study:

- Financial support by the EU regarding new recycling technologies for critical metals: A specified EU critical metals recycling program could include the encouragement of **research & development** activities as well as the installation of first demonstration plants. Such a program should focus on issues demanding for new technological solutions like the closed-loop recycling of lithium and rare earths from batteries and tantalum from electronic scraps etc.
- Special **investment programs** including low interest credits are important building blocks (e.g. by the by the Member States) to support the design and realization of large scale recycling plants for critical metals.
- Continuous improvements of the **EU legislation system** to ensure high plant utilizations for critical metals:
  - Extension of the WEEE Directive regarding the collection and recycling of post-consumer photo-voltaic modules (recycling of indium, gallium, tellurium etc.).
  - Further development of the ELV concerning critical metals due to the dismantling and recycling of large batteries from electric vehicles.
  - Improved legal frameworks for the distinction of used goods and scraps (e.g. in the case of WEEE, ELV) designated for the export in non-EU countries to rise the collection rate.
- Establishment of **Best Practice Guidelines** for the entire recycling value-chain for different applications / types of critical metals, inclusive product-design, collection, dismantling and pre-treatment on European level, bringing together the knowledge of the different stakeholders and considering different regulative area.
- **Campaigns and initiatives** by the EU and the Member States to draw attention of the public to the importance and value of critical metals: The activities should focus on used consumer goods, which are often bunkered for many years attempt less in households (e.g. mobile phones in drawers).
- **Comprehensive adaption** of technological issues regarding the recycling of critical metals in existing courses of study (special programs and professorships).
- **Technology transfer** and international cooperation should be decisively accelerated by international recycling conferences, technological implementation programs in emerging economies and developing countries and specific scientific exchange programs.

## 10 Literature

- Ackermann 2002                      Ackermann (Allgemeine Gold- und Silberscheideanstalt AGOSI, Pforzheim): Personal communication 06-06-2002.
- Andersson 2001                      Andersson, B. A.: Material Constraints on Technology Evolution: the Case of Scarc Metals and Emerging Energy Technologies, PhD Thesis, Department of Physical Resource Theory, Chalmers University of Technology and Göteborg University, Göteborg, Sweden 2001.
- Asian metal 2008                      “Gallium price curve for past 12 months, Gallium 99.99%min FOB China USD/kg”, [www.asianmetal.com](http://www.asianmetal.com) (accessed 10-29-2008)
- Behrendt 2007:                      Behrendt, S.: “Rare metals, Measures and concepts for the solution of the problem of conflict-aggravating raw material extraction – the example of Coltan”, Umweltbundesamt
- BGR 2006                              Bundesanstalt für Geowissenschaften und Rohstoffe: Rohstoffwirtschaftliche Steckbriefe für Metall- und Nichtmetallrohstoffe, 2006
- BMBF 2008                              German Ministry of Education and Research, Innovation Alliance, Lithium Ion Battery 2015 (2008), <http://www.bmbf.de/de/11828-php>
- Boliden 2008                              Boliden: <http://www.boliden.com/> (accessed 31-10-2008)
- Bray 2008                              Bray, E.L.: Aluminium, in Mineral commodity summaries 2008: U.S. Geological Survey
- BRGM 2008                              Bureau de recherches géologiques et minières: “Technologies innovantes et métaux High-Tech” 2008
- Buchert et al. 2008                      Buchert, M.; Hermann, A.; Jenseit, W.; Stahl, H.: Optimization of precious metals recycling – Analysis of exports of used vehicles and used electrical and electronic devices at Hamburg port, Öko-Institut in cooperation with Umicore Precious Metals Refining, Hanau; Darmstadt <http://www.umweltdaten.de/publikationen/fpdf-l/3199.pdf> 2007
- Bullion Desk 2008:                      [www.thebulliondesk.com](http://www.thebulliondesk.com)
- Bunz 2002                              Bunz, G. (Atelier Bunz, Dobel): Personal communication 06-07-2002.
- CDI 2007                              Cobalt Development Institute (CDI) “Cobalt Facts 2007”

- Christen 2005 Christen, M.: Die stofflichen Grenzen des Wachstums. Forschung und Technik, Neue Züricher Zeitung, 7th December 2005
- Claus 2008 Claus, D.: Materials and Processing for Lithium-Ion batteries, JOM, Minerals, Metals and Materials Society, September 2008
- Collard 2001 Collard, S. et al.: Precious Metal Recovery from Organic-Precious Metal Compositions with Supercritical Water Treatment, patent application WO 01/83834 A1, 2001.
- Continental 2008 Press release: Continental starts production of Lithium-Ion batteries for HEV, Nürnberg 09-24-2008
- Crystal 2008-10-31 Crystal International Consultants: Te-prices in 2008 for Te min 99.5%, BM-storage Bremen 2008, [www.crystal-consult.com](http://www.crystal-consult.com) (accessed 10-31-2008)
- Cunningham 2004: Cunningham, L.: Tantalum Recycling in the United States in 1998, in Sibley, S. "Flow studies for recycling metal commodities in the United States", U.S. Geological Survey, Reston, Virginia
- Di Francesco Hedrick 2007 Di Francesco, C.A.; Hedrick, J.B.: Rare Earth statistics, U.S. Geological survey, last modification November 20, 2007
- Di Francesco Kramer 2007 Di Francesco, C.A.; Kramer, D.A.: Gallium statistics, U.S. Geological survey, last modification September 28, 2007
- Donaldson et al. 2005 Donaldson, J.D. & Beyersman, D. "Cobalt and Cobalt Compounds" in in Ullmann's Encyclopedia of Industrial Chemistry, 2005
- Dornbusch 2002 Dornbusch (Fa. Christian Bauer, Welzheim): Personal communication 06-07-2002.
- DOWA 2008 DOWA metals and mining: overview of operations. [http://www.dowa.co.jp/en/jigyo/metalmine\\_summary.html](http://www.dowa.co.jp/en/jigyo/metalmine_summary.html) (accessed 10-31-2008)
- DOWA 2008 M. Naka, DOWA Eco-system Co. Ltd: Integration between mining & smelting business and environmental business, OECD-UNEP Conference on Resource Efficiency, 23-25 April 2008, Paris
- EM TB 1995 Degussa AG, Edelmetalltaschenbuch, Hüthig-Verlag Heidelberg, 1995.

- EM TB 2001 Edelmetall Taschenbuch, Hrsg. OMG AG & Co KG, Hanau, in former times: dmc<sup>2</sup> Degussa AG Metals Catalysts Cerdec AG, 3rd edition, Giesel Verlag 2001.
- EUWID 2008 EUWID Recycling und Entsorgung: Erste Recyclinganlage für Solar-Dünnschichtmodule, Publishing day 02-26-2008
- Felix 2005: Felix, N.: "Indium and Indium Compounds", in Ullmann's Encyclopedia of Industrial Chemistry, 2005
- First Solar 2008a Firstsolar: Information on Production, [www.firstsolar.com](http://www.firstsolar.com) (accessed 10-31-2008)
- First Solar 2008b Firstsolar Recycling Handout; download from [http://www.renosolar.de/datenblaetter/Solarmodule/First\\_Solar/Firstsolar\\_Recycling\\_handout.pdf](http://www.renosolar.de/datenblaetter/Solarmodule/First_Solar/Firstsolar_Recycling_handout.pdf) (accessed 10-31-2008)
- Fthenakis 2004 Fthenakis, V.M.: Life cycle impact analysis of cadmium in CdTe PV production, Renewable and Sustainable Energy Review 8 (2004) 303-334
- George 2007 George, M.W.: Minerals Yearbook 2006: Selenium and Tellurium, U.S. Geological Survey, October 2007
- George 2007 George, M.W.: Platinum Group Metals, in USGS Minerals Yearbook 2006, published in 2007.
- George 2008 George, M.W.: Platinum Group Metals, in Mineral commodity summaries 2008: U.S. Geological Survey
- George 2008 George, M.W.: Tellurium, in Mineral commodity summaries 2008: U.S. Geological Survey
- GFMS 2005 Hagelüken, C. (Umicore Precious Metals Refining); Buchert, M.; Stahl, H.; (Öko-Institut e.V.): Materials Flow of Platinum Group Metals – Systems Analysis and Measures for Sustainable Optimization of the Materials Flow of Platinum Group Metals. Umicore Precious Metals Refining and Öko-Institut e. V. ISBN 0-9543293-7-6, London: GFMS Ltd, 2005
- Gölitzer 2001 Personal communication Mr Gölitzer (Umicore) 11-02-2001 and 11-28-2001
- Greber 2002 Greber, J.F.: Gallium and Gallium compounds, copyright 2002, in: Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH 2005
- Grehl 2002 Grehl, M., Meyer, H.: Precious Metals Recovery from Spent Reforming Catalysts, Proceedings of European Workshop Spent Catalysts, DECHEMA, April 2002

- Groß-Stahl 2001                      Groß-Stahl (Platin Gilde International, Oberursel): Personal communication 12-17-2001 and 12-21-2001
- Hagelüken 1999                      Hagelüken, C.: Recycling of Spent Noble Metal Catalysts with Emphasis on Pyrometallurgical Processing, Oil Gas European Magazine 3, 1999
- Hagelüken 2007:                      Hagelüken, C.: Ressourcenknappheit bei Edelmetallen und seltenen Metallen? Presentation at EMPA Akademie Dübendorf, 12.04.2007
- Hagelüken 2008:                      Personal communication Christian Hagelüken (Umicore Precious Metals Refining) 08-27-2008
- Halada 2008:                          Halada, K., National Institute for Material Science: "Resource Risk and Possibility of Recycling" presented at OECD-UNEP Conference on resource efficiency, Paris 04-24-2008
- Haxel et al. 2002                      Haxel, G.; Hedrick, J.; Orris, G.: Rare Earth Elements – Critical Resources for High Technology, U.S. Geological Survey, Fact sheet 087-02, 2002
- Hedrick 2008a                          Hedrick, J. B.: Rare Earths, in Mineral commodity summaries 2008: U.S. Geological Survey
- Hedrick 2008b                          Hedrick, J. B.: Yttrium, in Mineral commodity summaries 2008: U.S. Geological Survey
- Hedrick 2008c                          Hedrick, J. B.: Minerals Yearbook 2006: Rare earths, U.S. Geological Survey, May 2008
- Heraeus 2002                          <http://www.wc-heraeus.com>, Stand 01-05-2002
- Hochfeld 1997                          Hochfeld, C.: Bilanzierung der Umweltauswirkungen bei der Gewinnung von Platingruppenmetallen für PKW-Abgaskatalysatoren, Öko-Institut e.V., Darmstadt 1997.
- ICGS 2007                              International Copper Study Group: ICSG Press Release: New edition of 'Directory of Copper Mines and Plants', 13 December 2007
- IPA 2008                                International Platinum Group Metals Association (IPA), <http://www.ipa-news.com/pgm/ruthenium/index.htm> (accessed 09-26-2008)
- Jäger-Waldau 2007:                      Jäger-Waldau, A.: PV Status Report 2007 – Research, Solar Cell Production and Market Implementation of Photovoltaics, European Communities 2007

- James 2008 James, M.; Lynas Corporation Ltd.: Presentation at Metal pages Minor metals & rare earths conference, 4 September 2008, Hong Kong
- Jaskula 2008 Jaskula; B.W.: Lithium, in in USGS Minerals Yearbook 2007, published in 2008.
- JM 2007 Memories are made of this (special feature about PGM and data storage technologies) in Platinum 2007:, Johnson Matthey Public Limited Company, Precious Metals Marketing, UK May 2007, ISSN 0268-7305
- JM 2008a Platinum 2008, Johnson Matthey Public Limited Company, Precious Metals Marketing, UK May 2008, ISSN 0268-7305
- JM 2008b Johnson Matthey: the home of PGM refining Setting the standard in global PGM refining services: <http://www.jmrefining.com/> (accessed 10-31-2008)
- Jorgenson 2005: Jorgenson, J.D.: Indium, in Mineral Commodity Profile, U.S. Geological Survey, 2005
- JRC 2005 Christidis, P.; Hernandez, H.; Georgakaki, A.; Peteves, S.D.: Hybrids for road transport, JRC-IPTS, JRC-IE, Sevilla 2005
- Kapusta 2006 Kapusta, J.: "Cobalt Production and Markets: A Brief Overview", published at JOM Journal, Oct.2006
- Karch 2001 Karch, R.: Rhodiumverbindungen in der homogenen Katalyse, in: Forschung und Entwicklung, ed. dmc<sup>2</sup>, Hanau, 2001.
- Kingsnorth 2008 Kingsnorth, D.J; Industrial Minerals Company of Australia (IMCOA): Rare earths: an industry at the traffic lights – are they green or red? Metal pages Minor metals & rare earths conference, 4 September 2008, Hong Kong
- Kleindrucker 2002 Kleindrucker, H. (Fa. Heinrich & Denzel): Personal communication 06-6-2002.
- Knoekaert 2005 Knoekaert, G.: Tellur and Tellurium compounds, in: Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH 2005
- Kramer 2007 Kramer, D.A.: Minerals Yearbook 2006: Gallium, U.S. Geological Survey, July 2007
- Kramer 2008 Kramer, D.: Gallium, in Mineral commodity summaries 2008: U.S. Geological Survey
- Kylander 2003 Kylander, M. et al.: Impact of automobile emissions on the levels of platinum and lead in Accra, Ghana, J. Environ. Monit., (Royal Society of Chemistry), 2003, 5, p. 91-95.



- Loferski 2008 Loferski, P.J.; Platinum Group Metals, in USGS Minerals Yearbook 2007, published in 2008.
- Matos et al. 2005 Matos, G.R.; Jorgenson, J.D.; Goerge, M.W.: Tellurium end-use statistics, U.S. Geological survey, last modification September 1, 2005
- Meskers 2008 Personal communication Christina Meskers (Umicore Precious Metals Refining) 08-27-2008
- Meskers et al 2009 Meskers, C.E.M.; Hagelüken, C.; Van Damme, G. (Umicore): Green recycling of EEE: special and precious metal recovery from EEE, TMS annual meeting 2009
- Metal Pages 2008: "Behind the quite face of Indium", 06-26-2008, [www.metal-pages.com](http://www.metal-pages.com) (accessed 09-12-2008)
- Metal Pages 2008a: "Demand for cobalt use in batteries set to reach a peak – Umicore", 16-05-2008, [www.metal-pages.com](http://www.metal-pages.com) (accessed 09-15-2008)
- NA 2008 Norddeutsche Affinerie AG <http://www.na-ag.com> (accessed 10-31-2008)
- National Academies 2008 "Minerals, Critical Minerals, and the U.S. Economy", Committee on Critical Mineral Impacts of the U.S. Economy, Committee on Earth Resources, National Research Council 2008
- NIMS 2008 National Institute for Materials Science (NIMS): Study on global flow of metals – an example of material recycling – Japan, May 2008
- NIMS 2008: National Institute for Material Science: "Study on global flow of metals –An example on material recycling-, 2008
- NREL 1999 National Renewable Energy Laboratory (NREL): assessment of critical thin film resources, RAF-9-29609, Tellurium, 1999
- O`Neill 2004: O`Neill, B.: "Indium: Supply, Demand & Flat Panel Displays", presented at Minor Metals 2004
- Papp 2006 Papp, F.: Minerals Yearbook: Niobium and Tantalum, U.S. Geological Survey
- Platinum Today 2008 PlatinumToday (Johnson Matthey): Lonmin posts full-year output decrease of 16 per cent, <http://www.platinum.matthey.com/>
- Platts 2008: Platts, "Japanese electronic firms consider zinc as an indium substitute", [www.platts.com](http://www.platts.com) (accessed 10-24-2008)

- Porter et al. 2007 Porter, K.E.; Jorgenson, J.D.; George, M.W.: Tellurium statistics, U.S. Geological survey, last modification: October 23, 2007
- RECUPYL 2008 RECUPYL: Recycling process of lithium batteries, <http://www.recupyl.com/117-recycling-process-lithium-batteries.html> (accessed 10-31-2008)
- Renner 1992 Renner, H.: Platinum Group Metals and Compounds, in: Ullmann's Encyclopedia of Industrial Chemistry, Vol. A 21, 75-131, Weinheim 1992
- Resource Efficiency 2008: Resource Efficiency Knowledge Transfer Network: Material Security, ensuring resource availability for the UK economy. Strategic report, Department for Business Enterprise & Regulatory Reform, Environment Agency, 2008
- RM 2008 Recapture Metals Inc.: [www.recapturemetals.com](http://www.recapturemetals.com); accessed 10-29-2008
- RWI 2007: RWI et al.: „Trends der Angebots- und Nachfragesituation bei mineralischen Rohstoffen“, research projekt of the german ministry of economic and technology (BMWi)
- Schwela 2007: Schwela, U.: Tantalum, in Mining Journal special publication
- Shedd 2008: Shedd, K.B.: Cobalt, in Mineral commodity summaries 2008: U.S. Geological Survey
- TIC 2008: Tantalum-Niobium International Study Center (T.I.C.) <http://www.tanb.org/tantalum1.html> (accessed 08-22-2008)
- Tolcin 2006: Tolcin, A.: Indium, in 2006 Minerals Yearbook, U.S. Geological Survey
- Tolcin 2008: Tolcin, A.: Indium, in Mineral commodity summaries 2008: U.S. Geological Survey
- Toxco 2008 Toxco, Anaheim, CA, United States, Lithium battery recycling process, <http://www.toxco.com/processes.htm>, (accessed 10-31-2008)
- Umicore 2008 Exploring Umicore, Umicore Precious Metals Refining, Antwerp, August 2008
- Umicore/ÖI 2008 Hagelüken, C. (Umicore Precious Metals Refining); Buchert, M (Öko-Institut e.V.): The mine above ground – opportunities & challenges to recover scarce and valuable metals from EOL electronic devices, IERC Salzburg, 01-17-2008.

- USGS 2007: Mineral commodity, Tantalum statistics, in Kelly, T.D., and Matos, G.R., Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series
- USGS 2007a: Mineral commodity, Cobalt statistics, in Kelly, T.D., and Matos, G.R., Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series
- USGS 2008: Mineral commodity summaries 2008: U.S. Geological Survey
- Van den Broeck 2008 Personal communication Kris Van den Broeck (Umicore Precious Metals Refining) 10-12-2008
- Van den Broeck 2008 Personal communication Kris Van den Broeck (Umicore Precious Metals Refining) 08-27-2008
- Wickens 2004: Wickens, J.: Development in the Tantalum markets, presentation at Minor Metals 2004
- Wietelmann et al. 2008 Wietelmann, U.; Bauer, R.J.: Lithium and Lithium Compounds, in Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2005.







## **About the UNEP Division of Technology, Industry and Economics**

The UNEP Division of Technology, Industry and Economics (DTIE) helps governments, local authorities and decision-makers in business and industry to develop and implement policies and practices focusing on sustainable development.

The Division works to promote:

- > sustainable consumption and production,
- > the efficient use of renewable energy,
- > adequate management of chemicals,
- > the integration of environmental costs in development policies.

### **The Office of the Director, located in Paris, coordinates activities through:**

- > **The International Environmental Technology Centre** - IETC (Osaka, Shiga), which implements integrated waste, water and disaster management programmes, focusing in particular on Asia.
- > **Sustainable Consumption and Production** (Paris), which promotes sustainable consumption and production patterns as a contribution to human development through global markets.
- > **Chemicals** (Geneva), which catalyzes global actions to bring about the sound management of chemicals and the improvement of chemical safety worldwide.
- > **Energy** (Paris), which fosters energy and transport policies for sustainable development and encourages investment in renewable energy and energy efficiency.
- > **OzonAction** (Paris), which supports the phase-out of ozone depleting substances in developing countries and countries with economies in transition to ensure implementation of the Montreal Protocol.
- > **Economics and Trade** (Geneva), which helps countries to integrate environmental considerations into economic and trade policies, and works with the finance sector to incorporate sustainable development policies.

*UNEP DTIE activities focus on raising awareness,  
improving the transfer of knowledge and information,  
fostering technological cooperation and partnerships, and  
implementing international conventions and agreements.*

For more information, see  
**[www.unep.fr](http://www.unep.fr)**

For more information, contact:

**UNEP DTIE  
Sustainable Consumption and  
Production Branch**

15 rue de Milan  
75441 Paris CEDEX 09, France  
Tel: +33 1 4437 1450  
Fax: +33 1 4437 1474  
E-mail: [unep.tie@unep.org](mailto:unep.tie@unep.org)  
[www.unep.fr/scp](http://www.unep.fr/scp)

[www.unep.org](http://www.unep.org)

United Nations Environment Programme  
P.O. Box 30552 Nairobi, 00100 Kenya  
Tel: (254 20) 7621234  
Fax: (254 20) 7623927  
E-mail: [unep@unep.org](mailto:unep@unep.org)  
web: [www.unep.org](http://www.unep.org)



**Öko-Institut e.V.**

Darmstadt Office  
Rheinstr. 95  
64295 Darmstadt  
Germany  
Tel: +49 (0) 6151 – 8191-47  
Fax: +49 (0) 6151 – 8191-33  
E-mail: [m.buchert@oeko.de](mailto:m.buchert@oeko.de)  
[www.oeko.de](http://www.oeko.de)

*The focus of this study lies on future sustainable technologies (FST), such as renewable energies and energy efficient technologies, which will make use of indium (In), germanium (Ge), tantalum (Ta), PGM [platinum group metals, such as ruthenium (Ru), platinum (Pt) and palladium (Pd)], tellurium (Te), cobalt (Co), lithium (Li), gallium (Ga) and RE (rare earths). These are also classified as 'green minor metals', which are the basis for cleaner technology innovation and therefore an issue for recycling.*