# Resource efficiency and resource policy aspects of the electro mobility system

## Work package 7 of the OPTUM research project: Environmental Relief through Electro Mobility

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## List of abbreviations

| | |
|---|---|
| a | anno = year |
| ADP | Abiotic depletion potential |
| Ag | Silver |
| Al | Aluminium |
| Au | Gold |
| BEV | Battery Electric Vehicle |
| BGR | Bundesanstalt für Geowissenschaften und Rohstoffe [Federal Institute for Geosciences and Natural Resources] |
| BMU | Federal Ministry for the Environment, Nature Conservation and Nuclear Safety |
| CED | Cumulative Energy Demand |
| CIS | Commonwealth of Independent States |
| CM | Combination matrix |
| $CO_2$ | Carbon dioxide |
| Comp | Components |
| Cr | Chromium |
| Cu | Copper |
| Dy | Dysprosium |
| EM | Electromagnet |
| EOL | End-of-life |
| E-PassV | Electric passenger vehicle |
| EV components | Electric vehicle components |
| E-vehicle | Electric vehicle |
| FCEV | Fuel Cell Electric Vehicle |
| Fe | Iron |
| g | Gram |
| Ga | Gallium |
| GaN | Gallium nitride |
| Ge | Germanium |
| GWP | Global Warming Potential |
| HEV | Hybrid Electric Vehicle |
| ICE | Internal Combustion Engine |
| In | Indium |
| IZT | Institut für Zukunftsstudien und Technologiebewertung [Institute for Futures Studies and Technology Assessment] |

| | |
|---|---|
| Kg | Kilogram |
| km | Kilometre |
| kW | kilowatt |
| KWh | kilowatt hour |
| LED | Light emitting diode |
| m | Millions |
| MJ | Megajoule |
| Nd | Neodymium |
| NdFeB | Neodymium iron boron |
| Ni | Nickel |
| OEM | Original Equipment Manufacturer |
| p.a. | per annum = per year |
| PassV | Passenger Vehicle |
| Pd | Palladium |
| PE | Power electronics |
| PGM | Platinum group metal |
| PHEV | Plug-In Hybrid Electric Vehicle |
| PM | Permanent magnet |
| $PO_4$ | Phosphate |
| ppb | Parts per billion |
| Pr | Praseodymium |
| $P_{reg}$ | Number of passenger vehicle registrations |
| Pt | Platinum |
| PV | Photovoltaics |
| $Q_{Recyc}$ | Quantity of recycled material (in kg) |
| R&D | Research and development |
| RE | Rare earths |
| REE | Rare earth elements |
| REX | Range Extender |
| RFID | radio-frequency identification |
| Ru | Ruthenium |
| Sb | Antimony |
| Sc | Scenario |
| $SO_2$ | Sodium dioxide |
| Tb | Terbium |
| $T_{foc}$ | Focus year |

| | |
|---|---|
| y | Year |

x

# 1 Summary

The anticipated market penetration of electro mobility which in Germany has been promoted through the national electro mobility platform will undoubtedly have considerable effects on the resource requirements for important and in some instances critical metals.

As there are already supply bottlenecks for a whole range of metals (e.g. rare earths, indium) due to the growth in demand in other sectors, the German Federal Environment Ministry (BMU) has commissioned the Öko-Institut to carry out research into the "Resource efficiency and resource policy aspects of the electro mobility system" as part of the BMU's project "Environmental Relief through Electro Mobility – integrated survey of vehicle use and energy management – OPTUM".

The Öko-Institut has therefore examined the following issues with support from its partners Daimler AG, Umicore and TU Clausthal.

- Which important raw materials are used in electric cars (or hybrid vehicles)?
- What quantitative requirement for these raw materials can be anticipated for the electro mobility system on a global scale by 2030?
- How important are the environmental effects associated with the extraction and further processing of the different raw materials?
- Compared to this, how much environmental relief can be expected from electric mobility?
- What is the current status of recycling for the important metals and what are the prospects for the future?
- What is the situation in terms of the primary raw materials, i.e. existing reserves and their lifetime, technical and political effects on the supply?
- What effects will the planned global development of electro mobility have on the supply situation and future price trends of the raw materials needed?
- What potential relief can be gained by reducing the requirements of specific metals for particular components or which alternative technologies could ease the demand for raw materials?

Based on the specific fields of expertise of the individual partners, the project team worked on responses to the above questions by carrying out in-depth research including personal interviews with external specialist institutions. An important element of this was the presentation and discussion of interim results at a total of three specialist workshops with scientific, economic and political experts.

After thoroughly investigating 56 metals and discussing these at the first specialist workshop, the project team produced an initial list of 15 top-priority metals for electro mobility. Of these, lithium and cobalt were not dealt with in depth in the project as they had already been looked

at in detail in other projects[1] in the BMU programme. Ruthenium was removed from the list of priority metals during the course of the project in agreement with all those involved. The remaining 12 priority metals which were studied in detail in the project are neodymium (Nd), praseodymium (Pr), dysprosium (Dy), terbium (Tb), indium (In), gallium (Ga), germanium (Ge), gold (Au), silver (Ag), copper (Cu), platinum (Pt) and palladium (Pd).

In order to be able to quantify the potential future demand for the priority metals from electro mobility, the project team built on the global market scenarios by McKinsey 2009 for the development of electro mobility. These were linked with detailed data on the quantities of metals (1st priority) in the important components[2] of the different electro mobility drive systems (hybrid, plug-in, range-extender, battery electric and fuel cell vehicles). The detailed data for the raw material requirements for the different components were defined by the project team by evaluating all available sources and after in-depth discussion with the experts at the specialist workshops.

The specific scenarios were initially based on the optimistic scenario for the development of electro mobility by McKinsey (baseline scenario I). Variations with different effects on the global requirement of primary metals were produced by

- Adding assumptions on increased material efficiency (less metal per component): Innovation scenario II
- Based on innovation scenario II, adding assumptions on increased recycling rates: Recycling scenario III
- Based on the recycling scenario III, adding assumptions on the partial substitution of electric motors with permanent magnets (rare earths) by alternative motors: Substitution scenario IV
- Finally, the growth of electro mobility in the moderate McKinsey scenario was combined with all the assumptions in the substitution scenario.

The results of the different scenarios provided clear trends for the global requirement of primary metals for electro mobility up to the year 2030. The rare earths (Nd, Pr, Dy, Tb) and gallium turned out to be particularly important in comparison with total primary production of these metals in the base year 2010. The most marked growth in demand from electro mobility was for dysprosium. The demand for this rare earth for electro mobility in the baseline scenario in 2030 corresponds to 482% of the total present production of this metal. Although the proposed measures do reduce the rise in demand in the other scenarios, the 287% (innovation scenario), 191% (recycling scenario) and 71% (substitution scenario)

[1] LithoRec: http://www.pt-elektromobilitaet.de/projekte/batterierecycling/lithorec; LiBRi: http://www.pt-elektromobilitaet.de/projekte/batterierecycling/libri

[2] All the important components such as the electric motor, power electronics etc. were included. This project excluded the battery component as the battery metals lithium and cobalt have already been studied in depth in the LiBRi and LithoRec projects and were the subject of the scenarios in LithoRec.

represent a rapidly growing future demand for dysprosium for electro mobility despite the comprehensive measures. This also applies to the results of the moderate scenario.

The scenario results acquire significant importance against the background of the existing supply bottleneck for dysprosium which is currently only produced in China. The short supply on the primary production side which is likely to continue for the next few years is accompanied by a steadily rising demand from the electro mobility sector. In addition, demand is also rising in other fields of application for neodymium iron boron magnets, which in turn require dysprosium. The growing wind power sector should be mentioned here, for example. Similar developments should also be noted for the other rare earth metals neodymium, praseodymium and terbium, although the situation for dysprosium is particularly pressurised in the unanimous view of the experts involved.

The primary production of metals is frequently linked to considerable environmental pollution from the mining, concentration and metallurgical transformation processes. This is applicable to the rare earths to an even greater degree as most of the ore deposits are polluted with radioactive nuclides (thorium etc.), bringing associated risks for human beings and the environment. Metal recycling can usually have a considerable effect on the net environmental relief, in addition to making an important contribution to reducing the demand pressure on the primary raw materials. However, there is no recycling of rare earth metals such as dysprosium being done anywhere in the world at present. However, the steep rises in the price of raw materials and the sometimes precarious supply situation have recently initiated research and development efforts in recycling of e.g. magnets which contain rare earth metals. This also applies to many other priority metals identified in the project.

The project team from the Öko-Institut, Umicore, Daimler AG and TU Clausthal, Institute of Mineral and Waste Processing, Waste Disposal and Geomechanics have drawn the following important conclusions from the comprehensive results of the project "Resource efficiency and resource policy of the electro mobility system":

- The supply of **rare earths** – especially dysprosium – is particularly critical. Resource efficiency and technological substitution show the greatest potential for controlling supply bottlenecks in the medium term. Recycling is an important option to reduce shortages in the medium and long term, but is likely to have insignificant effects over the next few years due to the steadily increasing total demand and the long lifetime of the products.
- **Gallium** is also used in many applications apart from electric mobility (e.g. PV, LED). Significant increases in demand are to be expected. With a steep increase in demand and the lack of counter measures, the supply of gallium could become critical in the longer rather than shorter term (development of global extraction capacity for gallium as a by-product of the Bayer process [alumina extraction] and an actual start to post-consumer recycling).

- **Indium** is not critical in terms of electro mobility. **HOWEVER** there are many competing fields of application with high growth rates. Indium only occurs as a minor metal and a close eye must therefore be kept on it.
- **Germanium** is not critical in terms of electro mobility. **HOWEVER** high growth rates could occur in other applications (e.g. fibre optic technology, LEDs) and basic information is lacking for germanium (the "phantom" element) and its demand development.
- **The precious metals silver, gold, palladium and platinum** are also used in the components for electro mobility, with platinum of particular importance in fuel cell vehicles. On the other hand, the development of electro mobility in terms of all-electric vehicles can reduce the demand for platinum and palladium as catalytic converters are no longer required.
- **The current critical supply situation for some rare earths** is a cautionary example of the fact that bottlenecks can occur at least temporarily despite globally high geological reserves if geopolitical factors (mining almost exclusively in one country) correlate with a rapid growth in demand. Lessons for the future should be learned from this so that proactive countermeasures can be planned (by timely exploration and development of deposits, diversifying the supply, promoting recycling etc.).

The project team produced recommendations for action from the results and conclusions and these were presented to the expert participants for discussion at the concluding workshop. The recommendations met with general agreement. Nonetheless, important suggestions about the recommendations for action were made to the project team by the group of external experts and these have been incorporated in the following list of recommendations for action:

- **In view of the risk of a bottleneck in the supply of rare earths, different relief strategies need to be pursued simultaneously**
  - R&D into reduction of REs (esp. dysprosium) in magnets for e-motors and into RE-free e-motors
    →*Responsible: Government ministries for promotion programmes, OEMs (manufacturers of electric motors, magnet manufacturers) and the scientific community with regard to innovation*
  - Development of recycling technologies for permanent magnets from different applications
    → *Responsible: Government ministries for promotion programmes, the recycling industry and the scientific community*
  - Promotion of environmentally friendly primary production of REs (standards required)
    → *Responsible: German government and EU Commission via international negotiations, companies involved in rare earth mining*

- **Promotion of more environmentally compatible mining for the extraction of critical metals**
  - There is significant potential to make better use of natural resources by improving extraction rates in the primary production and processing of many metals (e.g. rare earths). For important minor metals such as indium, potential also exists in the form of unused residues at mining sites some of which are now closed.

    → *Responsible: BGR and institutes involved in mining and processing which can prospect for mining residues and promote technical cooperation and knowhow transfer for optimised extraction*
- **Development of recycling strategies and technologies for the recycling of power electronics from EOL electric vehicles**
  - Recovery of copper, gallium, precious metals etc.
    → *Responsible: Government ministries for promotion programmes, the recycling industry and the scientific community*
- **General research needs**
  - Analysis of potential and recycling options for “conventional” electronic devices and other magnet applications in future passenger vehicles of all types in terms of precious and special metals incl. rare earths.

    → *Responsible: Government ministries for promotion programmes plus the recycling industry and OEMs (manufacturers of automotive electronics and magnets)*
- **Significant increases** are expected in the use of gallium, indium and germanium in other applications: it is currently not clear whether growth rates – and hence supply risks – resulting from technological revolutions such as LED technology or PV (post Fukushima) are still being underestimated.
  **The medium- and long-term effects on e-mobility need to be explored and solution strategies developed.**
  → *Responsible: Government ministries for promotion programmes*

In order to reach a broad audience and to stimulate important discussion, the project partners and the BMU intend to disseminate and present the project results to important groups of actors in a variety of ways, both at a national and international level.

## 2 Aims of the work package

The further development and successful implementation of electro mobility is an important key to sustainable mobility. The German government therefore adopted the National Electro Mobility Development Plan on 19 August 2009. The BMU programme "Promoting research and development in electro mobility" comes under the auspices of the National Electro Mobility Development Plan. After the resource aspects and future recycling of the high-performance batteries (lithium-ion batteries) needed for electro mobility had been addressed by the joint LithoRec and LiBRi projects as part of the BMU programme, the aim of the work package described here – "Resource efficiency and resource policy aspects of the electro mobility system" (part of the BMU project "Environmental Relief through Electro Mobility - integrated survey of vehicle use and energy management") – was to carry out a comprehensive study of the resource aspects of all the remaining components of the electro mobility system including the recycling options and prospects. Ultimately, the aim is to detect any potential political "bottlenecks or weak points" in the resources for the electro mobility system as soon as possible and develop strategies and practical proposals for avoiding or remedying them.

The following sub goals are addressed in the context of resource efficiency and resource policy in the electro mobility system, in order to provide scientific answers to the various important questions from the BMU.

- Determine the important raw materials used in electric vehicles (or hybrid vehicles); including their areas of application and the important components and parts of the system.
- Determine or estimate the quantitative requirement of these raw materials for the electro mobility system by means of scenarios. The period fixed for the scenarios is 2010 to 2030. The requirement is to be quantified using scenarios in demand ranges at a global scale.
- Research and presentation of the environmental effects connected to the extraction and further processing of the different raw materials plus a comparison of these environmental effects with the environmental relief which can be expected from electro mobility.
- Detailed study of the degree to which recycling of the constituent raw materials is currently technically and economically possible and which measures are necessary to guarantee the recycling or reuse of materials from electric vehicles and related components (e.g. charging stations etc.);
- Clear presentation of the existing reserves of these raw materials plus estimates of their lifetime and potential concentration of reserve and/or production capacities in a few countries;
- Determine and present the effects of the planned global expansion in electro mobility on the supply situation and the future price development of the necessary raw materials.
- Research into substitutes or alternative technologies for individual components to reduce demand for the necessary raw materials. This should focus on those raw materials which should be classified as critical in terms of their availability and far-reaching environmental effects.

# 3 Methods

The project team first carried out a methodical screening of a total of 56 metals in relation to their importance for electro mobility. The aim of this screening was to collect data for compiling a list of priority metals for electro mobility (see Section 5) which would then be studied in more detail later in the project.

The project partners were in agreement that this first broad investigation should be as comprehensive as possible to ensure that any less obvious metals which might have an important role for particular components of the electro mobility system were not overlooked. The investigation therefore included all elements in the periodic table excluding

- Non metals
- Radioactive elements,
- Obviously toxic elements such as cadmium, thallium and mercury,
- Sodium, potassium, calcium and
- Bulk metals and alloying metals such as iron/steel, aluminium, chromium and nickel.

The research into the 56 metals included all conceivable types of electro mobility for passenger vehicles i.e. hybrid vehicles, plug-in hybrid vehicles, range extender, all-electric vehicles and fuel cell vehicles. In addition to a full examination of the relevant specialist literature, wide-ranging research was carried out on the Internet (for sources in German and English). In addition, interviews were held with important companies and research institutions such as Bosch, Vacuumschmelze und Fraunhofer-ISI in order to complete and corroborate the data obtained by research with first-hand information. Finally, at the project's first specialist workshop, a proposal for a list of priority metals for electro mobility was presented along with the reasons for their selection to around 35 experts from industry, the scientific community and government authorities (see appendix for list of participants). The project team used the following criteria for this preliminary selection:

- **Requirement for 30 million electric vehicles: current technology** (in relation to current global production of the raw material)
- **Requirement for 30 million electric vehicles: future technology** (in relation to current global production of the raw material)
- **Anticipated growth in demand for the metal up to 2030**
  - Total demand incl. competing applications
  - Not substitutable
- **Reserves to production ratio**
  - Ratio of current demand to reserves (from USGS)

- **Restrictions due to availability of natural deposits**
    - Regional concentration
    - Temporary shortage (lag in production compared to demand)
    - Structural / technical shortage (metal as a by-product)
    - Political stability of the main producer countries
- **Recycling potential**
    - Current recycling situation
    - Anticipated recycling potential

The metals selected as 1st priority plus those of 2nd and 3rd priority were discussed in detail at the workshop. Most of the suggestions were agreed by the participants, but after the discussion some metals were moved to the 1st priority (e.g. silver). The procedure involving the research and agreement with a broad circle of experts proved very successful.

After coming to an agreement about the priority metals, the project team collated the quantitative information for the important components such as power electronics, electric motors etc. (cf. Section 6) for these metals (cf. Section 5) and used this to produce a data matrix (quantity of priority metals per component and per electric vehicle divided into the sub-types of hybrid vehicles etc. already specified). These data were combined with the scenario data on the global development of the passenger vehicle market up to 2030 with particular reference to the potential development of electro mobility (cf. the scenario predictions of the global PV market, Section 7).

This allowed the project team to quantify the global consumption of raw materials for electro mobility in terms of the priority metals up to 2030 for the different scenarios. The scenarios differ in terms of the assumptions about the global development of electro mobility in general and the different assumptions about material innovations (lower quantities of priority metals used per vehicle). They also differ as regards the decreased primary metal requirements from the reductions due to recycled metals and through substitution effects (saving on priority metals due to alternative technical components). Details of the scenario assumptions (in this case primarily the quantity of priority metals per component and per e-vehicle) were presented to the experts and subject to critical discussion at the second project workshop (see appendix for list of participants). Important comments from the group of experts were included when finalising the data set. This enabled the data base to be verified by a wide audience and a good consensus with the participants achieved. Details of the consolidated scenario assumptions and the results of the scenarios are described in detail in Section 7 of this report.

In order to estimate the future development of supply and demand, the project team also researched and presented the expected development in the total demand (all applications for the priority metals) and compared this with the demand from electro mobility (cf. Section 10).

In addition to the comprehensive evaluation of the global requirement for raw materials in terms of the priority metals for electro mobility, the project partners also studied the environmental effects of raw material extraction and the production of primary metals and compared this with the corresponding reductions from material savings due to the elimination of components (e.g. internal combustion engine) from the traditional internal combustion drive system. Furthermore, the situation of the reserves of priority metals and the corresponding reserves to product ratios were studied and described (details are given in Section 8). Last, the current status of recycling for the priority raw materials and the likely prospects for optimising the recycling processes were investigated and presented under the lead of the partner Umicore (cf. Section 9). Recycling makes an important contribution both to guaranteeing the future supply of critical metals for future technologies and also for an improved net environmental balance sheet.

The complete results and evaluations of the scenarios and the comprehensive research into the priority metals in terms of the raw material situation, the environmental balance sheet for their production and the current recycling situation and future prospects were then used to produce comprehensive recommendations for action for a variety of target groups in order to improve resource efficiency in electro mobility. These recommendations were put forward for detailed discussion at the final workshop (see appendix for list of participants) after presentation of the full results. The results of this discussion process are given in Section 11.

# 4 Short description of the electro mobility drive systems and market forecasts

The following sections present the electro mobility drive systems covered by this project and their components plus the market scenarios on which the forecasts are based.

## 4.1 Short description of the electro mobility drive systems

In general all vehicles with electrical drives i.e. both all-electric vehicles and those with hybrid drives are subsumed under the heading of electro mobility. All-electric vehicles are those which have only an electric engine (electric motor) which is driven using electrical power irrespective of the energy storage device used (for example batteries[3] or fuel cells). Besides the electric motor, hybrid vehicles have a second conventional engine (an internal combustion engine). The electric motor performs different jobs, depending on the degree of hybridisation, from energy recovery during braking to electrical driving.

The project "Resource efficiency and resource policy of the electro mobility system" deals with the hybrid and all-electric drive designs described in detail in the following sections.

[3] The electrical energy storage device in hybrid and electric vehicles is often called a battery in English usage. But it is actually an accumulator (secondary cells) which unlike a battery (primary cells) can be recharged.

### 4.1.1 Hybrid vehicles (Mild Hybrid Electric Vehicle und Full Hybrid Electric Vehicle – MHEV und FHEV)

Mild Hybrid is the name given to vehicles with internal combustion engines which are able to recover energy during braking with the aid of an additional electric motor[4] and store this in the hybrid battery. The electric motor uses the energy stored in this manner to support the internal combustion engine during acceleration (boosting).

An example of a vehicle with mild hybrid drive is the S class S400 made by Mercedes Benz. The electric motor has a power rating of 15 kW and the accumulator features a capacity of just less than 1 kWh.

In comparison with the mild hybrid, the full hybrid usually has a more powerful electric motor and an accumulator with a somewhat larger capacity. The crucial difference from a mild hybrid is that the full hybrid can also drive for short distances with electrical drive alone i.e. without the internal combustion engine.

One vehicle with this type of drive is the Toyota Prius in which the third generation (ZVW30) has an electric motor with a power rating of 60 kW. The accumulator in the Prius has a capacity of 1.3 kWh (nickel metal hydride) [Toyota, 2011]. The electrical range is approx. 2 km. Another series vehicle with full hybrid drive is the Mercedes Benz ML 450 hybrid. This has two electrical drives, one with 67 kW and one with 63 kW. The nickel metal hydride battery allows the vehicle to drive around 2.5 kilometres on electricity alone.

When calculating the requirements for the scenarios (see Section 7), no distinction was made between mild and full hybrid vehicles for the components, with averaged values being used for hybrid vehicles.

### 4.1.2 Plug-in hybrid vehicle (Plug-In Hybrid Electric Vehicle – PHEV)

The drive design for a plug-in hybrid goes a stage further. The capacity of a plug-in hybrid battery is significantly greater than that of a full hybrid for one thing and, for another, in a plug-in hybrid the accumulator can be charged from the power grid. Like the full hybrid, the plug-in hybrid supports the vehicle's drive via the electric motor, the internal combustion engine or the combination of both. However, the higher accumulator capacity enables considerably longer distances on electricity alone. Depending on the driving style and the accumulator capacity, current studies indicate that plug-in hybrids support up to 20-30 km of local emission-free driving. As vehicles with plug-in hybrid technology are designed for longer all-electric distances they usually have higher performance electric motors – in comparison with the full hybrid – with over 50 kW.

There are no series vehicles with plug-in hybrid technology to date. At the IAA 2009 Mercedes Benz exhibited the "Mercedes Benz Vision S 500 Plug-in HYBRID" which has an

[4] In regenerative braking the electric motor is used as a generator.

all-electric range of just under 30 kilometres with its lithium-ion battery supplying 10 kWh. There is also a plug-in version of the Toyota Prius which was first exhibited at the IAA 2009. This version is based on the third generation Prius. The battery capacity has been increased by over 5 kWh so that the vehicle now has an all-electric range of 20 kilometres. In 2010 Toyota started a leasing project with around 500 vehicles, some of which were and are used as part of the BeMobility research project. Toyota plans to have the vehicle in full-scale production from 2012 [Toyota 2011].

### 4.1.3 Range extender vehicles (Range Extender Electric Vehicle – REEV or REX)

Vehicles with range extender technology also have an internal combustion engine and one or even two electric motors (the second functions as a generator). In contrast to plug-in hybrid vehicles in which the internal combustion engine is the primary drive, in the range extender the electric motor is the main drive (typically 50 kW and above). The function of the internal combustion engine is to stabilise the state of charge of the battery (i.e. recharging the battery) if its charge falls below a certain level. The internal combustion engine drives a generator which charges the battery using the electrical power which it produces. Depending on the drive design of the range extender, both the generator and the internal combustion engine can be used as additional drive motors (cf. e.g. Opel Ampera and B-Class E-CELLPlus).

The Opel Ampera, one of the first series vehicles with range extender technology, will be available in Europe in the last quarter of 2011. It has an all-electric range of 40-80 kilometres using a 16 kWh lithium-ion battery [Opel 2011]. In 2009 Mercedes Benz exhibited a range extender vehicle at the IAA, the BlueZERO E-CELL PLUS in the BlueZero trilogy. At the IAA 2011 Mercedes Benz then exhibited the B-Class E-CELL PLUS near-series concept vehicle on the new B Class (BR246) platform. The all-electric range of the concept vehicle is around 100 km. The series vehicle is scheduled for 2014.

### 4.1.4 Battery Electric Vehicle – BEV

In contrast to all the drives described so far which have an internal combustion engine in addition to the electric motor, the battery electric vehicle only has an electric motor and no internal combustion engine. Energy is stored in an accumulator (battery), the most popular currently being based on lithium

Because the drive is provided solely by the electric motor, these vehicles tend to have larger electric motors with power ratings over 50 kW to achieve an adequate road performance. Electric vehicles require battery capacities of 15 kWh and above, depending on the vehicle's size and the desired range.

The early near-series or series vehicles on the German market were the Mitsubishi i-MiEV with a 49 kW electric motor and a 16 kWh Li battery [Mitsubishi 2011] and the smart Electric Drive (smart ed) which uses a 50 kW electric motor and has a lithium-ion rechargeable battery of around 17 kWh in the newest generation. The manufacturers' specified range is around 150 km for the i-MiEV and over 140 km for the smart ED.

### 4.1.5 Fuel Cell Electric Vehicles – FCEV

Like the battery electric vehicle, a fuel cell electric vehicle has no internal combustion engine but only an electric motor. The energy store in this case is hydrogen which is converted by the fuel cell into electric energy for driving the electric motor. Depending on the size of the vehicle, size of the hydrogen tank and its permitted maximum pressure of approx. 700 bar, these type of vehicles can currently achieve ranges of 400 km and over with one tank of fuel. Fuel cell vehicles also have a small battery as an additional energy store besides the hydrogen tank. This battery has a similar capacity and functionality to the mild hybrid. It is charged both by the fuel cell and by energy which is recovered during braking. The energy stored in the accumulator is used to cover the drive's peak power requirements.

Mercedes Benz has been using the A Class (BR168) with a fuel cell (A Class F-CELL) in fleet tests since 2004. This was replaced by the B Class (B Class F-CELL based on the BR245 series) in 2005. The B Class F-Cell is produced as a small batch under series manufacturing conditions. The electric motor produces 100 kW and the range is around 400 kilometres. The lithium-ion battery has a storage capacity of 1.4 kWh. In addition to Mercedes Benz, Honda also manufactures a fuel cell vehicle. Honda started supplying the FCX in 2002, replacing it with the second generation, the Honda FCX Clarity, in 2008. These vehicles are available as leasing models for selected private and business customers in the USA and Japan. The electric motor produces 100 kW and the range is around 400 km. The lithium-ion battery has a capacity of around 1.2 kWh [Honda 2011].

## 4.2 Components of hybrid, electric and fuel cell vehicles

Besides the components of the electric motor (or generator) and battery already mentioned in the previous section, hybrid, electric and fuel cell vehicles need additional components for electric drive systems, such as power electronics and additional cables which do not occur in the same form or quantity in conventional drives based on the internal combustion engine.

The **electric motor** already mentioned carries out the function of the drive or supports a second (conventional) drive, depending on the type of vehicle and drive system. In addition, the electric motor functions as a **generator** by generating electrical energy from kinetic energy (regenerative braking).

The electrical energy is stored in a **battery** which can also be charged at a charging point or a domestic power socket in the case of some electric drives.

The **power electronics** are a further important component of electrical drives. The main function of the power electronics is to convert electrical energy from the accumulator (direct current) into the correct voltage and frequency for the electrical drive motor.

### 4.2.1 Hybrid vehicles (MHEV, FHEV and PHEV)

As already described in Sections 4.1.1 and 4.1.2, besides the conventional internal combustion engine, hybrid vehicles have a more or less powerful electric motor depending on the degree of hybridisation. Increasing the performance of the electric motor also increases the demands on the power electronics, meaning that more powerful electric motors also require more powerful power electronics.

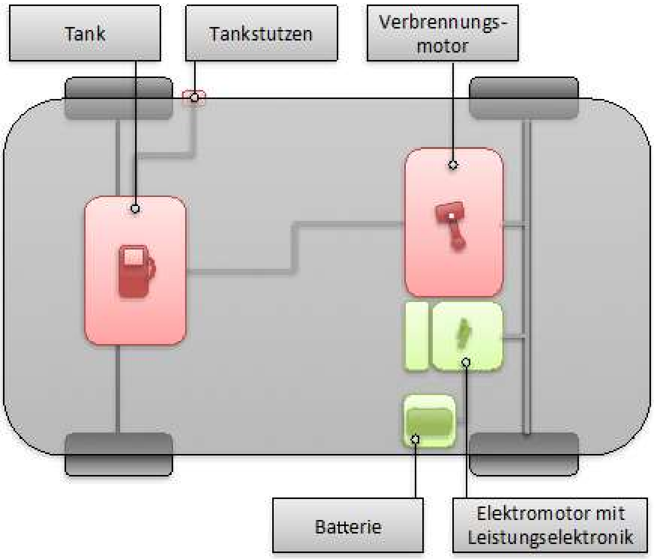



Figure 1 Diagram of the components of a full hybrid vehicle (figure Daimler AG)

The battery capacity increases parallel with the degree of hybridisation. The plug-in hybrid also requires a charging socket.

### 4.2.2 Range extender vehicle (REEV or REX)

Range extender vehicles use the electric motor as their main drive, so that these and the accompanying power electronics need to have a correspondingly powerful design. The range extender drive also needs an additional electric motor with accompanying power electronics as a generator, and a charging socket.

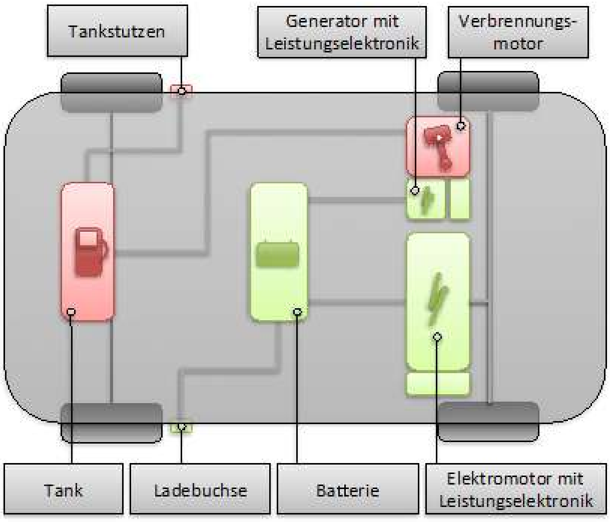



Figure 2 Diagram of the components of a range extender vehicle (figure Daimler AG)

### 4.2.3 Battery electric vehicles (BEV)

As battery electric vehicles only have an electric drive and therefore tend to have powerful electric motors, this also necessitates the use of powerful power electronics.

Battery electric vehicles do not have an internal combustion engine, so that there is no need for a catalytic converter nor the whole exhaust system and tank.

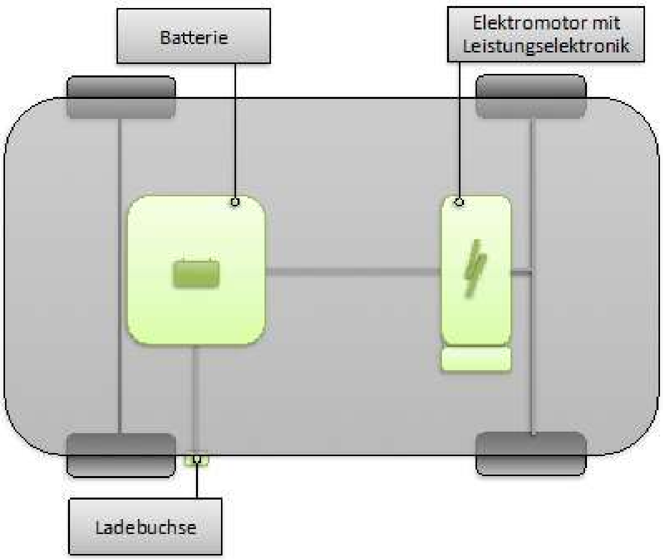



Figure 3 Diagram of the components of a battery electric vehicle (figure Daimler AG)

### 4.2.4 Fuel cell vehicle (FCEV)

The fuel cell vehicle occupies a special position amongst electrically driven vehicles. Besides the electric motor, accumulator and – due to the powerful electric motor – large power electronics, the fuel cell powertrain includes three further components: the fuel cell stack, the fuel cell system modules and the hydrogen tank.

The **fuel cell stack** is the core of the fuel cell and performs the function of generating electrical energy from atmospheric oxygen and hydrogen from the vehicle's tank, which are then used to drive the electric motor. The components which ensure that the fuel cells have enough oxygen and hydrogen in accordance with the road load are called the **fuel cell system module**. These components also ensure that the hydrogen and oxygen are fed to the fuel cell at the correct pressure. They also remove excess heat via the cooling circuit and steam from the vehicle. The **hydrogen tank** – consisting of aluminium and carbon fibre – stores the gaseous hydrogen under very high pressure.

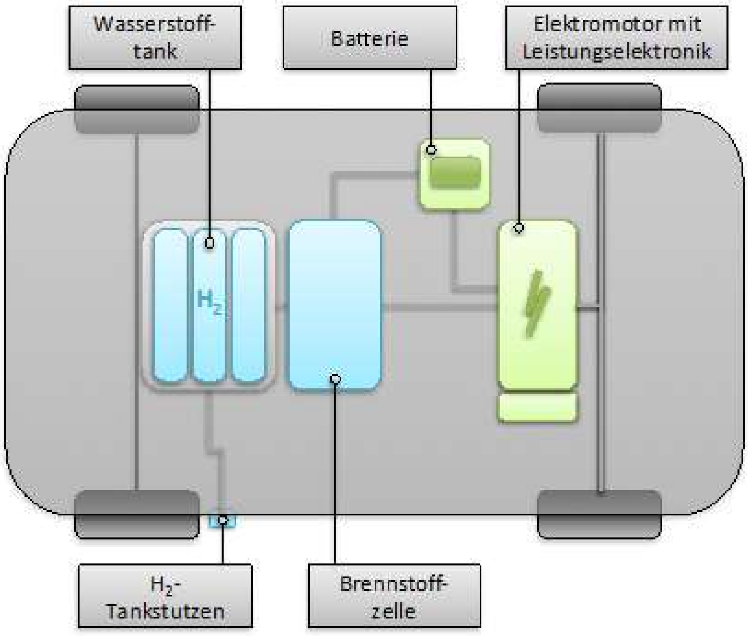



Figure 4 Diagram of the components of a fuel cell vehicle (figure Daimler AG)

Like the battery electric vehicle, the fuel cell vehicle does not need a catalytic convertor or conventional tank as it has no internal combustion engine.

## 4.3 Market scenarios

The future penetration of the global automotive market by electric powertrains is of considerable importance for estimating the future requirements for raw materials. However, as statements about future developments – especially considering a period up to 2020 or 2030 – are characterised by considerable uncertainties, it makes sense to consider different development scenarios.

In recent years various institutions [McKinsey&Company 2009], [McKinsey&Company 2010], [Boston Consulting Group 2009], [Fraunhofer ISI 2010] and [International Energy Agency 2009] have developed and published market scenarios for electro mobility. No independent scenarios were therefore developed for the "Resource efficiency and resource policy aspects of the electro mobility system" project but selection criteria were defined using suitable scenarios for subsequent use in the project.

The following selection criteria were considered: The scenarios should ...

- describe the total market and market share of different electric drive systems for the years 2020 & 2030
- depict the largest possible range of potential developments,
- be internally consistent and comparable with the alternative scenarios,
- be well documented and understandable

Of the numerous scenarios reviewed, those published by the management consultant McKinsey in 2009 [McKinsey&Company 2009] best fulfil the specified requirements and were therefore used for further consideration in this project.

The study by McKinsey (2009) describes three scenarios which lead to different $CO_2$ reduction goals depending on the specific packages of measures.

The **Optimised ICE Scenario** (ICE: Internal Combustion Engine) focuses on increasing the efficiency of conventional drives. Hybrid vehicles only achieve a marginal market penetration (approx. 1%). According to McKinsey, this scenario would enable a reduction in well-to-wheel $CO_2$ emissions from 270 g/km in 2006 to 170 g/km in 2030.

The **Mixed Technology Scenario** assumes a more conservative development of the ratio of different drive technologies (conventional and electric), reducing well-to-wheel $CO_2$ emissions to 150 g/km in 2030.

The **Hybrid and Electric Scenario** assumes a very dynamic development of passenger vehicles with electrified powertrains, coupled with rapid development of the electrical charging infrastructure. The well-to-wheel $CO_2$ emissions in this scenario are reduced to 130 g/km in 2030.

Although out of all the scenario sets looked at these ones best meet all the requirements mentioned above, they still have some important shortcomings. The scenarios only describe 3 different categories of vehicles with electrical powertrains: hybrid vehicles (HEV), plug-in hybrids (PHEV) and battery electric vehicles (BEV). However, when investigating the raw material requirements of electric vehicles, it is important to consider the possible market penetration by fuel cell vehicles (FCEV) as well. These scenarios also do not distinguish the hybrid vehicles which can be charged using a power socket (PHEV and REX).

For these reasons the scenarios were modified by splitting the PHEV percentage into three components i.e. PHEV, REX and FCEV. In view of the fact that the infrastructure for supplying hydrogen is only at the development stage, a percentage of 10% of PHEVs was assumed for FCEVs in 2020 (i.e. 0.5% or 0.6% of all registrations) and 20% of PHEVs in 2030 (i.e. 3% or 5% of all registrations). Note: naturally a FCEV cannot be charged using a connector and therefore does not belong to this class of vehicle. However, FCEVs were assigned to this market sector due to their characteristics of zero emissions for a large range.

The **Scenarios from McKinsey&Company** from 2009 therefore form the basis of the further analysis and calculations for the "Resource efficiency and resource policy aspects of electro mobility" project, although **modified by the project team** (in order to make further distinctions in the various drive designs which are of relevance for looking at resources).

This results in the following:

In 2020, in the **Mixed Technology Scenario** 5 out of 6 passenger vehicles (84%) still have only an internal combustion drive even though this is considerably more efficient that at present. A further 10 percent of vehicles are HEVs, with only 2% being PHEVs or REX and 0.5% being FCEV. In the same scenario the percentage of HEVs more than doubles (23%) by 2030, as do the percentages of the other drive types. Vehicles with only an internal combustion engine still comprise over half of all new vehicles worldwide.

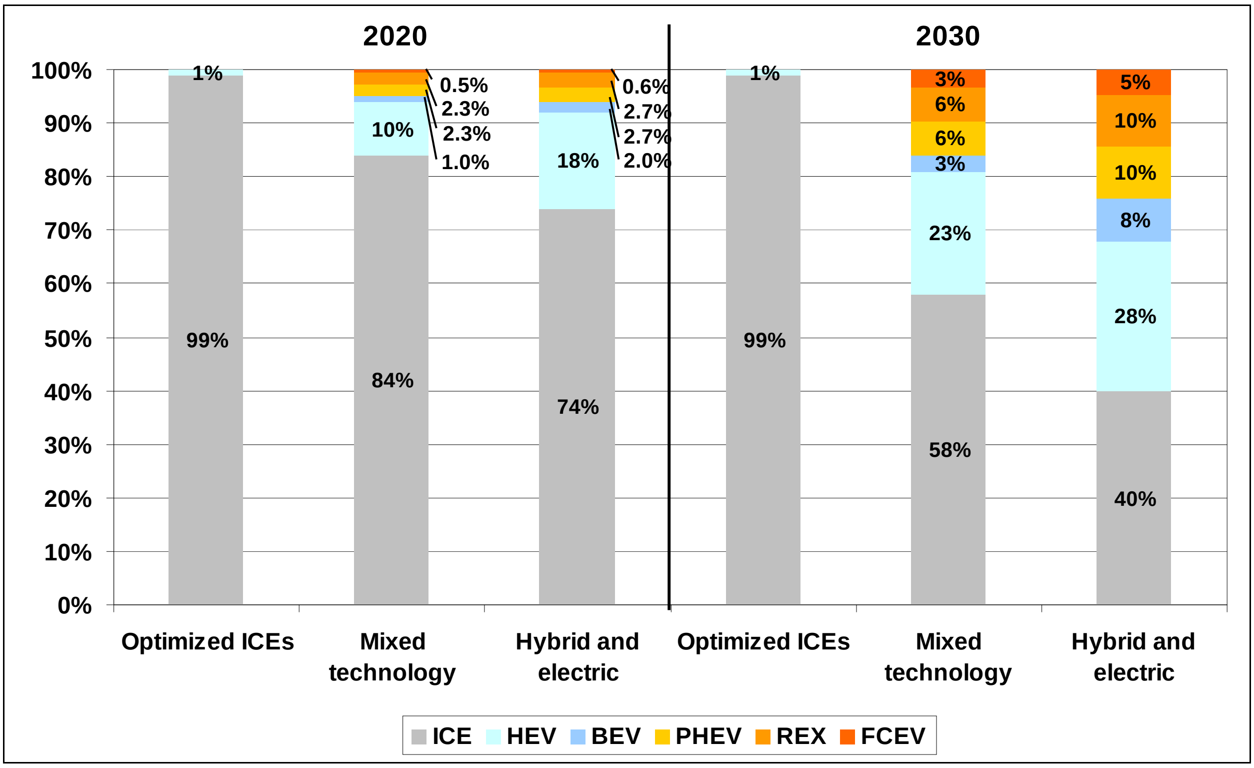



Figure 5 Structure of new passenger vehicle registrations categorised by drive system (based on scenarios by McKinsey&Company 2009, modified by the project team)

In the **Hybrid and Electric Scenario** the percentage of vehicles with an electric powertrain is significantly higher, with every fourth new vehicle falling into this category. HEVs are also the dominant type here with 18%. In 2030 60% of all vehicles will then have an electric powertrain, of which just under half are HEVs.

The global development of new registrations will not actually differ in these scenarios. Taking 61 million passenger vehicles p.a. (new registrations) in 2010 as a starting point, it is assumed that there will be 75 million new passenger vehicle registrations p.a. in 2020 and 90 million in 2030.

If these new registration figures are combined with the corresponding percentages in the different scenarios, this gives the registration figures (in millions) shown in Fig. 6:

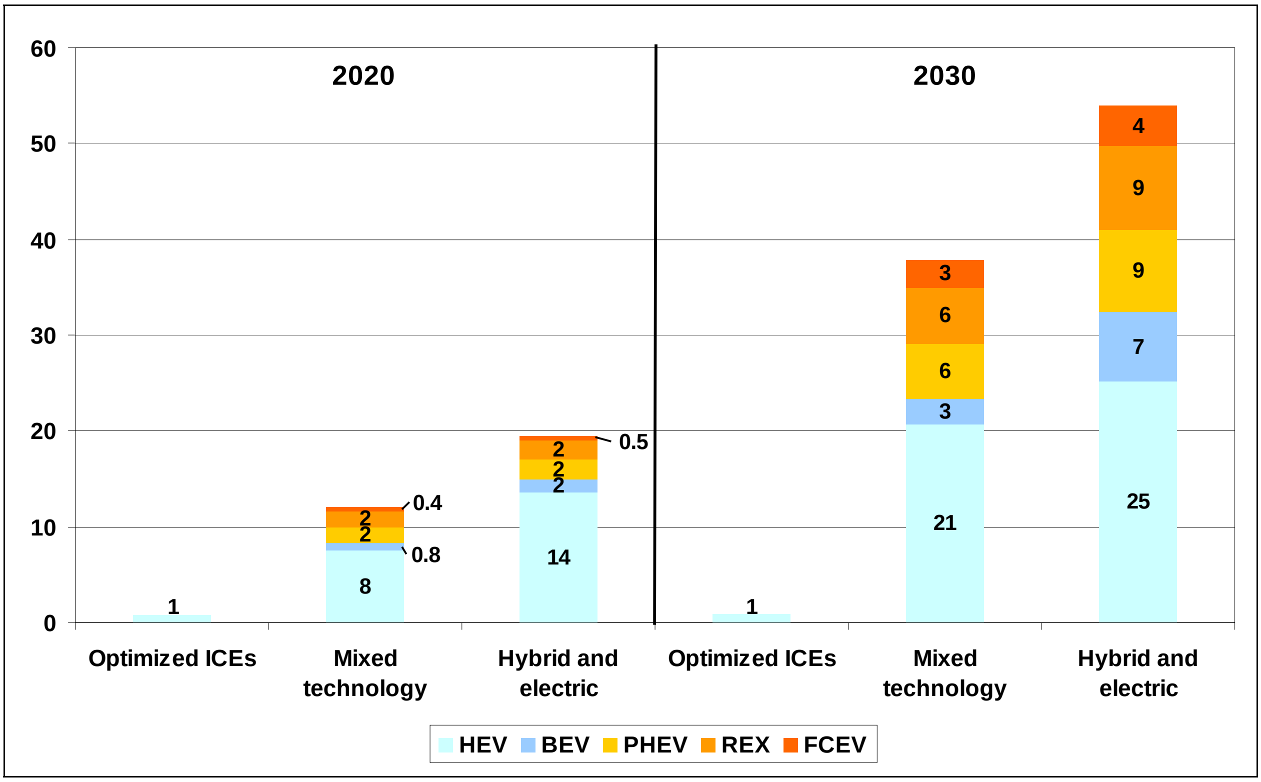



Figure 6 Registrations of new passenger vehicles and production figures for vehicles with electric powertrain divided according to drive system (based on scenarios by McKinsey&Company 2009, modified by the project team)

Whilst the **Optimised ICE Scenario** only envisages 1 million hybrid vehicles being produced in both 2020 and 2030, this figure rises from approx. 12 million (2020) to approx. 38 million (2030) in the **Mixed Technology Scenario** and from just under 20 million to approx. 54 million vehicles in the **Hybrid and Electric Scenario**.

HEVs still comprise the largest percentage of new drives for all scenarios and time periods, although with decreasing dominance in the period to 2030. All-electric battery vehicles amount to less than 10% in all cases considered, in most cases as low as a maximum of 3%.

Hybrid vehicles with and without the ability to be charged from the electricity grid will dominate electrification of the powertrain over the next 20 years, while in all scenarios battery electric vehicles and fuel cell vehicles remain in the single-percent and million ranges. Vehicles with only internal combustion drive will become much more efficient and remain the dominant drive system in all scenarios, even in 2030.

The **Hybrid and Electric Scenario**, being the most ambitions market penetration scenario for electro mobility, is used as the baseline scenario for the calculation of raw material requirements presented later.

## 5 The priority metals for the electro mobility system

56 metals (see Figure 7) were examined in an initial extensive search using the search criteria "Elektrofahrzeuge", "Elektromobilität", "electric vehicle" und "electric mobility". The selection of 56 metals was carried out over the widest range of the periodic table as possible. Non-metals, radioactive elements, obviously toxic elements (e.g. cadmium, mercury), bulk metals and alloying metals (Fe, Al, Cr, Ni) plus sodium, potassium and calcium were excluded from the analysis.

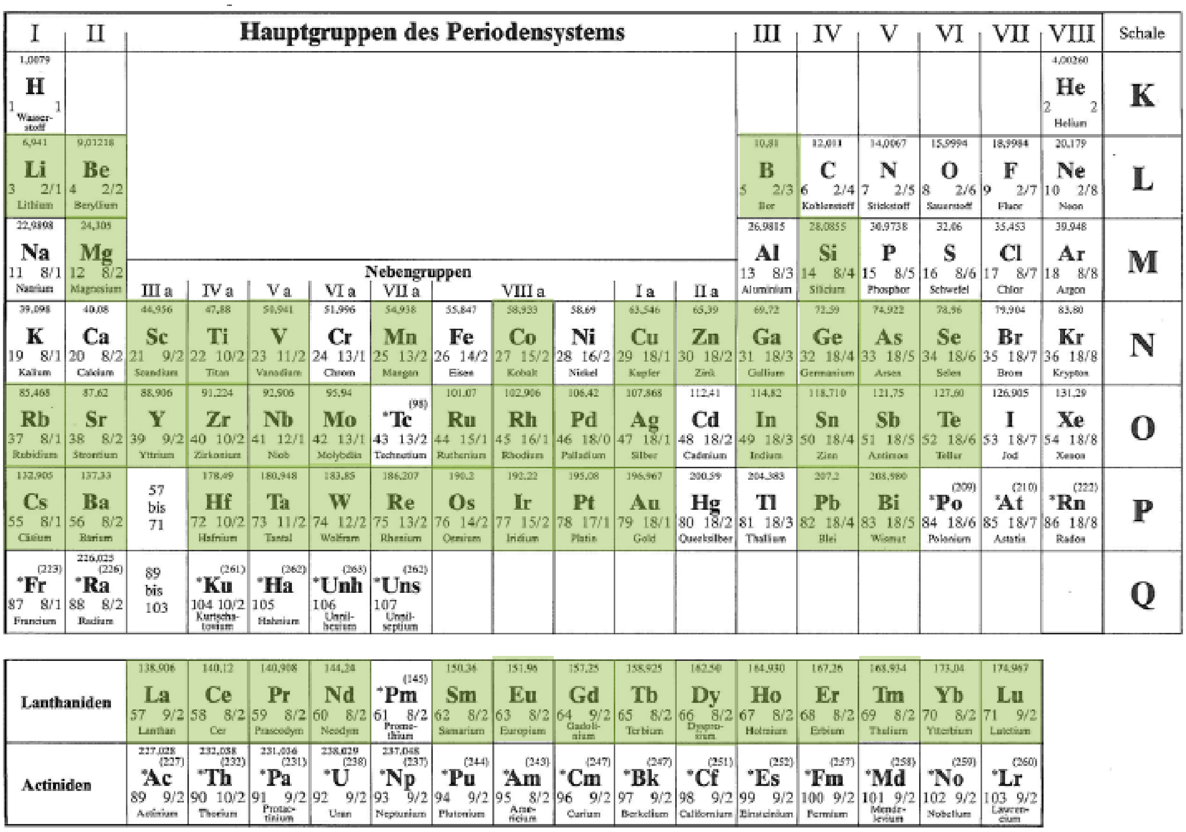



Figure 7 The 56 study elements in the periodic table

In addition, detailed research was carried out on individual metals and components (e.g. power electronics).

The study elements were then divided into three groups: 1st priority, 2nd priority and 3rd priority.

The criteria for prioritising the metals were both a high material requirement in electro mobility and potentially rapidly growing competing applications for the metal. A high material requirement for electro mobility was established for the rare earths neodymium, praseodymium, dysprosium and terbium as well as for gallium, lithium and cobalt. The four rare earths are mainly used in the permanent magnets needed for the vehicle's electric motor. In addition to large material requirements, there are very rapid increases in competing applications such as e.g. wind power plants, so that these elements have been classified as particularly critical.

There are relatively smaller material requirements for indium, germanium, gold, silver, platinum, palladium, ruthenium and copper. These metals have many competing applications which necessitate their classification in the 1st priority group. For example, indium is used in the power electronics of electric vehicles. Indium is classified in the group of critical metals due to the very fast growth in competing applications such as photovoltaic systems and the low potentials of the primary resources as a minor metal.

The results were discussed at the first expert workshop in Berlin in September 2010 (for list of participants, see Appendix 1). To obtain the greatest possible range of expert views, participants were invited from the scientific community (including TU Braunschweig, University of Augsburg), government (German Federal Environment Agency), the automotive industry (BMW, Volkswagen) and suppliers (including Vakuumschmelze, Aurubis, Magnequench, Hitachi, Bosch, I+ME ACTIA).

An important result of the workshop was agreement on the following 15 first priority elements:

- Neodymium
- Praseodymium
- Dysprosium
- Terbium
- Indium
- Gallium
- Germanium
- Gold
- Silver
- Copper

- Platinum
- Palladium
- (Ruthenium)
- (Lithium)
- (Cobalt)

In the course of further research, ruthenium was downgraded to priority 2 as, on further analysis, no important contribution could be established for it.

The metals lithium and cobalt also belong to the 1st priority metals. As the batteries for electric vehicles are being researched in depth in the LiBRi and LithoRec parallel projects and the battery component of electric vehicles is therefore explicitly excluded in this "OPTUM resources" work package, lithium and cobalt are not included in any further studies in this work package.

The remaining 12 priority elements are included in the project's more detailed further research.

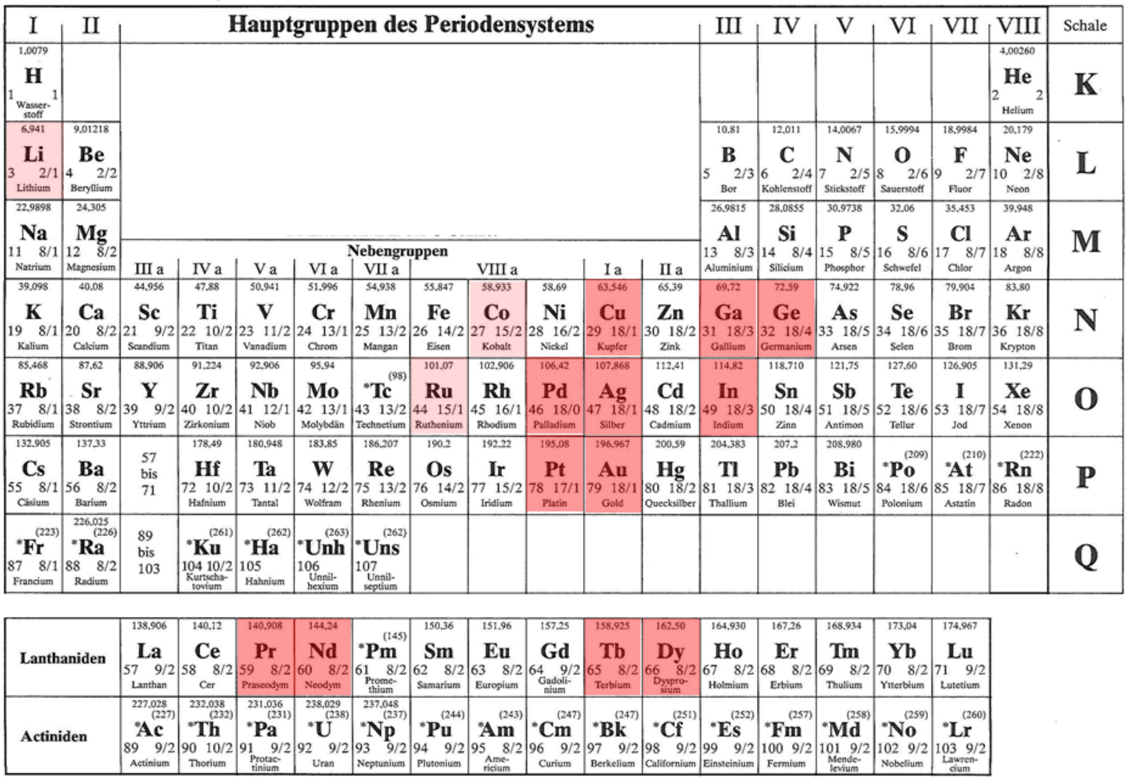



Figure 8 The 1st priority metals in the periodic table

# 6 Priority metal requirements for the important components of electro mobility

The figure below shows the current importance of the 1st priority metals for the important components (excluding battery) of electro mobility. This table gives an overview in a semi-quantitative form (the detailed data for the components is given in Section 7). The priority metals are used in the individual components either in milligrammes, grammes or even kilogrammes, depending on the size of the circles. The kilogramme range applies only to copper, which occurs in several different electro mobility components. The rare earths neodymium, praseodymium, dysprosium and terbium are contained in the upper gramme range in permanent magnets for electric motors as well as in permanent magnets in specific components for fuel cell vehicles. Of the remaining primary metals, the gramme range includes silver for power electronics and platinum in fuel cells for the corresponding vehicles. Gold, indium, germanium, gallium and palladium occur primarily in the power electronics of electro mobility at present, although only in the milligramme range (see data in Section 7).

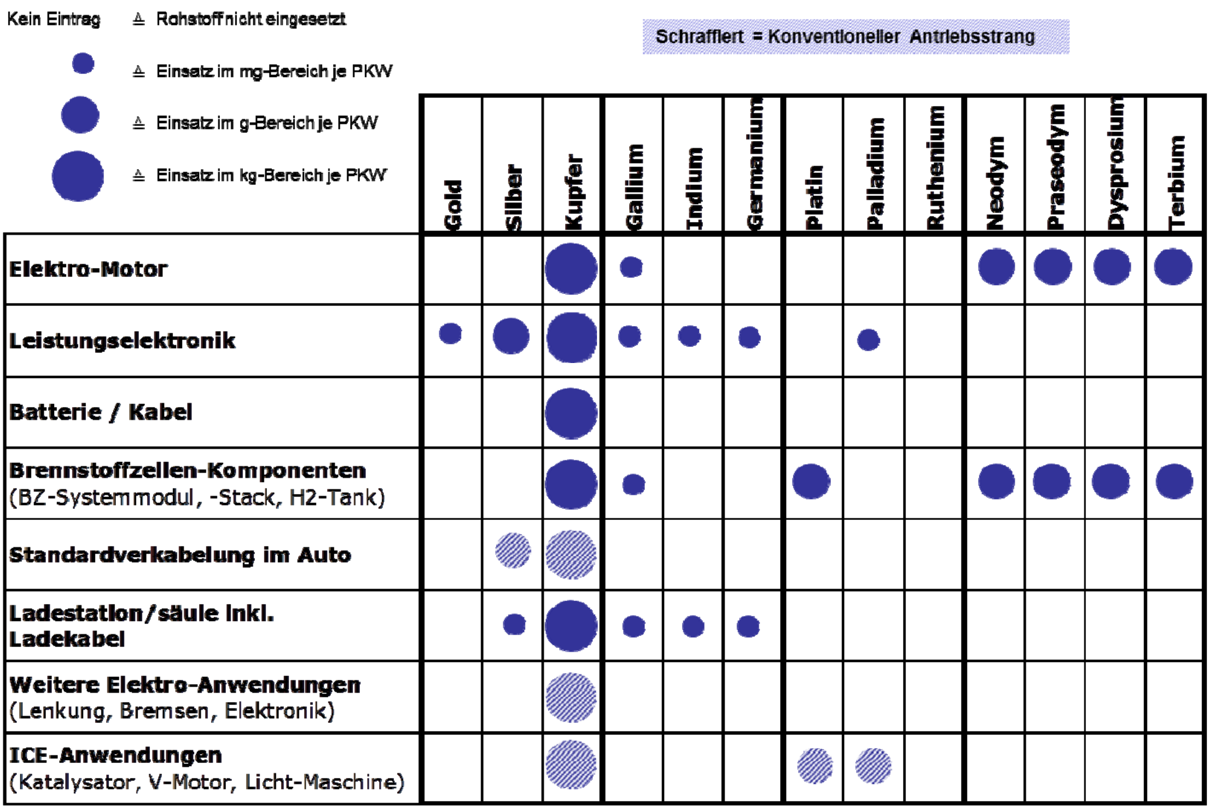



Figure 9 Overview of components and raw material requirements for each metal in 2010

Lastly, in the above figure the magnitude of the quantity of metals for components in conventional (ICE = internal combustion engine) powertrains is shown hatched. Copper (standard cabling, alternator etc.) and platinum and palladium (catalytic converter) should be emphasised in particular. In the case of platinum and palladium there are interesting contradictory effects, as electro mobility increases the requirement on the one hand (platinum for fuel cells, palladium in the power electronics) but, on the other hand, in all-electric and fuel cell vehicles the catalytic converter is not required, therefore saving on the corresponding platinum and palladium demands.

# 7 Scenarios for material usage in electro mobility

The material usage for priority elements in electro mobility is illustrated by means of simple scenarios. Material usage in this context is taken to mean the quantity of priority materials used in the vehicles without extraction, preparation or production losses. The scenario outcomes are calculated for the three focus dates 2010, 2020 and 2030.

The requirement according to drive system (e.g. hybrid vehicle, battery electric vehicle) is chosen as the starting point for the scenarios. These drive systems are assigned standard components in a combination matrix. This means that the hybrid vehicle is assigned a small e-motor, the BEV a large e-motor and the REX (e-vehicle with range extender) 2 large e-motors. The components are varied at the focus dates for the different versions of the scenario (for details of the assumptions in the scenarios see Section 7.2.4) Material savings are estimated in the "Efficiency" scenario starting from the 2010 data. The effect of recycling on the material requirement is calculated cumulatively. In addition, the specific material requirement is substituted for selected drive systems.

The following section describes these scenario modules:

1. Scenario developed according to the e-passenger vehicle drive system
2. Standardised components for e-mobility
3. Combination matrix of vehicle drive systems with components
4. Modelling the scenarios

## 7.1 Data sources

Building on the expertise of the project partners (Öko-Institut, TU Clausthal, Daimler AG, Umicore) and a thorough review of the literature, the basic data was discussed and verified with the assistance of specialists in the expert workshops (see appendix) and the interviews. The experts from the various scientific fields (TU Braunschweig, Uni Erlangen-Nürnberg, IZT, BGR), the automotive manufacturers (Volkswagen, BMW) and the manufacturers and suppliers of the electric vehicle components (Bosch, Siemens, Magnequench, Vakuumschmelze, Aurubis, I+ME ACTIA, Hitachi, Chemetall, Voest-Alpine) confirmed the specification of the basic data.

## 7.2 Scenario modules

The scenario modules are described in the following sub-section.

### 7.2.1 Creating the scenarios for different e-vehicle drive systems

Section 4 gave brief descriptions of the drive systems and discussed the chosen market scenarios:

- Conventional scenario (optimised ICE)
- Moderate scenario (mixed technology)
- Ambitious scenario (hybrid and electric)

The following table illustrates the available scenario outcomes. New vehicle registrations per drive system are identical for all scenarios for the focus year 2010. In 2020 and 2030, although the total number of new vehicle registrations is identical, their distribution over the different drive systems varies. The different additive scenario versions will be discussed for the ambitious scenario. Only the cumulative results are shown for the moderate scenario.

Table 1 Scenario data sets for the focus years 2010, 2020 and 2030.

| Scenarios /Focus year | 2010 | 2020 | 2030 |
|---|---|---|---|
| Conventional | **identical** | not included | |
| Moderate | | only cumulative | only cumulative |
| Ambitious | | Basic, Innovation, Recycling, Substitution | Basic, Innovation, Recycling, Substitution |

The number of new registrations is the same for all three scenarios. 60.4 million vehicles are registered worldwide in 2010, 75 million in 2020 and 90 million in 2030.

In the table for the moderate scenario, the new registrations are specified according to drive system. Electric drive systems (i.e. everything except for conventional ICE) make up 16% of total new registrations in 2020 and 42% in 2030.

Table 2 New passenger vehicle registrations for 2020 and 2030 in the **moderate** scenario (based on scenarios by McKinsey&Company 2009, modified by the project team)

| New PassV registrations | 2020 | | 2030 | |
|---|---|---|---|---|
| FCEV | 0.4 million | 1% | 2.9 million | 3% |
| BEV | 0.8 million | 1% | 2.7 million | 3% |
| Range extender | 1.7 million | 2% | 5.8 million | 6% |
| Plug-in hybrid | 1.7 million | 2% | 5.8 million | 6% |
| Mild/Full hybrid | 7.5 million | 10% | 20.7 million | 23% |
| ICE (diesel/petrol) | 63.0 million | 84% | 52.2 million | 58% |
| **Total market** | **75 million** | **100%** | **90 million** | **100%** |
| **of which electrified** | **12 million** | **16%** | **38 million** | **42%** |

Table 3 New passenger vehicle registrations for 2020 and 2030 in the **ambitious** scenario (based on scenarios by McKinsey&Company 2009, modified by the project team)

| New PassV registrations | 2020 | | 2030 | |
|---|---|---|---|---|
| FCEV | 0.5 million | 1% | 4.3 million | 5% |
| BEV | 1.5 million | 2% | 7.2 million | 8% |
| Range extender | 2.0 million | 3% | 8.6 million | 10% |
| Plug-in hybrid | 2.0 million | 3% | 8.6 million | 10% |
| Mild/Full hybrid | 13.5 million | 18% | 25.2 million | 28% |
| ICE (diesel/petrol) | 55.5 million | 74% | 36.0 million | 40% |
| **Total market** | **75 million** | **100%** | **90 million** | **100%** |
| **of which electrified** | **20 million** | **26%** | **54 million** | **60%** |

In the ambitious scenario the percentage of electric drive systems increases to 26% in 2020 and 60% in 2030.

### 7.2.2 Standardised e-mobility components

Only the material requirement of the priority metals covered in this study are included for the components.[5] Estimates have not been made for other metals e.g. steel or aluminium in this project. To simplify the calculations, this description concentrates on the following components:

- Electric motor
- Power electronics
- EV components
- FCEV components

5 As no application could be demonstrated for ruthenium, this element is not discussed further in the following documentation.

- Charging station/pillar including charging cable
- Standard in-car cabling (for information only)
- Other electric applications (for information only)
- Other (for information only)

Short description of the components

A short description of the components is given below. The detailed list of priority metals and their forward projection until 2030 are given in the tables below.

***Electric motor***

This term refers to the electric motor which is used to drive the vehicle. As the passenger vehicles in the scenarios for this project are based on market scenarios from Kinsey which are not classified according to the size of individual segments (there is only an average hybrid vehicle, an average fuel cell vehicle, etc.) all components including the electric motor are defined as average components. The electric motor is listed in a small version (<50 kW) and a large version (>50 kW) (the assignment of engine size to drive system and their percentages are shown in Table 11). The total material requirement of the large version of the e-motor is a little less than twice the requirement of the smaller version.

Currently, automotive manufacturers prefer electric motors with permanent magnets (PM) of the neodymium iron boron (NdFeB) type for use in passenger vehicles. Permanent magnet motors require magnets containing alloys with at least 30% rare earths. Besides other metals, copper is used to produce the power distribution and the rotor. Besides iron and boron, the magnets contain the rare earths neodymium and praseodymium. The material dysprosium is added in order to withstand the high thermal loads. Some manufacturers also specify an admixture of terbium and gallium. Alternatively, electromagnets (EM) can be used. Permanently excited electric motors definitely have important advantages such as high power densities with low volume and weight.

***Power electronics***

The power electronics serve as the control system for the electric vehicle. They control both the current flow from the battery to the electric motor, the current flow from the recuperator to the battery and charging the battery from an external power supply. There have been clear indications from some participants at the expert workshops that gallium semiconductors (GaN) in particular will be used for the power electronics in the future. Additional traditional metals used in power electronics are small quantities of palladium, gold, germanium and indium. Silver is mostly used as a contact metal. Copper is used in the PCBs and in cabling. Copper is the main metal in terms of quantity.

***EV components***

The EV components consist of the battery and accompanying cables. The batteries make use exclusively of lithium-ion accumulators.

The metals lithium and cobalt in the lithium batteries are not dealt with in this study as they are the subject of a separate project [LithoRec 2011]. This leaves copper as an important conductive material.

The three types of batteries have capacities of 0.8 kWh, 12.1 kWh and 24.2 kWh. The copper percentages are taken from the generic battery types in the LiBRi project [LiBRi 2011].

In addition, the copper cabling for the battery is included. The cabling conducts the power between the battery, power electronics and electric motor.

### *FCEV components*

The fuel cell vehicle (FCEV) constitutes a special form of electro mobility. The FCEV has a fuel cell which creates electric current from hydrogen and air. The electricity is converted to drive energy by means of an e-motor. The design includes a battery as a temporary store. Auxiliary units for supplying the "combustion air" and cooling, plus the hydrogen tank are classified as auxiliary modules.

The literature contains highly variable data on the amount of platinum in the fuel cell. An important reason for this is as ever the rapid pace of development. The data from SolviCore [SolviCore 2011] have been used for the FCEV as they appear to be realistic (also in economic terms). The platinum percentages are fixed for all scenarios at those values given in the table.

Table 4 Estimates for fuel cells [after SolviCore 2011]

| | 2010 | 2020 | 2030 |
|---|---|---|---|
| Pt (g/PassV) | 80 | 30 | 10 |

The modules quantified in the existing group of components are listed below. It was not possible to verify the use of priority metals in the hydrogen tank.

Table 5 Additional modules from FCEVs

| Module | Requirement per vehicle | Source/Comment |
|---|---|---|
| System modules (water, air) | 10% of the electric motor (pumps, fans) | Öko-Institut estimate |
| Electric motor | 1 x 100 kW type | Truckenbrodt 2011 |
| Power electronics | 1x PE large + 2x cable | Double cable set, as there are 2 power sources |
| Battery | 0.5 x battery unit in 2010<br>1 x battery unit in 2020, 2030 | According to Truckenbrodt (2011) FCEVs have a 6 kWh auxiliary battery. |
| Cabling | 1x electric vehicle | In-car cabling |
| Charging station | none | No charging planned |
| Additional electronic applications | 1x non ICE-spec. application | |

The auxiliary units are estimated as having a capacity of 10% of the nominal capacity of the fuel cell. This means that these electric motors use 10% of the metal usage of the electric drive motor.

The additional elements for equipping a FCEV are listed in the table above.

### *Charging station/column including charging cable*

Two basic types (in different versions) are planned for the external charging of electric vehicles. First, the electric passenger vehicle can be charged at home using a standard house connection (also includes other commercial individual connections) or in a central electric filling station. The house connection has a low capacity and therefore a small requirement for copper. However, due to the low capacity of the house connection, it must be assumed that only one or two users can be supplied. In contrast, the equipment of an e-filling station is designed for rapid charging with high capacity. As it is anticipated that the e-filling station will serve many users, the copper requirement per electric vehicle is estimated to be approx. 30% lower compared to the house connection. The electronics for recording and managing the power consumption makes an allowance for a rough estimate of the requirement for the contact material silver plus the electronic materials gallium, indium and germanium.

### *Standard car cabling (not specifically for electro mobility)*

Conventional standard cabling is allowed for with an estimated requirement for copper for the cable and silver for the contacts. These components are only used for calculating the basic requirement for ICEs, as they do not constitute an additional requirement for electric vehicles.

### *Additional electronic applications (not specifically for electro mobility)*

The normal requirements for priority metals are summarised under the additional applications in order to include applications for ICE vehicles such as the starter and alternator and for all vehicles such as windscreen wipers, window regulators etc. These components are also only used for calculating the ICE requirement.

***Other (not specifically for electro mobility)***

To estimate the amount of platinum and palladium required for automotive manufacture, the following requirement for precious metals was used for the global automotive manufacture after Umicore [Umicore 2011]. This is a rough estimate as no further specification was made in the scenarios either for the future division into petrol / diesel vehicles nor for the future environmental standards e.g. Euro 6 [DfT 2010]. The values given in Table 6 are therefore used for all the scenarios in all three focus years.

Table 6 Estimate of use in catalytic converter (constant for all scenarios):

| | |
|---|---|
| Pt (g/PassV) | 2.3 |
| Pd (g/PassV) | 2.7 |

Average values after Umicore [2011]

Table 7 Baseline scenario for 2010, 2020, 2030 [raw material requirement in kg]

| | Neodymium | Praseodymium | Dysprosium | Terbium | Platinum | Palladium | Gold | Silver | Gallium | Germanium | Indium | Copper |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electric motor | | | | | | | | | | | | |
| Small e-motor | 150,0E-3 | 50.0E-3 | 90.0E-3 | 9.0E-3 | | | | | 435.0E-6 | | | 7.0E+0 |
| Large e-motor | 360.0E-3 | 120.0E-3 | 210.0E-3 | 21.0E-3 | | | | | 1.0E-3 | | | 12.6E+0 |
| Power electronics: | | | | | | | | | | | | |
| Small PE | | | | | | 64.0E-6 | 160.0E-6 | 4.0E-3 | 30.0E-6 | 30.0E-6 | 30.0E-6 | 2.4E+0 |
| Large PE | | | | | | 80.0E-6 | 200.0E-6 | 6.0E-3 | 50.0E-6 | 50.0E-6 | 50.0E-6 | 2.5E+0 |
| EV components | | | | | | | | | | | | |
| Battery (small) | | | | | | | | | | | | 2.1E+0 |
| Battery (med.) | | | | | | | | | | | | 9.2E+0 |
| Battery (large) | | | | | | | | | | | | 18.5E+0 |
| Cable | | | | | | | | | | | | 4.5E+0 |
| FCEV components: | | | | | | | | | | | | |
| FCEV system modules (water, air) | 36.0E-3 | 12.0E-3 | 21.0E-3 | 2.1E-3 | | | | | 103.5E-6 | | | 1.3E+0 |
| FCEV stack | | | | | 80.0E-3 | | | | | | | |
| H2 tank | | | | | | | | | | | | |
| Charging station/column including charging cable | | | | | | | | | | | | |
| Single column | | | | | | | | 1.0E-6 | 1.0E-6 | 1.0E-6 | 1.0E-6 | 11.0E+0 |
| Electric filling station | | | | | | | | 1.0E-6 | 1.0E-6 | 1.0E-6 | 1.0E-6 | 7.5E+0 |
| Standard in-car cabling | | | | | | | | | | | | |
| ICE | | | | | | | | 1.0E-3 | | | | 5.0E+0 |
| E-vehicle | | | | | | | | 1.0E-3 | | | | 5.0E+0 |
| Additional electronic applications | | | | | | | | | | | | |
| ICE-spec. applications Alternator, starter | | | | | | | | | | | | 13.0E+0 |
| Other: | | | | | | | | | | | | |
| Catalytic converter | | | | | 2.3E-3 | 2.7E-3 | | | | | | |

Table 8 Innovation scenario 2020 [raw material requirement in kg]

| | Neodymium | Praseodymium | Dysprosium | Terbium | Platinum | Palladium | Gold | Silver | Gallium | Germanium | Indium | Copper |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electric motor | | | | | | | | | | | | |
| Small electric motor | 135.0E-3 | 45.0E-3 | 76.5E-3 | 8.1E-3 | | | | | 391.5E-6 | | | 6.3E+0 |
| Large electric motor | 324.0E-3 | 108.0E-3 | 178.5E-3 | 18.9E-3 | | | | | 931.5E-6 | | | 11.3E+0 |
| Power electronics: | | | | | | | | | | | | |
| Small PE | | | | | | 57.6E-6 | 144.0E-6 | 3.6E-3 | 540.0E-6 | 27.0E-6 | 27.0E-6 | 2.2E+0 |
| Large PE | | | | | | 72.0E-6 | 180.0E-6 | 5.4E-3 | 900.0E-6 | 45.0E-6 | 45.0E-6 | 2.3E+0 |
| EV components | | | | | | | | | | | | |
| Battery (small) | | | | | | | | | | | | 1.9E+0 |
| Battery (med.) | | | | | | | | | | | | 8.3E+0 |
| Battery (large) | | | | | | | | | | | | 16.7E+0 |
| Cable | | | | | | | | | | | | 2.7E+0 |
| FCEV components: | | | | | | | | | | | | |
| FCEV system modules (water, air) | 32.4E-3 | 10.8E-3 | 17.9E-3 | 1.9E-3 | | | | | 93.2E-6 | | | 1.1E+0 |
| FCEV stack | | | | | 30.0E-3 | | | | | | | |
| H2 tank | | | | | | | | | | | | |
| Charging station/column including charging cable | | | | | | | | | | | | |
| Single column | | | | | | | | 900.0E-9 | 900.0E-9 | 900.0E-9 | 900.0E-9 | 9.9E+0 |
| Electric filling station | | | | | | | | 900.0E-9 | 900.0E-9 | 900.0E-9 | 900.0E-9 | 6.8E+0 |

Table 9 Innovation scenario 2030 [raw material requirement in kg]

| | Neodymium | Praseodymium | Dysprosium | Terbium | Platinum | Palladium | Gold | Silver | Gallium | Germanium | Indium | Copper |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electric motor | | | | | | | | | | | | |
| Small electric motor | 108.0E-3 | 36.0E-3 | 53.6E-3 | 6.5E-3 | | | | | 352.4E-6 | | | 5.7E+0 |
| Large electric motor | 259.2E-3 | 86.4E-3 | 125.0E-3 | 15.1E-3 | | | | | 838.4E-6 | | | 10.2E+0 |
| Power electronics: | | | | | | | | | | | | |
| Small PE | | | | | | 51.8E-6 | 129.6E-6 | 3.2E-3 | 1.2E-3 | 24.3E-6 | 24.3E-6 | 1.9E+0 |
| Large PE | | | | | | 64.8E-6 | 162.0E-6 | 4.9E-3 | 2.0E-3 | 40.5E-6 | 40.5E-6 | 2.0E+0 |
| EV components | | | | | | | | | | | | |
| Battery (small) | | | | | | | | | | | | 1.7E+0 |
| Battery (med.) | | | | | | | | | | | | 7.5E+0 |
| Battery (large) | | | | | | | | | | | | 15.0E+0 |
| Cable | | | | | | | | | | | | 4.9E+0 |
| FCEV components: | | | | | | | | | | | | |
| FCEV system modules (water, air) | 25.9E-3 | 8.6E-3 | 12.5E-3 | 1.5E-3 | | | | | 83.8E-6 | | | 1.0E+0 |
| FCEV stack | | | | | 10.0E-3 | | | | | | | |
| H2 tank | | | | | | | | | | | | |
| Charging station/column including charging cable | | | | | | | | | | | | |
| Single column | | | | | | | | 810.0E-9 | 810.0E-9 | 810.0E-9 | 810.0E-9 | 8.9E+0 |
| Electric filling station | | | | | | | | 810.0E-9 | 810.0E-9 | 810.0E-9 | 810.0E-9 | 6.1E+0 |

Table 10 Substitution scenario 2010, 2020, 2030 (partial substitution of the electric motor) (raw material requirement in kg)

| | Neodymium | Praseodymium | Dysprosium | Terbium | Platinum | Palladium | Gold | Silver | Gallium | Germanium | Indium | Copper |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electric motor: Substitution scenario 2010, as baseline scenario 2010 | | | | | | | | | | | | |
| Small electric motor (PM) | 150.0E-3 | 50.0E-3 | 90.0E-3 | 9.0E-3 | | | | | 435.0E-6 | | | 7.0E+0 |
| Large electric motor (PM) | 360.0E-3 | 120.0E-3 | 210.0E-3 | 21.0E-3 | | | | | 1.0E-3 | | | 12.6E+0 |
| Electric motor: Substitution scenario 2020 | | | | | | | | | | | | |
| Small electric motor (PM) | 135.0E-3 | 45.0E-3 | 76.5E-3 | 8.1E-3 | | | | | 391.5E-6 | | | 6.3E+0 |
| Large electric motor FCEV, BEV, REX (EM) | | | | | | | | | | | | 34.0E+0 |
| Large electric motor (PM) | 324.0E-3 | 108.0E-3 | 178.5E-3 | 18.9E-3 | | | | | 931.5E-6 | | | 11.3E+0 |
| Electric motor: Substitution scenario 2030 | | | | | | | | | | | | |
| Small electric motor (PM) | 108.0E-3 | 36.0E-3 | 53.6E-3 | 6.5E-3 | | | | | 352.4E-6 | | | 5.7E+0 |
| Large electric motor FCEV, BEV, REX (EM) | | | | | | | | | | | | 30.6E+0 |
| Large electric motor (PM) | 259.2E-3 | 86.4E-3 | 125.0E-3 | 15.1E-3 | | | | | 838.4E-6 | | | 10.2E+0 |

### 7.2.3 Combining the vehicle drive systems with the components

The scenario outcome (Sc outcome) is calculated for each focus year (y) and scenario (Sc) using the combination matrix (CM) (see Table 11) as follows:

Sc outcome (y, Sc) = drive system (y, Sc) X components (y, Sc) X CM

<u>Example calculation for the baseline scenario in 2030, BEV, raw material requirement for dysprosium:</u>

1,512,000 kg Dy in 2030 (Baseline scenario) =

7.2 million BEV in 2030 x 0.210 kg Dy in 2030 (in the electric motor, baseline Sc) x 100% (see CM)

Quantification of the drive systems in the scenarios is documented using the new passenger vehicle registrations (see Table 2 and Table 3). The raw material requirements for the components are shown in Table 7 to Table 10.

The combination value (e.g. 50%) is shown in Table 11, the combination matrix for drive systems and components. In some cases the allocation of vehicle drive systems to components is divided into various component sub-types. The coefficients are estimates produced by the project team.

There are two sizes of drive motors specified. The hybrid vehicle drive system is allocated a small electric motor 100%. The plug-in hybrid is allocated a large electric motor 75% and a small one 25%. The range extender (REX), in contrast, is allocated mathematically 200% of the electric motor (large) as it has both a generator and an electric motor. The other drive systems (BEV, FCEV) are allocated the large electric motor. For specific details of the substitution scenario as regards electric motors, see the following Section 7.2.4.4.

Allocation of the power electronics largely follows the electric motor size. The exception to this is that the REX is given a slightly different allocation here.

The battery size is allocated to the drive systems in accordance with the power requirements. The hybrid passenger vehicle has only a small battery in accordance with the comments in Section 4. In contrast, the fully electric passenger vehicle (BEV) has the large battery. The other electric vehicles are allocated a medium battery in accordance with the experience of the project team. The hybrid, plug-in hybrid and all-electric vehicles are fitted with one cable set each. The REX and FCEV require two cable sets as they use two power sources (generator and battery in the REX, fuel cell and battery in the FCEV).

Only the FCEV vehicle has a fuel cell.

Each passenger vehicle has standard cabling which is divided into ICE and non-ICE here on grounds of model flexibility. The charging infrastructure (charging pillar / electric filling station) is allocated to the "chargeable" electric vehicles. There are no charging installations allocated to the ICE, FCEV and hybrid vehicles. The project team carried out a division of the infrastructure into (private) charging pillars and "public" electric filling stations based on the current state of knowledge (e.g. electro mobility platform).

Catalytic converters are allocated to all ICEs plus electric vehicles which also have an internal combustion engine.

Table 11 Combination matrix (CM) of drive systems and components

| Vehicle type according to drive | Electric motor | | | Power electronics | | EV components | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Small electric motor (PM) | Large electric motor (PM) | Large electric motor (EM)* | Small PE | Large PE | Battery (small) | Battery (medium) | Battery (large) | Battery cable |
| Mild/Full hybrid | 100% | | | 100% | | 100% | | | 100% |
| Plug-in hybrid | 25% | 75% | | 25% | 75% | | 100% | | 100% |
| Range extender | | | 200% | 25% | 75% | | 100% | | 200% |
| BEV | | | 100% | | 100% | | | 100% | 100% |
| FCEV | | | 100% | | 100% | | 100% | | 200% |
| ICE (diesel/petrol) | | | | | | | | | |

*) Applies only to the substitution scenario; in all other scenarios the percentages are applied to the large electric motor (PM).

Table (continued)

| Vehicle type according to drive | FCEV components | In-car cabling | | Charging station/column | | Additional electronic applications | | Other | |
|---|---|---|---|---|---|---|---|---|---|
| | | ICE | E-vehicle | Single column | Electronic filling station | ICE spec.: alternator/starter | non-ICE spec: | Catalytic converter | ICE motor |
| Mild/Full hybrid | | | 100% | | | 100% | 100% | 100% | 100% |
| Plug-in hybrid | | | 100% | 60% | 20% | 100% | 100% | 100% | 100% |
| Range extender | | | 100% | 60% | 20% | 80% | 100% | 100% | 100% |
| BEV | | | 100% | 60% | 40% | | 100% | | |
| FCEV | 100% | | 100% | | | | 100% | | |
| ICE (diesel/petrol) | | 100% | | | | 100% | 100% | 100% | 100% |

### 7.2.4 Modelling the scenarios

Four scenarios were selected from the various model variations in order to illustrate the possible range of scenarios, as shown in the following figure:

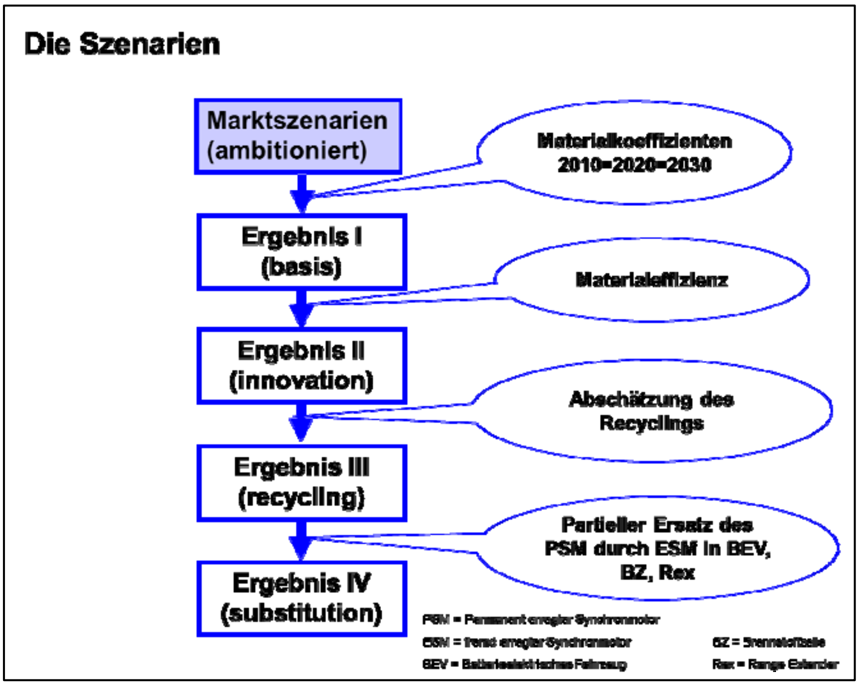



Figure 10 Flow diagram for the scenarios

The various changes are applied cumulatively i.e. added to the previous scenario. In addition, a fifth scenario is produced by combining the accumulated changes with the drive systems of the moderate passenger vehicle registration scenario. The following table shows the structure of the scenarios in detail:

Table 12 Modelling flow diagram

| | Drive systems | | Components / measures | | | |
|---|---|---|---|---|---|---|
| Scenarios | Ambitious | Moderate | Baseline/ Table 7 | Innovation Table 8; Table 9 | Recycling | Substitution Table 10 |
| I - Baseline | X | | X | | | |
| II - Innovation | X | | | X | | |
| III - Recycling | X | | | X | X | |
| IV - Substitution | X | | | X | X | X |
| V - Moderate | | X | | X | X | X |

#### 7.2.4.1 Baseline scenario

The baseline scenario combines the drive systems for the ambitious passenger vehicle scenario with the baseline components (see Table 7).

#### 7.2.4.2 Innovation scenario

Improvements in efficiency are assumed in the innovation scenario. A moderate improvement in efficiency of 5% per decade is applied in the conventional applications such as cabling and "other applications". A higher improvement in efficiency is assumed for components which are used specifically in electric vehicles as some of these components are still being developed. An overall improvement in efficiency of 10% is assumed. Greater pressure for innovation is expected in the case of the rare earths. An improvement of 10% is assumed in the first decade from 2010 to 2020 for neodymium, praseodymium and terbium and for the other metals. However, in the second decade from 2020 to 2030, a doubling is assumed, as it can be expected that there will be greater pressure to avoid these metals. Due to the extremely high price and uncertain supply situation, an increase in efficiency of 15% is assumed for dysprosium in the first decade and 30% in the second one. The estimated increases in efficiency for the metals in the components are shown in the following table.

Table 13 Increase in efficiency in the innovation scenario (increase per decade)

| | 2020 (increase 2010-2020) | | 2030 (increase 2020-2030) | | |
|---|---|---|---|---|---|
| | Metals | Dysprosium | Rare earths | Dysprosium | Metals |
| Electric motor | 10% | 15% | 20% | 30% | 10% |
| Power electronics | 10% | n.a. | n.a. | n.a. | 10% |
| EV components | 10% | n.a. | n.a. | n.a. | 10% |
| FCEV components* | 10% | 15% | 20% | 30% | 10% |
| Cabling | 5% | n.a. | n.a. | n.a. | 5% |
| Charging infrastructure | 10% | n.a. | n.a. | n.a. | 10% |
| Additional applications* | 5% | n.a. | n.a. | n.a. | 5% |

* without platinum in fuel cells; without platinum and palladium in the catalytic converter

#### 7.2.4.3 Recycling scenario

The recycling scenario builds on the innovation scenario. The outcome of the innovation scenario is reduced by the amount of metals recovered from recycling. The quantity recovered ($Q_{recyc}$) at the focus time ($T_{foc}$) is calculated from the vehicle registrations $P_{re}$ ($T_{foc}$ – 10 years), the components (Comp) and the recycling rate (Rec-rate)

$Q_{recyc}$ (in kg) = $P_{re}$ ($T_{foc}$ – 10) X Comp ($T_{foc}$ – 10) X Rec-rate

Example calculation for the year 2030, BEV, dysprosium (electric motor):

214.800 kg recycled Dy from BEV in 2030 =

1.5 million BEV registrations in 2020 x 0.179 kg Dy in the electric motor in 2020 x 80% recycling rate (2030)

To calculate the amount recycled in 2010 it is assumed that in 2000 there were 50.6 million vehicle registrations [$P_{reg}$ ($T_{foc}$ – 10 years)].

The chosen approach is necessarily a simplification of potential actual developments. It enables the important features of recycling and the effects of recycling on the overall outcome to be shown. The following table shows the estimated recycling rates.[6] Whilst verified estimated values are available for 2010 based on the known status of current recycling (see e.g. [Graedel et al. 2011]), recycling rates for 2020 and 2030 have to be estimated using the potential advances in the recycling systems. It should be noted that greater pressure on exploiting recycling potential for metals is to be expected due to these scenarios.

Table 14 Global recycling rates for the priority metals in automotive engineering (project team estimate based on [Graedel et al. 2011])

| | 2010 | 2020 | 2030 |
|---|---|---|---|
| Rare earths (Dy, Tb, Nd, Pr) | 0% | 60% | 80% |
| Pt, Pd | 55% | 70% | 80% |
| Ag, Au | 2% | 15% | 40% |
| Cu | 50% | 75% | 80% |
| Ga | 0% | 10% | 25% |
| In, Thr | 0% | 5% | 15% |

#### 7.2.4.4 Substitution scenario

The scenario outcomes displayed further down show a high material requirement for rare earth (RE) metals which are primarily used in electric motors. The main use of rare earths is

6 This refers to what are known as the end-of-life recycling rates (EoL RR) [Graedel et al. 2011]. For post-consumer materials this describes the total yield of metals across all stages of the recycling system i.e. collection, pre-treatment, refining to secondary metal, which is then available to the market again.

in permanent magnets (PM). These permanent magnets enable a very compact design and in some applications avoid the necessity for a gear mechanism. However, it is possible to replace these magnets based on rare earths with electromagnets (EM) (see Table 10). The disadvantage of these motors with electromagnets is their large design and additional weight. Substitution is therefore only recommended for some electric vehicles. As it appears less practicable to have an integrated design (ICE, gear mechanism) in electric motors fitted with electromagnets, the substitution option focuses on the all-electric vehicle (BEV), the fuel cell vehicle (FCEV) and the range extender (REX). Substitution is only used for these types of vehicles and for the large electric motors.

## 7.3 Scenario outcomes

The scenario outcomes show the standardised requirements for priority metals. This standardisation is based on the annual primary production of the specific metal. "100%" on the y axis therefore corresponds to the annual primary production in 2010. The values used for the standardisation are shown in the following table.

Table 15 Primary production of metals* in 2010 for standardising the scenario outcomes

| Metal | Neodymium | Praseodymium | Dysprosium | Terbium | Platinum | Palladium |
|---|---|---|---|---|---|---|
| t/a | 25,000 | 8,000 | 1,980 | 375 | 188 | 227 |
| Source | FVA IZT 2011 | FVA IZT 2011 | BGR 2011 | BGR 2011 | Johnson Matthey 2011 | Johnson Matthey 2011 |

| Metal | Gold | Silver | Gallium | Germanium | Indium | Copper |
|---|---|---|---|---|---|---|
| t/a | 2,500 | 22,200 | 106 | 120 | 574 | 16,200,000 |
| Source | USGS 2011b | USGS 2011c | USGS 2011d | USGS 2011e | USGS 2011f | USGS 2011g |

*The data for the rare earths show the rare earth oxide trade unit

The availability is considerably higher for some metals as secondary production from recycling e.g. for copper and the platinum metals makes a significant contribution.

### 7.3.1 Baseline scenario

The results of the calculation for the baseline scenario are shown as a graph in the following figure. The baseline scenario is calculated from the new vehicle registrations in the ambitious market penetration scenario and the material input from the baseline scenario.

As the material requirement for conventional passenger vehicles (=ICE) is not included in the calculation, the material requirement in 2010 is negligible. In 2020 an increasing requirement is clearly visible for the rare earths neodymium, praseodymium, dysprosium and terbium plus platinum, gallium and copper. In 2030 the extra demand from electro mobility shows a significant further increase.

An extra demand can be calculated for palladium, gold, silver, germanium and indium which nevertheless only uses less than two per cent of the primary production. A clear additional demand for copper of approx. 1.6 million t/a, i.e. approx. 10% of the 2030 primary production can be seen. The reason for this is its use as a conducting material generally as well as in electric motors.

The requirement for platinum also shows a significant increase. A requirement of approx. 42 t/a or 23% of primary production is calculated for 2030. This demand results mainly from its use in fuel cell vehicles (FCEV).

The requirement for rare earths and gallium is significantly higher when compared to primary production. Rare earths are mostly used for the drive motors and partly for auxiliary motors. As electro mobility makes very high demands on performance, also at increased temperatures, these motors contain a large percentage of dysprosium (and also high percentages of terbium, depending on the manufacturer). This new application results in an estimated 2030 requirement for dysprosium of approx. 482% of the 2010 primary production and for terbium of 255% of the 2010 primary production.

Gallium is used in large amounts in the power electronics and in smaller quantities in electric motors so that this metal also has an estimated 2030 requirement of approx. 144% of 2010 primary production.

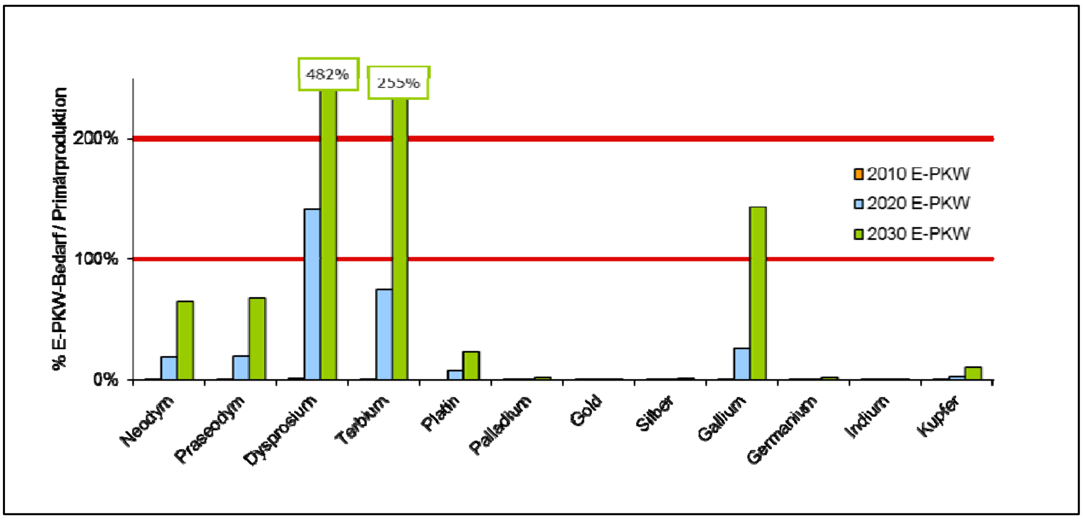



Figure 11 Baseline scenario: ambitious market penetration; material coefficients 2010 = 2020 = 2030 (except for platinum)

The baseline scenario clearly shows that the requirement for rare earths in particular is extremely high in an ambitious scenario. In contrast to copper and platinum, the automotive industry does not currently use these metals in any significant quantity. The requirement for dysprosium in particular requires urgent discussion, as the primary supply comes almost exclusively from China.

**Baseline scenario including conventional components**

If the conventional components are added to this (catalytic converter, cabling, etc. see Section 7.2.2) this gives higher material requirements especially for platinum and palladium as well as copper. These conventional requirements are shown hatched in the following figure. It should be noted that the increase in e.g. palladium is due entirely to the increase in the global new vehicle registrations. Even without the special requirements due to the introduction of electro mobility, the increasing worldwide production necessitates an increased requirement of priority metals for conventional components.

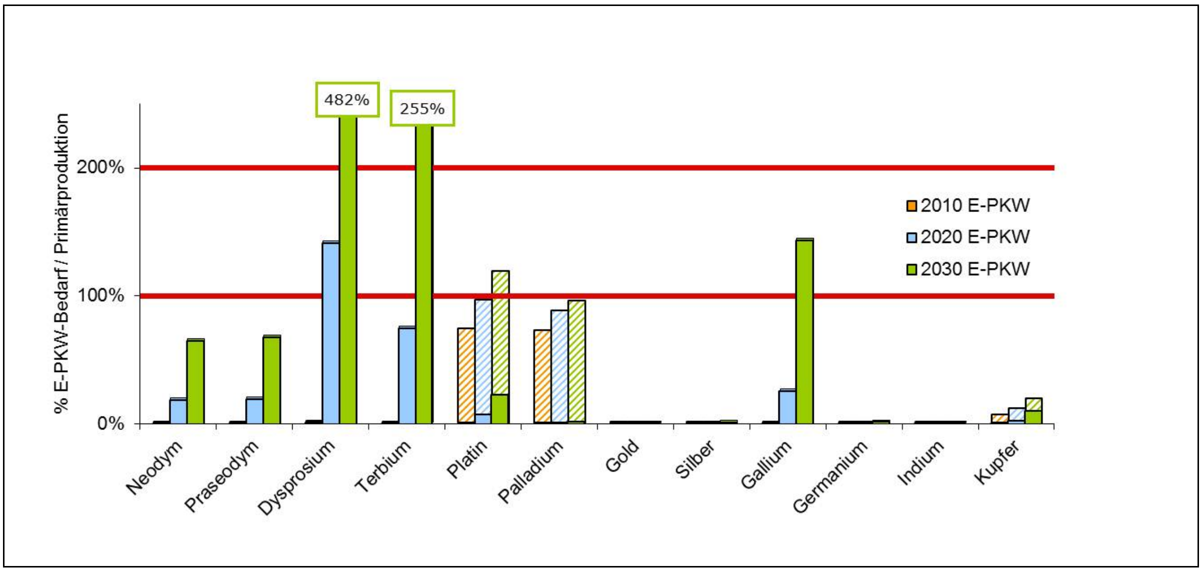



Figure 12 Baseline scenario including conventional ICE components (shown hatched): ambitious market penetration; Material coefficients 2010 = 2020 = 2030 (excluding platinum)

In contrast to Figure 11, in the figure above the metal requirements for the conventional components are shown hatched. Including the conventional components also has an effect on the metals platinum and palladium (catalytic converter) and copper (cabling).

### 7.3.2 Innovation scenario

A further development of the baseline scenario gives the innovation scenario where the material coefficients are modified. The reason for this is the assumption that the material requirement per unit will fall in the case of the components i.e. the material efficiency will rise as a result of on-going R&D driven by the aim of making savings in weight, cost and volume. The increase in efficiency is therefore estimated as being significantly higher for new components (electric motor) in comparison with the previous standard components (copper cabling). The changes in the material requirements are documented in Section 7.2.4.2.

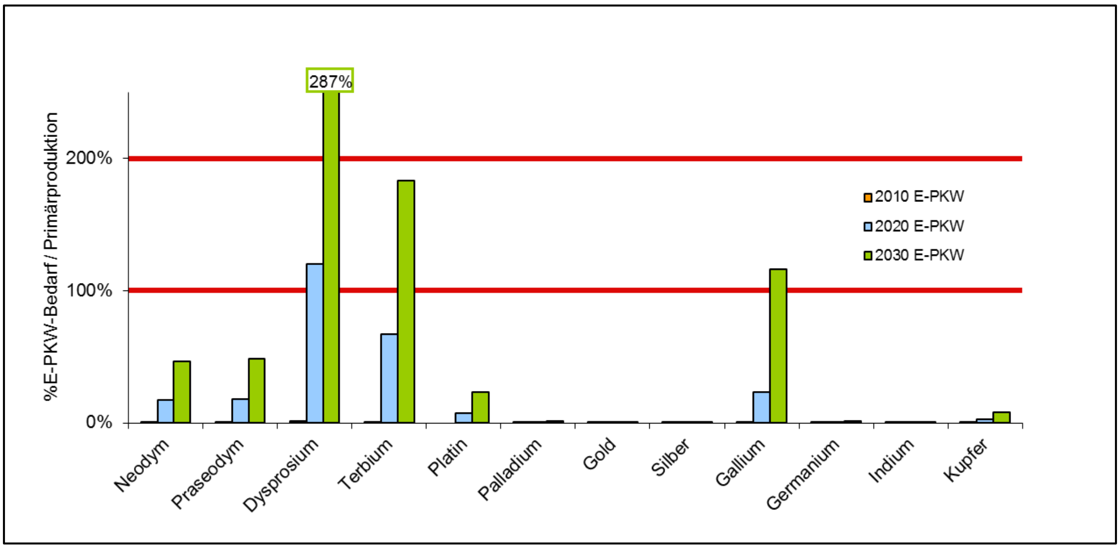



Figure 13 Innovation scenario: ambitious market penetration minus innovation potentials/material efficiency

This effect is illustrated in the figure for the innovation scenario. The material requirements for the rare earths fall significantly. The requirements for neodymium and praseodymium are reduced by approx. 28% in 2030 compared to the baseline scenario. A decrease of over 40% is estimated for dysprosium.

Despite these efficiency measures the requirement for neodymium and praseodymium in relation to the current primary supply remains high and for terbium and dysprosium extremely high.

### 7.3.3 Recycling scenario

One option for lowering the primary requirement for electro mobility is to recycle the metals. The assumptions made about this are discussed and presented in Section 7.2.4.3. The following figure shows the recycling measures added to the innovation scenario. The metals recovered by recycling are offset directly against the metal requirement.

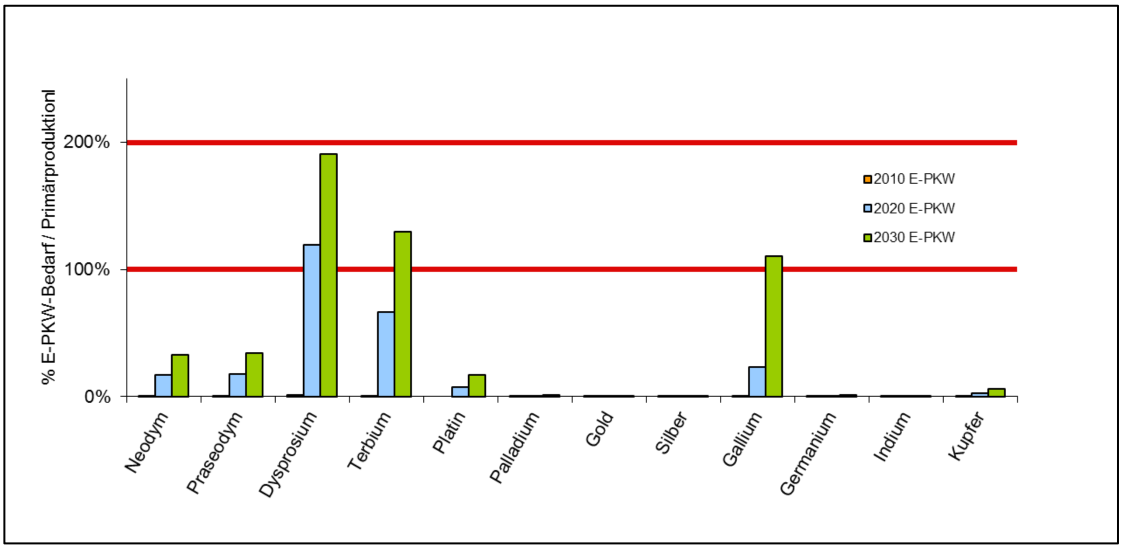



Figure 14 Recycling scenario: ambitious market penetration minus innovation potentials minus recycling

This measure gives a further reduction in demand. However, this reduction is not as significant as the supposed recycling rates would indicate. As the metal recycling which can be achieved is calculated from the use of these metals in passenger vehicles 10 years previously, the recovery of metals which were not typical of the automotive industry up until now is very low. Based on the 2030 requirements, the reduction in demand from recycling is greatest for copper and platinum from conventional passenger vehicles which, however, are not included in this scenario.

Based on the predicted high growth in electro mobility and assumed 10-year lifespan of the passenger vehicles, with high recycling rates recycling can indeed make a very important contribution to reducing the net requirements, but the full effect will only be felt after a time delay. During the "introductory phase" a large percentage of the metals have to be met by primary production or other sources.

### 7.3.4 Substitution scenario

Due to its high requirement for rare earths, the electric motor has been identified as the component with a particularly high demand relative to primary production. The electric motor design using a permanent magnet is relatively new and there are other designs which function without permanent magnets. As discussed in Section 7.2.4.4, it is possible to substitute the rare earths especially for the FCEV, BEV and REX electric passenger vehicles. The result for this substitution scenario is shown in the following figure. In this scenario the substitution measure is calculated in addition to the recycling scenario.

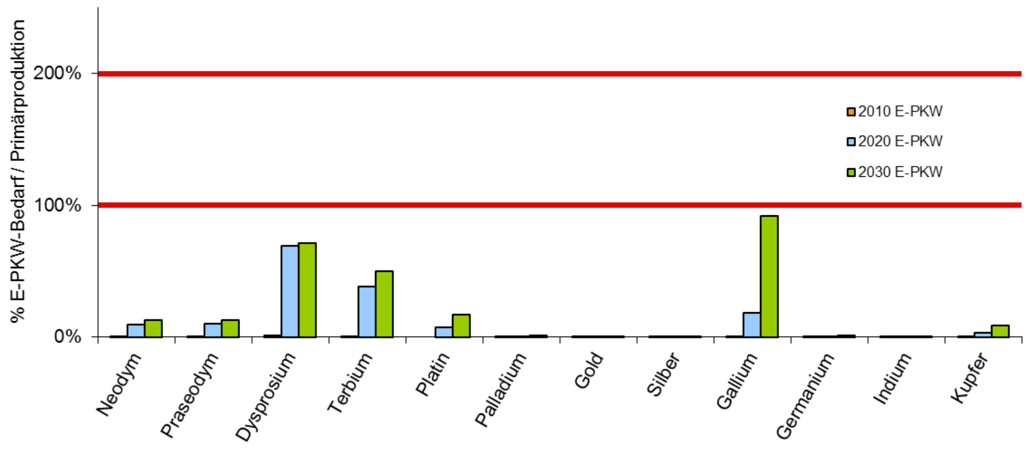



Figure 15 Substitution scenario: ambitious market penetration minus innovation potentials, minus recycling, minus substitution of some of the electric motors by externally excited motors (for BEV, REX and FCEV)

The requirements, especially of rare earths, are significantly reduced for 2030 to 13% of the current primary production for neodymium and praseodymium and to 71% for dysprosium. Requirements can therefore be reduced by over 60% using this measure.

It is noticeable that the requirements for rare earths only increase slightly from 2020 to 2030. On the one hand the growth in hybrid passenger vehicles (mild or plug-in hybrid), the main application area for rare earths, only amounts to a further 17 percentage points in this decade from 21 percentage points in 2020 to 38 percentage points in 2030. This corresponds to an increase of 80%. At the same time a significant increase in efficiency is assumed for this decade, with the return flow from recycling starting at the same time (reduction of requirement in neodymium from 21% to 13% of primary production). On the other hand FCEV, BEV and REX passenger vehicles increase by 5 percentage points to 22 percentage points. However, as the rare earths in the electric motors have been substituted in these three types of electric vehicles, the increase in passenger vehicles in this scenario does not result in a rise in the requirement for rare earths.

### 7.3.5 Moderate scenario

The previous scenarios have been calculated based on an ambitious market penetration for new passenger vehicle registrations. In order to illustrate the alternative of a reduced electro mobility market penetration the ambitious scenario is replaced by the moderate one here. The scenario details are discussed in Sections 4.2 and 7.2.1. The scenario presented in this section works with the reduced market penetration figures of the moderate scenario, but assumes the components of the substitution scenario, i.e. including material efficiency, recycling and substitution.

The results of this scenario resemble those of the substitution scenario. The requirements for 2030 are of the same order of magnitude. For instance, the requirement for neodymium is calculated as 13% in the substitution scenario and 12% in the moderate scenario. The reasons for this are first the small increase in rare earth consumption by hybrid passenger vehicles (from 29% to 38%) and second a lower return flow calculated from recycling.

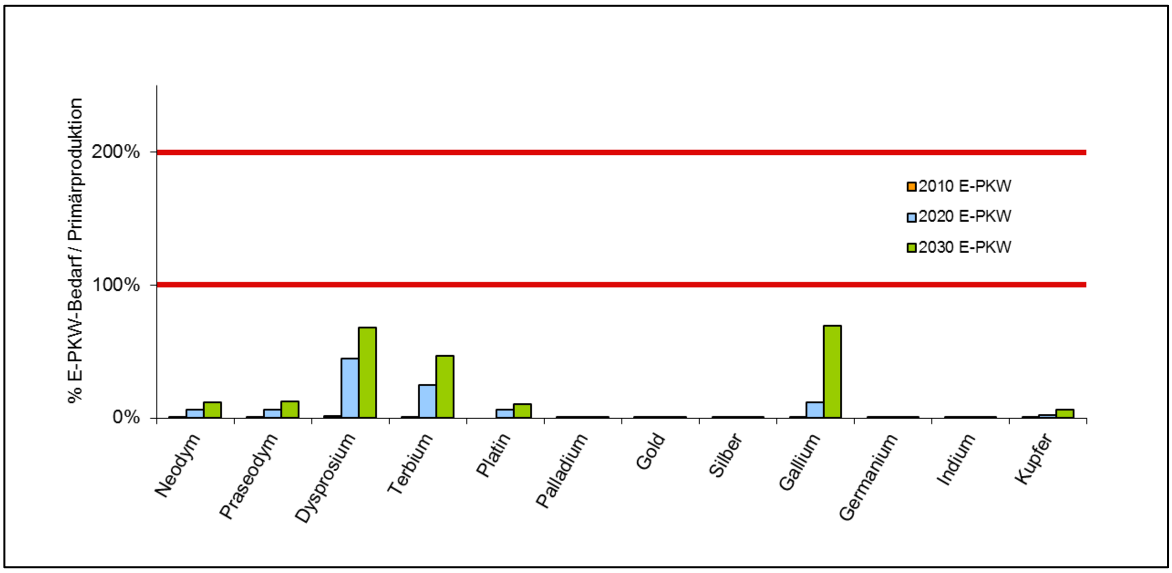



Figure 16 Moderate scenario: moderate market penetration, minus innovation potentials, minus recycling, minus substitution

A significant reduction can be seen for gallium. The requirement for this metal is linked to the total number of new registrations for vehicles with electric powertrains, whose percentage falls from 60% to 42%. A comparable reduction applies to copper for similar reasons. The requirement drops from 9% to 6% of primary production.

Furthermore, the requirement for platinum is also reduced, which is due almost exclusively to the reduction in fuel cell vehicles (from 5% to 3%).

# 8 Environmental impacts of primary extraction, reserves and reserves-to-production ratios of the priority metals

This section gives an overview of the reserves and reserves-to-production ratios of the 12 priority metals, the characteristics of their occurrence as raw materials plus the environmental impacts of their primary extraction and production. The environmental parameters are developed on the basis of the Ecoinvent database V2.2 (2010). This study does not produce its own environmental balance sheet, but makes use of existing environmental data. The review of the environmental impact includes only the primary production of the 12 priority elements.

This section starts by defining the key concepts. The selected environmental parameters are then presented for the priority elements. The section ends with a presentation of the specific environmental impacts of primary extraction plus the reserves and reserves-to-production ratios of the 1st priority metals.

## 8.1 Definition of reserves-to-production ratio, major and minor metals

The term reserves-to-production ratio used in what follows means how long a reserve would be available if subject to the current amounts of primary production. A reserve in this context is a proven and precisely specified deposit which could be economically worked under current conditions [USGSAppc 2011]. It is clear that this parameter can only give a rough estimate of the extent of a material because it does not portray price trends and changing consumption. Nevertheless, the reserves-to-production ratio is a recognised indicator for the shortage of a raw material, as it can supply an initial index of the shortages of raw materials in a rapid and relatively simple manner.

Metals obtained from primary sources can be divided into two groups depending on the method of extraction: major metals and minor metals.

Major metals are those metals which are exposed by mining activities and which are also the main product of such activities. They are generally mined in large quantities and also form the main revenue generator of the operation. Specially adapted processes are generally used along the whole production chain as a result of the large quantities and the often long years of experience in the mining and processing of these ores.

Minor metals are obtained as accessory metals to the major metals during mining activities and are thus by-products of the mining operation or the subsequent processing stages. Often these metals occur only in very low concentrations in the extracted ore and therefore require greater effort to extract, but can sometimes, however, form a crucial part of the viability of the mining operation. Minor metals therefore depend directly on the primary production of one or several major metals. It should be noted for this discussion that individual metals can be viewed both as major metals and minor metals, depending on the deposit and its distribution [USGSAppc 2011].

## 8.2 Environmental impact parameters

The analysis of the environmental impacts of the priority elements include the primary production parameters GWP (global warming potential), over-fertilisation potential, photochemical oxidation, acidification potential, CED (cumulative energy demand) and ADP (abiotic depletion potential) for each element. The results of these environmental parameters for the 12 priority elements are presented in what follows. The rare earths are shown combined, due to a lack of detailed data. Based on the Ecoinvent data for rare-earth oxides, the OI has calculated its own estimate for rare earth metals which is used in the studies which follow.

The parameter **climate change**, also known as GWP (global warming potential), is shows as kg $CO_2$ equivalents per kilogramme of primary metal extracted. The precious metals gold, platinum and palladium have the highest GWP with over 10,000 kg $CO_2$ equivalents each. Gallium, germanium, indium and silver amount to around 130 to 2010 kg $CO_2$ equivalents per kg of primary metal. Whilst the primary extraction of the rare earth metals gives rise to 21 kg $CO_2$ equivalents, copper makes the lowest environmental impact per extracted kg of primary metal for this parameter (see Figure 17).

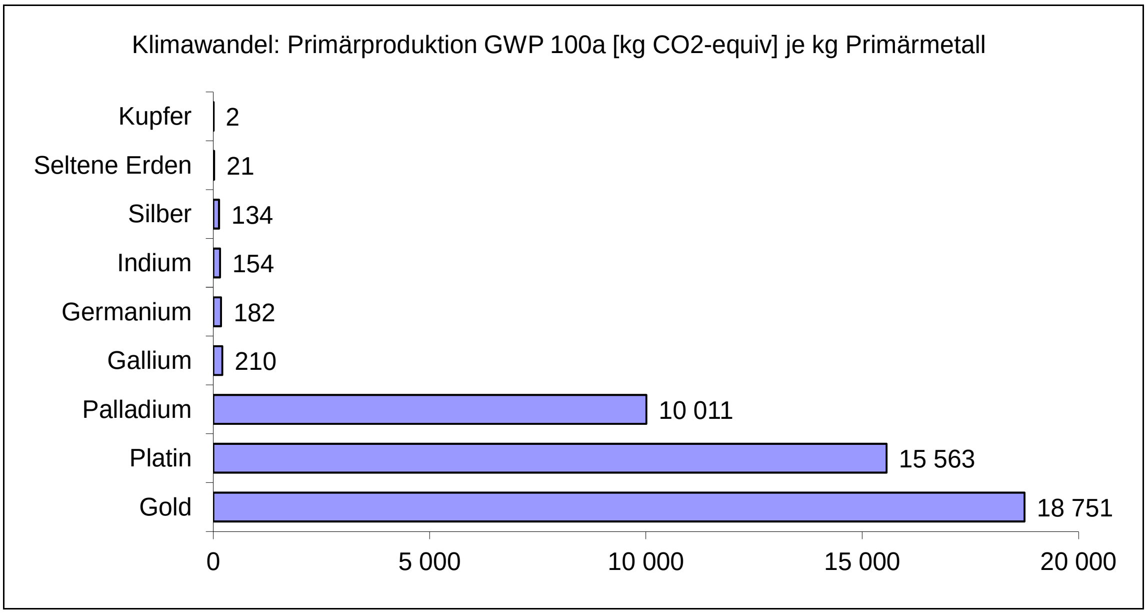



Figure 17 Environmental impact in terms of GWP for the 12 priority elements (Öko-Institut calculations from Ecoinvent data 2010)

The **over-fertilisation potential** is specified in kg $PO_4$ equivalents per kilogramme of primary metal extracted. The rare earth metals plus the metals copper, gallium, germanium and indium show an over-fertilisation potential of less than one kilogramme $PO_4$ equivalent per kilogramme of primary metal extracted. Gold has by far the highest over-fertilisation potential at 1.089 kilogramme $PO_4$ equivalents per kilogramme of primary metal extracted. (see Figure 18).

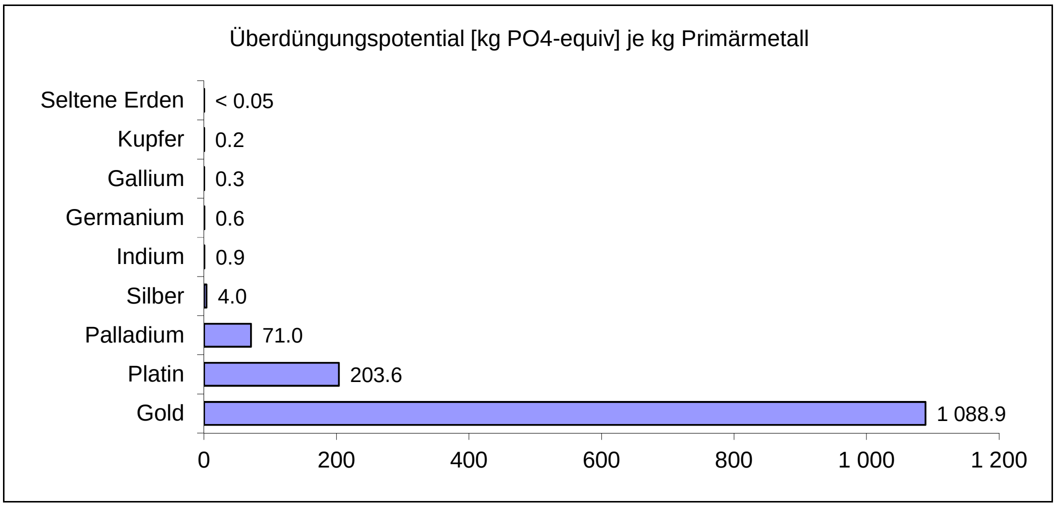



Figure 18 Environmental impact in terms of over-fertilisation potential for the 12 priority elements (Öko-Institut calculations from Ecoinvent data 2010)

**Photochemical oxidation** is shown in kilogrammes of ethylene equivalents per kilogramme of primary metal extracted. Whilst the rare earth metals, copper and gallium have very low values with < 0.05 kg of ethylene equivalents, as do germanium, indium and silver with 0.1 kg of ethylene equivalents, the platinum group metals, platinum and palladium, fall between 140 and 292 kg ethylene equivalents per kg of primary metal extracted (see Figure 19).

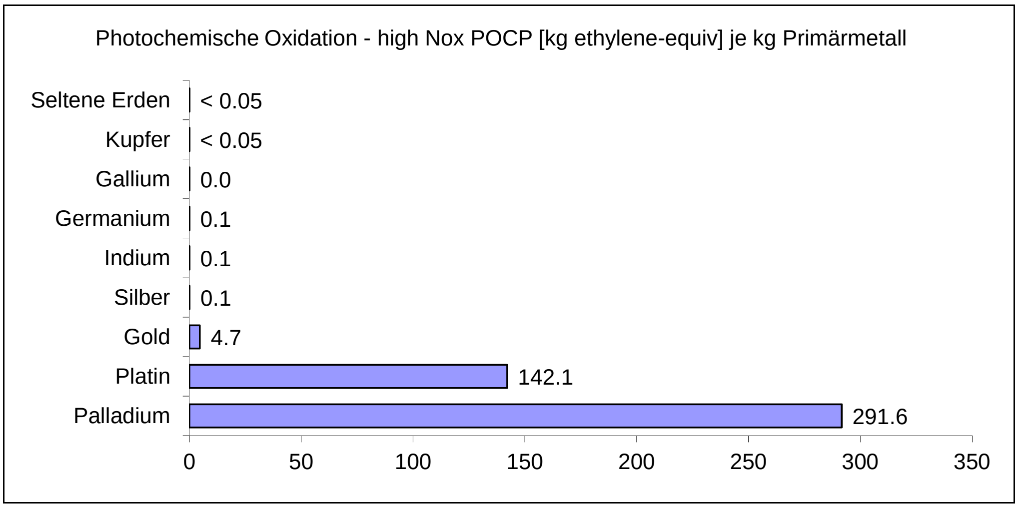



Figure 19 Environmental impact in terms of photochemical oxidation for the 12 priority elements (Öko-Institut calculations from Ecoinvent data 2010)

The **acidification potential** is shown in kilogrammes of $SO_2$ equivalents per kilogramme of primary metal extracted. The platinum group metals platinum and palladium are also at a very high level (2,970-6,080 kg of $SO_2$ equivalents per kg of primary metal extracted) for this environmental parameter. The rare earth metals, copper and gallium show less than a kilogramme of $SO_2$ equivalents and germanium and indium between one and two kilogrammes of $SO_2$ equivalents per kilogramme of primary metal extracted (see Figure 20).

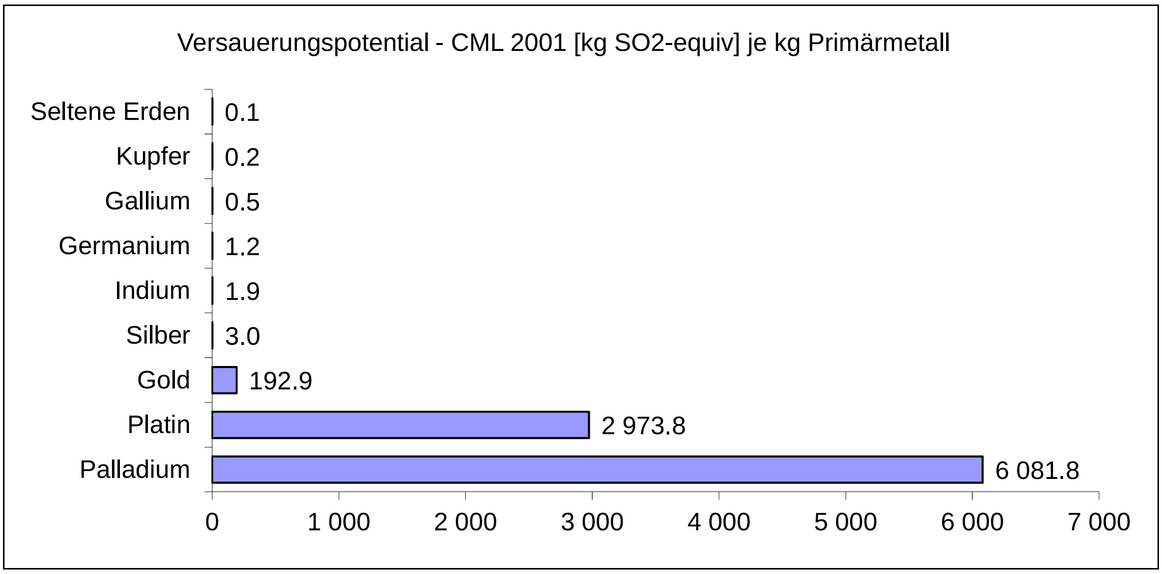



Figure 20 Environmental impact in terms of acidification potential for the 12 priority elements (Öko-Institut calculations from Ecoinvent data 2010)

The **CED** (cumulative energy demand) comprises the energy demand for renewable (biomass, water, wind, sun) and non-renewable (fossil, nuclear, primary forest) energy sources. This parameter is expressed in MJ equivalents per kilogramme of primary metal extracted. Whilst copper and the rare earth metals display a CED of less than 400, the platinum group metals palladium and platinum plus gold lie between 187,000 and 314,000 MJ equivalents (see Figure 21).

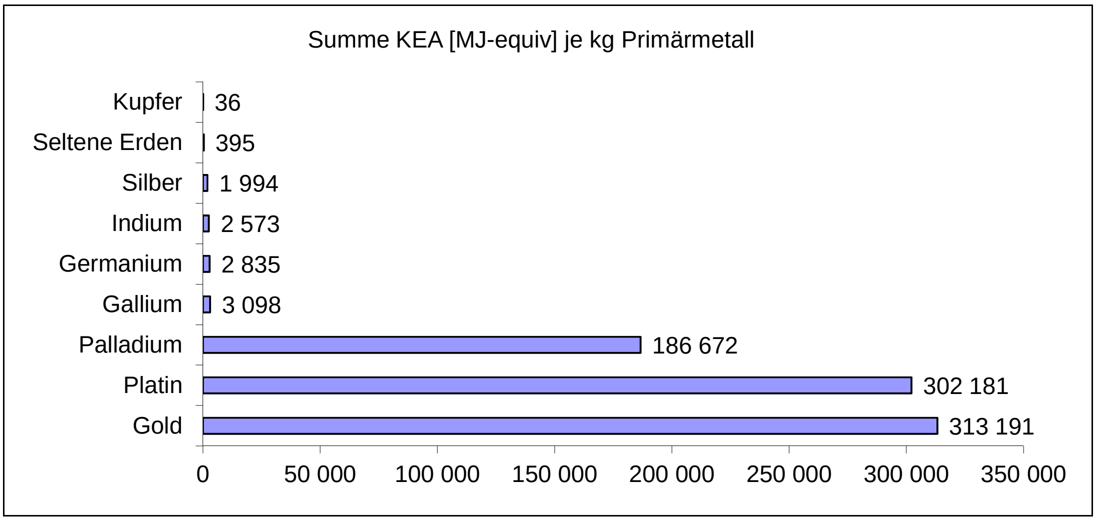



Figure 21 Environmental impact in terms of CED for the 12 priority elements (Öko-Institut calculations from Ecoinvent data 2010)

The parameter **ADP** (abiotic depletion potential = consumption of abiotic / elementary resources) in relation to the reserve base is given in kilogrammes of antimony (Sb) equivalents per kilogram of primary metal extracted. This parameter represents the reduction in the global stock of raw materials which results from the removal of non-renewable resources.

Copper and indium have a low ADP with only 0.0037 and 1.08 kg Sb equivalents per kilogramme of primary metal extracted. Gold is comparatively high at 40.4 kg Sb equivalents, (see Figure 22).

Due to a lack of data there is no information available for gallium, germanium and the rare earths.

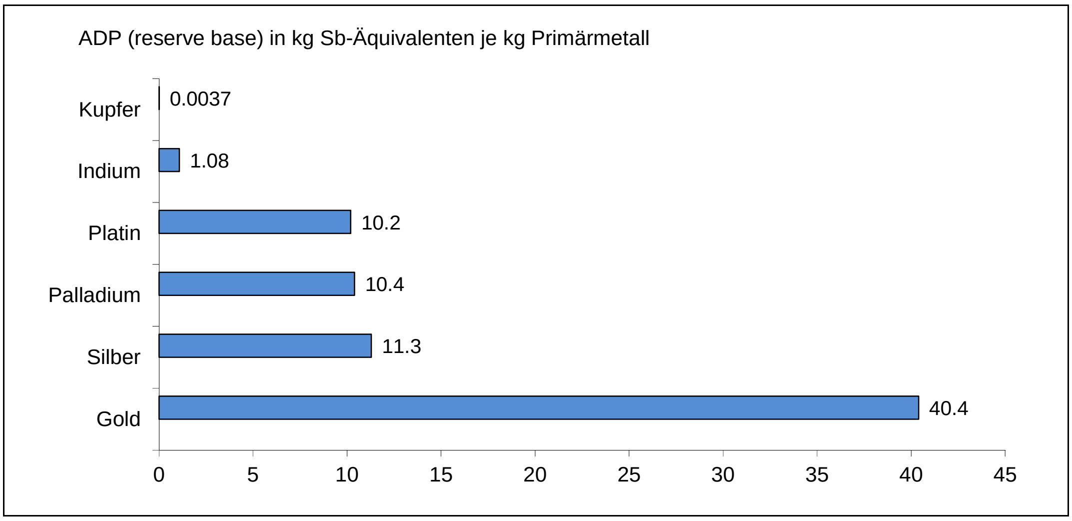



Figure 22 Environmental impact in terms of ADP (data set after Ecoinvent V2.01, characterisation factors after van Oers et al. 2002)

The $CO_2$ loading in relation to raw material requirements for electro mobility in the baseline scenarios for 2020 and 2030 is shown in Figure 23. The current GWP values are extrapolated unchanged for the years 2020 and 2030, as an estimate of changes in these values would be subject to very large uncertainties.[7]

The figure shows firstly (in solid colours) the load from the original electro mobility components (minus conventional technology such as catalytic converters or standard cabling). In addition, the hatched bars show the $CO_2$ loadings from the primary production of the raw material requirements for the components starter, alternator and catalytic converter in the conventional drive plus for the conventional components in the electric vehicle (catalytic converter for the hybrid drive, standard cabling and brakes).

7 The GWP could decrease as technologies become more efficient or it could increase as the deposits contain less ore due to the advancing exploitation, thus making primary extraction more expensive.

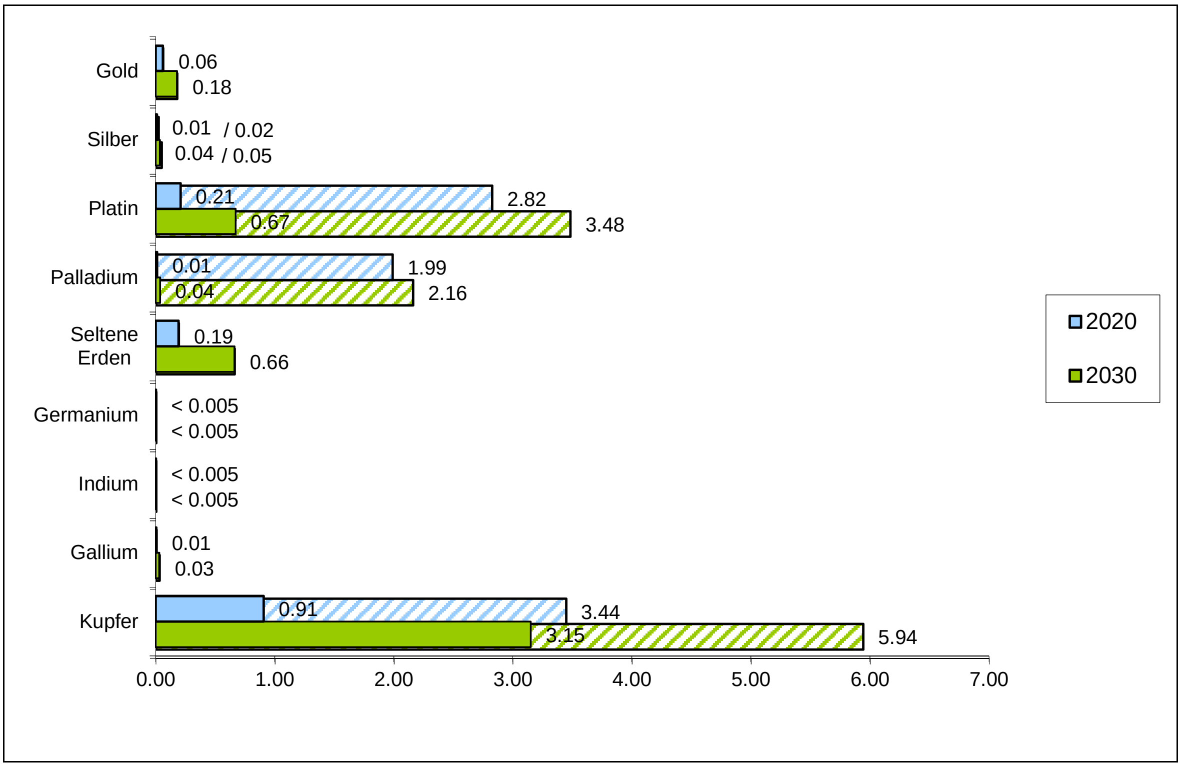



Figure 23 $CO_2$ loading (in million tonnes of $CO_2$ equivalents) of the additional raw materials in the electric vehicles in the baseline scenarios for 2020 and 2030 (Öko-Institut calculations from scenarios and Ecoinvent data)

When interpreting the data it should be noted that this figure does not include the batteries.

Copper has the largest impact on the environment with 0.9 (or 3.4) million tonnes $CO_2$ equivalents in 2020 and 3.15 (or 5.9) million tonnes $CO_2$ equivalents in 2030. Despite the lowest GWP per extracted kilogramme of primary metal for copper (see Figure 17) the $CO_2$ loading is the highest due to the very high additional material requirements for the components electric motor, power electronics, cabling, fuel cell system module and loading station.

Besides copper the requirements for rare earth metals result in a $CO_2$ loading of 0.19 million tonnes $CO_2$ equivalents in 2020 and 0.66 million tonnes $CO_2$ equivalents in 2030 due to their use in the electric motor.

The following figure shows the $CO_2$ loading for the individual scenarios taking the metal copper and the rare earths as examples.

Figure 24 shows the $CO_2$ equivalent loadings for primary extraction combined with the metal requirements of the individual scenarios.

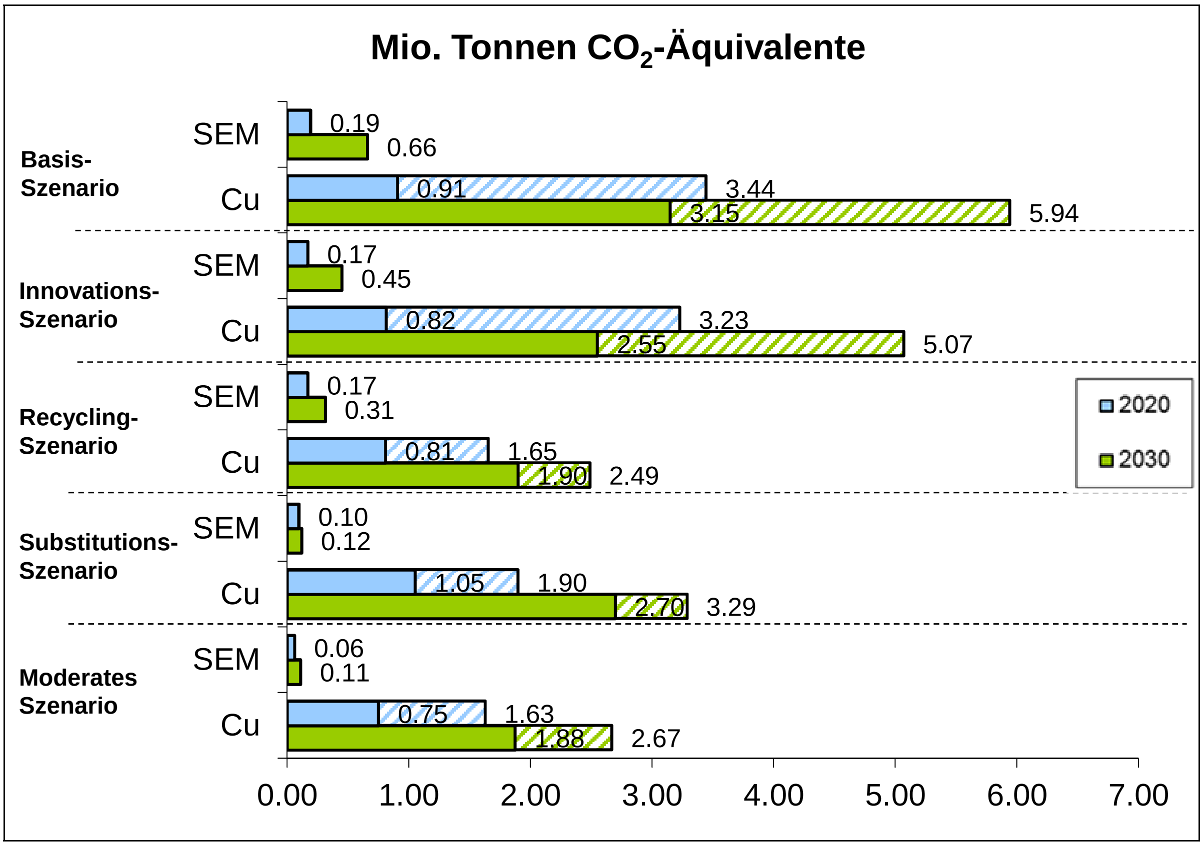



Figure 24 $CO_2$ loading (in million tonnes of $CO_2$ equivalents) of the additional raw material requirements in electric vehicles in all scenarios for 2020 and 2030 (Öko-Institut calculations from scenarios and Ecoinvent data)

The data for the $CO_2$ loading for the primary extraction of the requirement in the baseline scenario corresponds to the information for rare earths and copper from the previous Figure 23. The innovation scenario displays a reduced environmental loading resulting from a lower material requirement due to technological innovations and material efficiency in all the components. The reduced requirement for primary metal due to the use of secondary material from recycling also reduces the primary metal requirement in the recycling scenario[8]. In the substitution scenario the material requirements for rare earths drop due to the additional scenario assumption of substituting the electric motors in battery electric vehicles, fuel cell vehicles and range extender vehicles by new motor technologies. This affects approx. 33% of all electric vehicles in 2030. This innovation in motor technology is, however, accompanied by an increased demand for copper.

The graph of the moderate scenario includes the assumptions for innovation, recycling and substitution and relates to a moderate penetration of the global market by electro mobility

[8] The global recycling rates for copper for the automotive industry were assumed to be 75% for 2020 and 80% for 2030. Global recycling rates for the rare earths for the automotive industry were taken as 60% in 2020 and 80% in 2030.

(see Section 4). The smaller number of electric vehicles leads to a lower metal requirement, resulting in a reduced $CO_2$ equivalent loading.

## 8.3 Environmental impacts of the primary production of the main elements

Besides the purely quantitative assessment of the environmental impact using environmental indicators for the primary extraction of the elements considered here, a qualitative evaluation should also be presented. This will look at mining and processing in particular in order to demonstrate the specific problems of the various extraction processes. The current facts relating to reserves and reserves-to-product ratios plus the characteristics of the raw material deposits will be presented.

### 8.3.1 Copper

Copper occurs in the earth's crust at a concentration of approx. 60 ppm [Lide 2005] and therefore has a similar concentration to zinc and cobalt. There are numerous copper minerals of which around 20 are of economic importance [Lossin 2001]. Copper ores occur mostly in the Precambrian shield and in Tertiary folded mountains, and are therefore present on all continents. The ores used for extracting copper are of great importance for the production of numerous elements besides copper (e.g. Fe, Pb, Zn, Au, Ag), these being obtained as by-products in the copper treatment process. The reserves of copper amount to approx. 630 million tonnes [USGS 2001g] giving a reserves-to-production ratio of approx. 39 years.

Copper ores can be economically extracted in opencast above a copper content of 0.5% and underground above a Cu content of 1%, especially if the ores contain additional valuable metals such as gold or silver [Lossin 2001]. The largest mines at present are the terraced opencast mines for extracting copper ore. They often cover more than a square kilometre and are several hundred metres deep. These mines produce huge intrusions in the biosphere and hydrosphere (lowering ground water levels, water acidification) which can lead to local changes in the natural balance [Restle 2009]. Currently over 100,000 t of copper ore are extracted per day throughout the world. In addition, large quantities of overburden are produced in order to expose the ore-bearing rock [Lossin 2001]. Apart from the power required for moving these volumes, the large area required for storage, processing and deposition must be taken into account.

Around 80% of the primary copper production comes from sulphide ores. Their typical processing sequence can be shown as follows [Lossin 2001], cf. also Figure 25:

Concentration:

This involves grinding the ore finely followed by flotation, which concentrates over 90% of the copper while 95% of the solids are separated out.

Option: Roasting (is rarely used any more)

This is done in order to obtain oxidised material; preparation of the material for subsequent processes

- Two-phase pyrometallurgical extraction
    - o Smelting to copper matte
    - o Oxidation of copper matte to blister copper
- Refining the blister copper
- Pyrometallurgical
- Electrolytic: extraction of anode sludge for separating the gold and silver

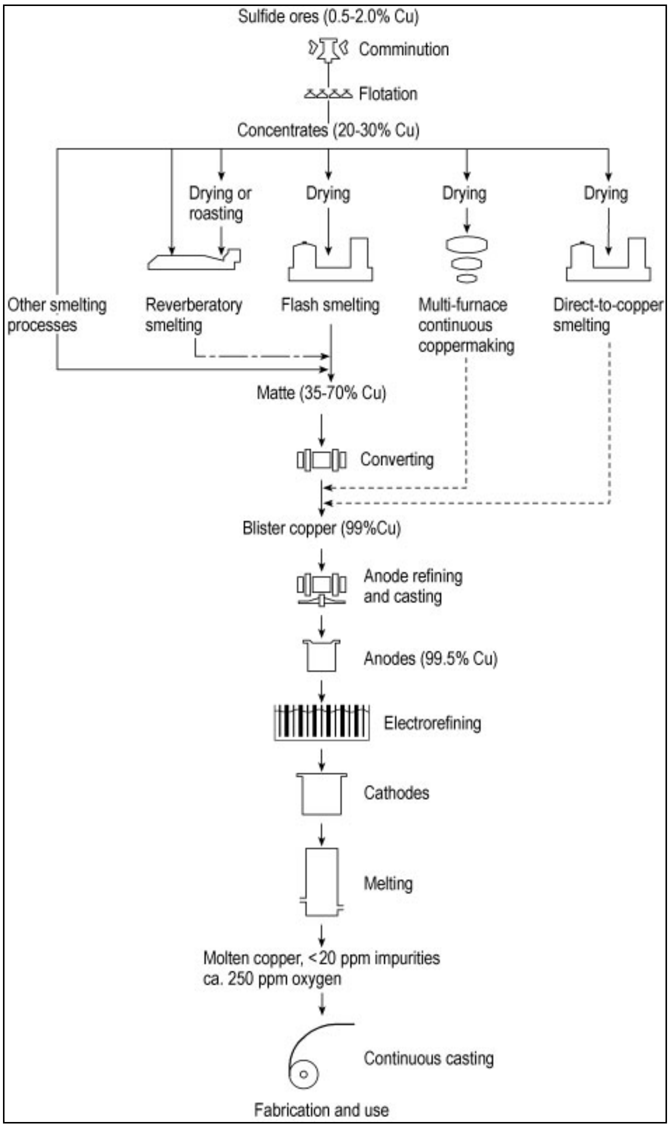



Figure 25 Principal process for extracting copper from sulphide ores [Lossin 2001]

Thanks to a long-standing tried and tested process and large quantities, copper extraction can be carried out extremely efficiently. The actual amounts of energy required are relatively small despite the quantities to be moved and processed. The large environmental impacts are therefore due primarily to the absolute quantities extracted and produced (global annual production for 2010: 16.2 million tonnes of copper [Edelstein 2011]). Copper mining produces massive intrusions in the hydrosphere, lithosphere and biosphere [Restle 2009], leading to a fall in the ground water level, water acidification, ground subsidence, habitat destruction, erosion and land consumption. Processing results in large quantities of overburden which have to be deposited. In addition there is a risk of polluting the environment with sulphur oxides and heavy metals due to inadequate filter systems in the hydrometallurgical processes.

### 8.3.2 Gold

Gold is found in the earth's crust at a concentration of approx. 0.005 ppm [Binder 1999], although the specified values cover a wide range. It occurs practically always in native form with approx. 2-20% silver content [Pohl 2005].

Natural deposits with native gold can be divided into two types. First there are primary deposits where the gold occurs in veins along with minerals such as quartz, calcite and alunite and various sulphides (pyrite, galena, chalcopyrite etc.). Second are what are known as the secondary deposits where weathering processes have exposed the gold and it has then been deposited in gravel, streams or rivers [Pohl 2005]. The current reserves-to-production ratio is approx. 20 years with reserves of around 51,000 tonnes [USGS 2011b].

Native gold very rarely occurs as nuggets, with deposits usually being in the form of finely distributed nanoparticles which are bound in the surrounding rock. Extracting gold is therefore mainly a matter of exposing the rock followed by concentration of the gold [Pohl 2005].

Thanks to the high price of gold, extracting primary gold can exploit deposits with concentrations of only 5 g gold per tonne of rock and treatment processes with high material and energy inputs can be operated cost effectively [Renner 2000].

As a result of the high price and the relatively easy process for extracting gold, a comparatively large proportion of the gold is obtained by individual prospectors or very small (illegal) businesses, especially in developing countries. These mostly operate illegally and without any state control [Ebel 2007]. These operators accept dangers to life and limb and environmental hazards resulting from a lack of safety measures due to poverty, ignorance or profit-seeking. The small businesses use simple treatment processes which require little or almost no investment of capital and materials, limiting these operations to gold deposits in loose material (gravel, sand and clay) obtained from rivers or poorly stabilised mines excavated by these operators.

The gold-bearing material is suspended in water and then treated with a simple density separation process. The gold concentrate produced from this is then further concentrated by means of the amalgam method, previously used as the standard industrial process. In this process the gold-bearing concentrate is mixed with mercury (manually in some cases) so that the gold forms an amalgam with the mercury. After separating the amalgam it is heated at over 600 °C so that the mercury vaporises and the raw gold is left behind. Due to the high quantities of mercury, up to 5 $kg_{Hg}/kg_{Au}$, which are mainly released to the atmosphere, large areas are affected by severe long-term pollution [Gasmi 2004].

As the price of gold is high, considerable efforts can be made to extract the gold from the ore. Industrial gold extraction therefore invests significant amounts of capital and material in order to extract even the ores which are difficult to reach and require complex technical processing. For example, in South Africa there are plans to extract gold ore from depths of over 4 km [Glüsing 2008]. Extracting gold ore from great depths combined with the low concentration of gold in the rock requires considerable amounts of energy for transporting the material to the processing plants on the surface.

Due to the low amounts of gold in the rock, large quantities of material need to be mined, moved and processed. Large amounts of land are required for the mines themselves, especially in opencast mining, but also for slagheaps and processing sites. In addition, due to the deep cuts in the land, there can be significant changes to the ecosystem and hydrological system (water acidification, lowering of the water table) for the affected region [Ebel 2007].

The mined material is crushed into very small pieces in several stages to release the fine-grained gold from the surrounding rock. This requires large amounts of crushing.

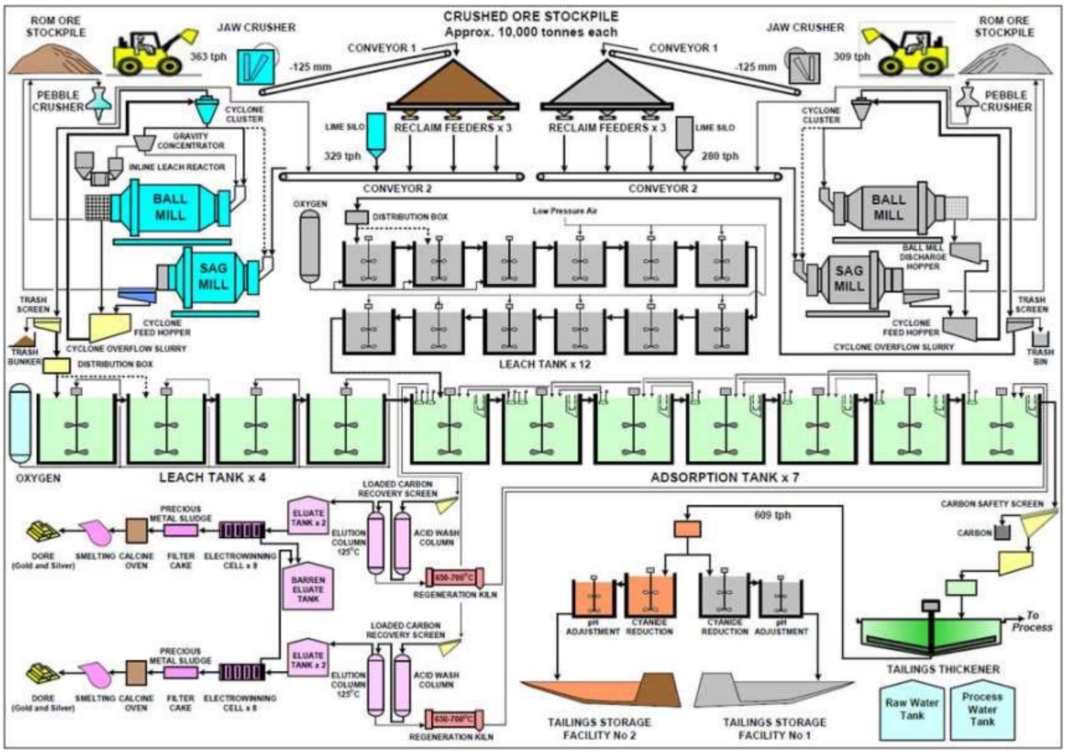



Figure 26 Industrial extraction of gold using the carbon in pulp process (CIP) [Kingsgate 2011]

On an industrial scale gold is currently extracted mainly using the cyanide process. The gold is dissolved from the surrounding rock using cyanide which is poisonous. This either involves the finely crushed ore being stored in stockpiles and then mixed with cyanide leach (for low Au content) or exposed to the cyanide in large forced mixers. The cyanide dissolves the gold from the surrounding rock and is then collected. The gold is recovered either by cementation in which zinc is added to the gold leach or (more common nowadays), by adsorption on active carbon (CIP) where the gold is recovered by desorption in autoclaves, cf. Fig. 26.

The cyanide leach is recycled in the process, necessitating large settling tanks and reservoirs. Incorrect storage can lead to serious accidents with the poisonous cyanide escaping to the surroundings and whole areas being seriously affected, as was the case in Baia Mare in Romania in January 2000 [IAD].

The remaining debris (the rock from which the gold has been removed) still often contains large amounts of heavy metals and cyanide residues [Renner 2000] which are a significant potential hazard.

Additional sources of primary gold are other metal extraction processes, particularly copper smelting (see Section 8.3.1), in which gold is obtained as a by-product. When the copper matte is cleaned in the anode process, what is known as anode sludge is produced which contains other more precious metals (Ag, Au, Pt).

### 8.3.3 Silver

Silver occurs at a concentration of 0.079 ppm in the earth's crust [Arnold 2007]. Besides the native form, it occurs in various mineral forms such as, for example, argentite ($Ag_2S$) or polybasite ($(Ag,Cu)_{16}Sb_2S_{11}$) [Pohl 2005]. Silver is an element which is extracted both as a major and a minor metal. Only a third of the primary silver is obtained from silver mines and the larger part of production is a by-product from the production of other non-ferrous metals. The extraction processes for lead, copper and gold are the main ones involved here [Pohl 2005].

The reserves-to-production ratio is currently estimated to be approx. 23 years, though it should be noted that silver is often released as a by-product of other extraction processes and is therefore dependent on these. Silver reserves amount to 510,000 tonnes [USGS 2001c].

Primary production of silver from native silver is carried out by means of cyanide leaching, thiosulphate leaching or the amalgam process, but the last-named is rarely used nowadays due to environmental risks and low yields. Thiosulphate leaching is a similar process to cyanide leaching but has been replaced nowadays by the more cost-effective cyanide process [Brumby 2008]. The likely environmental effects are similar to those arising from gold extraction using the cyanide process.

Extracting silver from lead/(zinc) ores is done by means of the Parkes process and subsequent cupellation. In lead processing the silver accompanies the lead through the individual process steps to the lead bullion, during which it is preconcentrated from 0.01% to 1%. In the Parkes process, after roasting and reducing the lead ore, the resulting liquid lead bullion is mixed with liquid zinc. Due to the high solubility of silver in zinc, when the molten metal is cooled, the silver passes from the melt into the solidifying zinc, forming what is known as zinc scum. After separating the remaining lead, this is distilled in a retort or vacuum furnace. Besides lead, the residue contains up to 50% silver plus small amounts of other elements. The subsequent cupellation is carried out by introducing air into the melted residue (high grade lead). In contrast to the precious silver, the lead oxidises along with the other impurities and can be extracted. This enables high purity silver to be obtained [Brumby 2008].

When extracting silver from copper ores, the separation of copper and silver only takes place near the end of the copper extraction process chain. The two metals pass through all the mechanical and pyrometallurgical treatment processes together (see 8.3.1). Separating the copper and silver (and gold) only happens during the electrolytic purification of the copper matte to pure copper. This process produces what is known as the anode sludge which contains the precious metals, copper and other metals. This anode sludge is then sieved and leached in order to remove a large proportion of the copper. The subsequent treatment of the anode sludge depends to a large degree on the specific composition which can vary greatly. Very varied industrial treatment process have been developed which are mostly not published by the industrial companies [Brumby 2008].

Native gold nearly always has a certain alloy content of silver [Pohl 2005]. This is almost always treated along with the gold through the whole treatment process (mining, concentration, leaching and extraction from the leach). The silver is only separated from the gold during purification of the raw gold. In the standard Miller process, silver and other metals are separated by chlorination. This involves blowing chlorine gas through the molten metal which causes the metals which are less precious than gold to form chlorine compounds which float as a scum. The scum is then leached in stages until silver chloride remains. Extracting the elementary silver is then done by a reduction using zinc powder followed by an electrolytic purification [Brumby 2008].

Like gold, the extraction of silver ores is associated with considerable negative environmental effects. These are due in particular to the large material throughput, the amount of energy required for extraction and the use of poisonous cyanide. In the case of the other extraction processes where silver is to be considered as a minor metal, silver only accounts for part of the environmental impacts of the whole process chain.

### 8.3.4 Gallium

The element gallium is present in the earth's crust at 16 ppm [Krauß 1989] and is therefore more abundant than lead. It forms scarcely any minerals itself (with the exception of gallite

[Krauß 1989]) and is only found in larger quantities in (zinc and) aluminium ores [Pohl 2005]. This is due to the close geochemical relationship between gallium and aluminium based on the similar atomic radii of each of the ions [Krauß 1989]. This enables gallium to use the lattice positions of aluminium ions in bauxite, so achieving concentrations of 0.003% - 0.008% in the bauxite [Greber 2000].

Economically it is not worth mining bauxite purely because of the gallium [Greber 2000]. There is therefore no primary mining of gallium [Pohl 2005, Mikolajczyk 2009] and it is therefore purely a minor metal. 95% of primary gallium currently comes from bauxite which has been extracted for producing aluminium oxide. The remaining percentage comes from zinc ores [Pohl 2005], but this method is becoming much less important for obtaining gallium because of changes in the zinc production process [Weiss 1985]. Due to this close connection of gallium production to bauxite processing the reserves-to-production ratio for gallium is directly linked to that for bauxite which is currently approx. 130 years. Reserves of bauxite total around 28 billion tonnes [USGS 2011h].

Aluminium oxide (a starting material for primary aluminium extraction) is extracted from bauxite using the Bayer process, which is currently the only process used in production anywhere in the world [Weiss 1985]. In addition to aluminium oxide, gallium can also be obtained from the Bayer process using additional plant. The gallium extraction plant is almost always located in or close to the site where aluminium oxide is produced [Greber 2000] i.e. there are no dedicated production plants for primary gallium [Metalsplace 2011]. The maximum size of the gallium works therefore depends directly on the existing aluminium oxide smelter.

The Bayer process, in which the bauxite is ground and mixed with sodium hydroxide, is the standard method for obtaining aluminium from bauxite ore. What is unusual about the Bayer process is that the aluminium-containing minerals (which also contain gallium) in the bauxite are dissolved with NaOH under relatively moderate hydrothermal conditions while the other components in the process are almost completely inert [Greber 2000].

By passing the sodium/aluminium solution several times through the Bayer process the gallium content in the solution increases to 70-150 mg/l, with only a part of the total recirculated quantity being extracted at a time. Extracting the gallium from the leach can be done in three different ways [Greber 2000], cf. Figure 27:

- Selective precipitation
- Electrolytic process
- Extraction using complexing agents (currently the standard process)

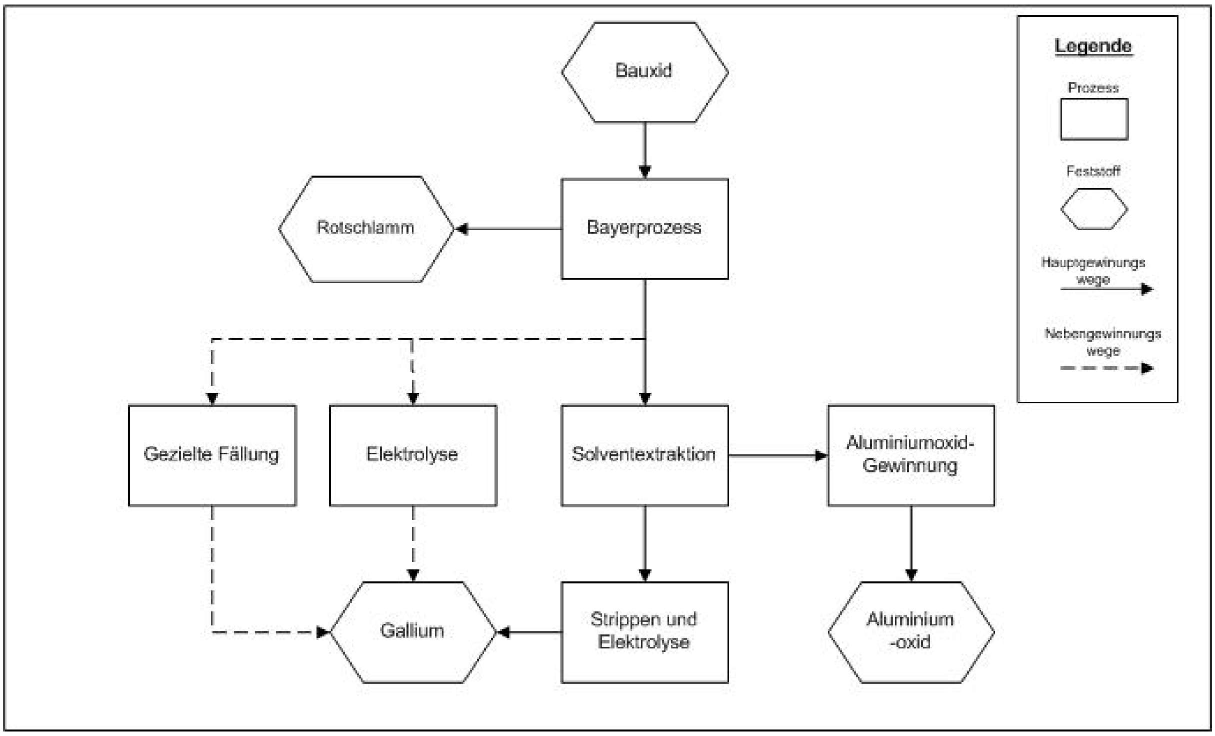



Figure 27 Diagram showing principles of gallium extraction (Figure from TU Clausthal)

In the selective precipitation process the sodium aluminate solution is mixed with $CO_2$. Pure aluminium hydroxide is precipitated out first, increasing the percentage of gallium in the solution. This is followed by more precipitation steps to further increase the gallium concentration. The gallium is finally precipitated as hydroxide along with the remaining aluminium. This is dissolved in sodium hydroxide following which the gallium can be extracted using electrolysis. This method is very labour-intensive because of the large number of precipitation stages and can therefore only be used if the labour and energy costs are low. There is currently only one known plant in China which uses this process (annual production 5 t/a).

The electrolytical process exploits the fact that gallium forms an amalgam with mercury from which the gallium can be recovered using sodium hydroxide. The mercury is recirculated. This method requires relatively high gallium concentrations in the leach, so that it can no longer be used in modern aluminium oxide plants. It also produced increased mercury concentrations in the leach stream. There is probably no longer any gallium produced by this method, except for a small plant in Hungary.

In the extraction process using complexing agents the gallium is obtained from the (watery) solution using solvent extraction. Complexing agents which suit the specific conditions (e.g. Kelex 100) are used: these are bound in an organic phase or are present as solids. In this process not only the gallium but also aluminium, sodium and other metals from the solution are bound to the complexing agents. These can mostly be stripped (separated from the complexing agent) using weak acids so that the gallium can be extracted using stronger acids (hydrochloric or sulphuric acid) at the next stage. The remaining impurities can be treated using electrolysis, so that purities of up to 99% (sometimes 99.9%) can be achieved. This is currently the standard method for obtaining primary gallium from the leach.

The whole process of extracting gallium from bauxite uses only slightly more leach compared to the aluminium oxide works as a whole [Morawietz 1964]. The materials used for solvent extraction (complexing agents, acids) can be used in a circulation process and only require a small amount of topping up.

Example: Ingal Stade (Process: complexing agent):

Production: 1 million t Aluminium oxide -> 4,000 t $Na_2O$

30 t Gallium -> 10 t $Na_2O$

Therefore 0.25% more $Na_2O$ is required than already used by the existing aluminium oxide works [Lochte 2010].

The total energy consumption per tonne of aluminium oxide produced is estimated at approx. 16,000 MJ [Greber 2000]. Extracting gallium (using a complexing agent) requires less than one per cent of the electricity consumption of the plant and far less in relation to the total energy consumption (although for considerably smaller quantities produced in comparison with aluminium oxide). The resulting wastes can either be fed back into the overall process (weak sodium hydroxide) or easily processed by thermal treatment (no chlorides or similar) [Lochte 2010]. How far the opportunities for recycling and environmentally compatible disposal can be implemented probably has to be judged on a regional basis. No information is available for China, the largest producing country.

Because, as mentioned above, primary gallium works never operate in isolation but are always linked to an aluminium oxide smelter, the primary gallium production must be considered in this context. By exploiting the Bayer process applied to aluminium oxide production, high synergies can result for the raw material handling. The processes used specifically for gallium production are state-of-the-art and have been tested over a long period in other areas of hydrometallurgy (copper extraction).

As the total global quantity of gallium produced – at 78-110 t/a [Jaskula 2010] – is still very low, the absolute energy consumption and materials used for the whole alumina production system are considered to be relatively minor. However, due to the small quantities produced, the low concentrations in the starting material and the special processes used, relatively high specific environmental effects are to be expected.

### 8.3.5 Indium

Indium occurs at approx. 0.05 ppm in the earth's crust [Tolcin 2010]. The best-known and most common minerals of the metal are indite and roquésit [Schwarz-Schampera 2002], however these do not occur in workable quantities. Indium therefore has to be obtained as a by-product from other metal extraction processes. Indium occurs in workable quantities as an impurity primarily in zinc blende, galenite and copper pyrites [Felix 2000]. The most important economic concentrations occur in volcanic-hosted and sediment-hosted massive sulphide deposits which are by far the largest accumulations of indium worldwide [BGR 2005]. Ores with a high percentage of indium often contain concentrations of other high-tech metals such as Ge, Ga, Bi and tellurium [BGR 2005]. The metal is extracted by smelting these polymetallic ores which mainly contain non-ferrous metals such as lead, zinc, copper and tin.

As a minor metal, the reserves-to-production ratio of indium is directly related to that of the relevant major metals (tin and zinc) which have reserves-to-production ratios of 20 and 21 years respectively. Reserves of tin amount to around 5.2 million tonnes [USGS 2011j] and those of the zinc ores to 250 million tonnes [USGS 2011k].

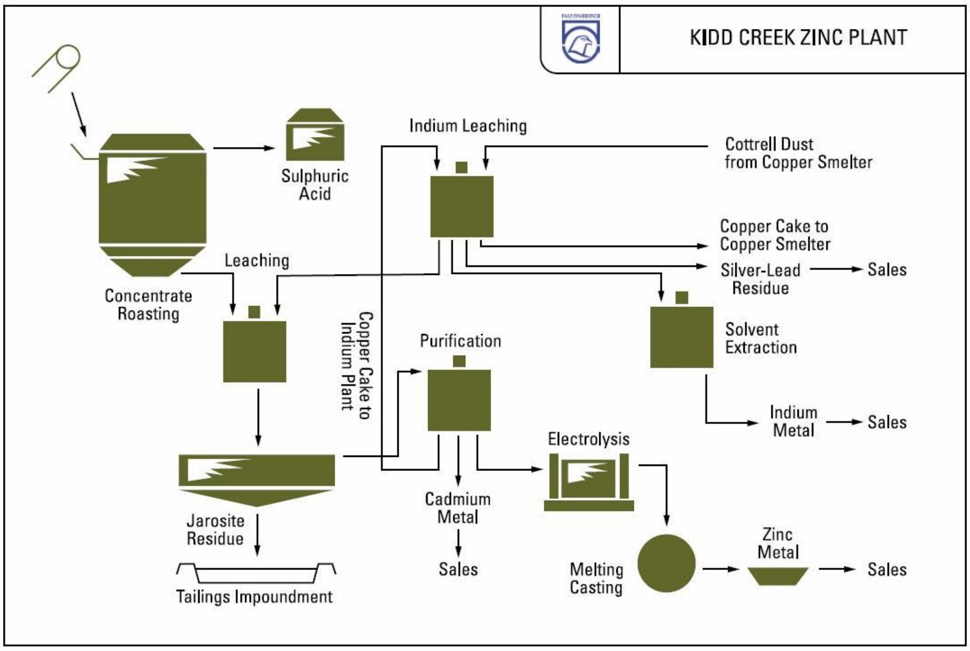



Figure 28 Flowchart to show the zinc smelter process with indium extraction at the Kid Creek zinc smelter [Falconbridge 2002]

Indium extraction mostly occurs from residues in the production of zinc. The parent material sphalerite (zinc blende) usually contains 10-20 ppm of indium, but occasionally far higher concentrations of up to 10,000 ppm can be found [Felix 2000].

Indium extraction is carried out using material flows from processes which deliver Indium concentrations in increased percentages. Concentrated residues of this kind are, for example, fly ash from roasting lead-zinc ores, wash zinc in the New Jersey distillation, lead sulphate leaching residues in zinc leaching for electrolysis and cadmium cementite for purifying the leach liquor for the lithopone precipitation [Morawietz 1964].

The recovery of the pure metals from the main process is done by processes which depend on the concentrate. These processes cover various leach stages (HCl, $H_2SO_4$), solvent extraction for further concentration if required and suitable steps to recover the metal from the leach. Only approx. 50-80% of the indium can actually be extracted depending on the process used for the raw material treatment. Other by-products such as e.g. silver, can be obtained depending on the deposit in question [Felix 2000].

The environmental impact of primary production can be divided into two areas, as is the case with germanium and gallium. On the one hand those which are determined by the major metal i.e. mining and main process. These should not be counted against the minor metal (in this case indium). On the other hand are those areas which are specifically related to the extraction of indium. These include the specific processes and the associated material and energy consumption for the extraction of the pure indium from the concentrates in the main process.

Due to the low production amounts (approx. 600 t/a) in comparison to the major metals associated with indium (e.g. zinc), the required material and energy consumption are kept within limits in absolute terms. However, the specialised process for concentration, i.e. solvent extraction in particular in this case, the low concentrations and the small amounts produced mean that high specific energy and material inputs must be anticipated..

### 8.3.6 Germanium

Germanium occurs in the earth's crust at a concentration of approx. 6.7 ppm [Binder 1999], at a similar concentration to zinc or lead, but is more sparsely distributed. It forms a number of natural minerals such as germanite ($Cu_{26}Fe_4Ge_4S_{32}$), but no workable ores or deposits are known. Germanium is therefore obtained as a by-product from other processes.

The reserves-to-production ratio for germanium as a minor metal is directly linked to its main metal, so that a reserves-to-production ratio of approx. 21 years (zinc) can be assumed.[9] Germanium must be viewed as a strategic metal as it is an important component of (military) night vision devices, amongst other things. For this reason it is generally difficult to obtain reliable data on this metal and any data are not generally applicable. Germanium is currently mainly obtained from the smelting of zinc and copper sulphide ores plus from fly ash from the combustion of some germanium-rich coals for electricity generation [Gubermann 2009]. The concentration can reach 400 ppm in zinc ores, 640 ppm in copper ores and 300 ppm in coals.

The extraction processes make use of natural germanium sinks in the individual main processes. For example, in thermal processes use is made of the volatility of GeO or GeS, in hydrometallurgical processes precipitation of Ge as the sulphide or hydroxide is used to concentrate the germanium. The concentrates created from the main process contain Ge at a concentration between 7% and 50% [Scoyer 2000].

9 Zinc ore reserves total approx. 250 million tonnes [USGS 2011k]

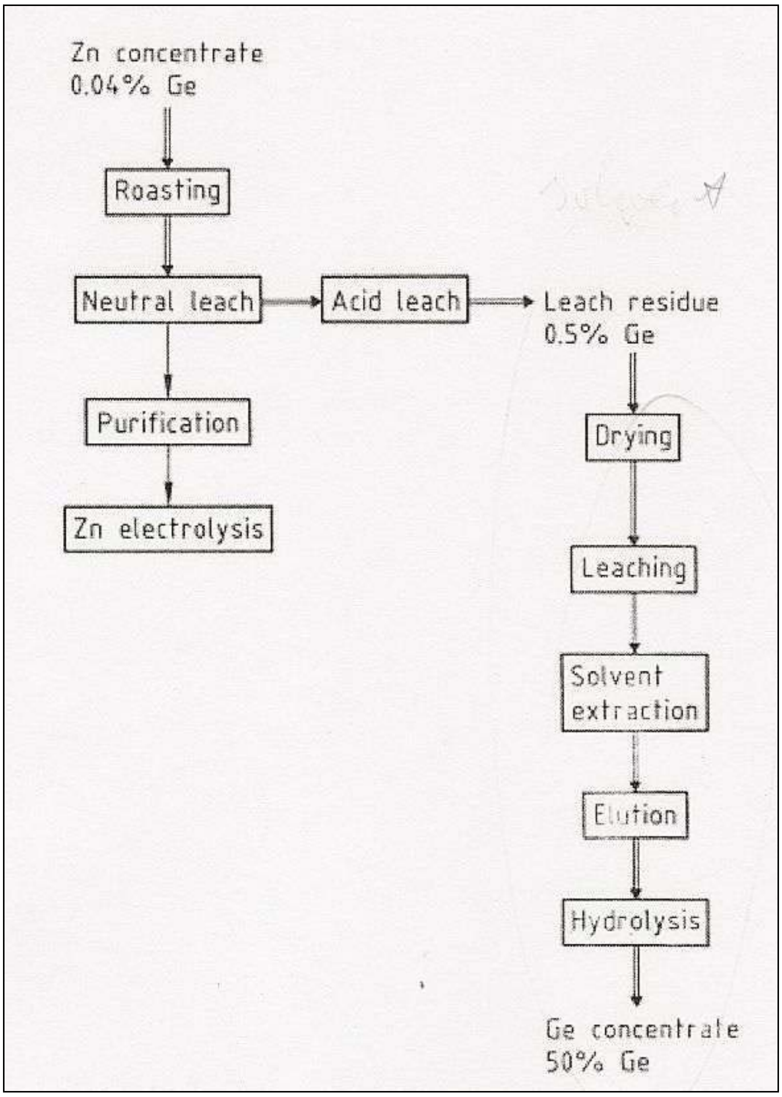



Figure 29 Example for extraction of a germanium concentrate from a main process [Scoyer 2000]

This can then be concentrated to germanium using almost the same method, irrespective of the preceding processes. The germanium concentrate is mixed with hydrochloric acid in a chlorine atmosphere.

$GeO_2$+4 HCl (>6M) -> $GeCl_4$ +2 $H_2O$ at approx. 83 °C

Ge + 4 $HCl_2$ -> $GeCl_4$ + 2 $H_2O$

The $GeCl_4$ produced in this way vaporises at 83 °C, releasing germanium from the compound. The $GeCl_4$ gas which is then cleaned of impurities is hydrolysed so that pure $GeO_2$(solid) precipitates out. After drying, hydrogen reduction is performed in a tubular furnace at approx. 650 °C in order to obtain elementary germanium [Scoyer 2000].

Many of the environmental effects from producing germanium are not attributable to it directly but are really due to the main process such as, for example, the $SO_2$ pollution from the zinc industry. Due to the small annual global production of germanium of approx. 90 t/a, the necessary material and energy consumption is kept within reasonable limits, however large specific inputs of energy and materials can be expected because of the low concentration, the specialised concentration process and the small quantities.

### 8.3.7 Rare earths

The reserves of the rare earths neodymium, dysprosium, praseodymium and terbium oxide studied amount to approx. 24 million tonnes (Öko-Institut calculations after USGS 2011). Primary production in 2010 was approx. 35,355 tonnes for the four priority rare earths (Öko-Institut calculations after USGS 2011 and BGR 2011). According to BGR 2011, dysprosium oxide accounts for 1,980 tonnes and terbium oxide for 375 tonnes. Looking at these four rare earths together gives a reserves-to-production ratio of 679 years.

The rare earths are major metals which are extracted from the natural ores bastnaesite, xenotime, monazite and the ion-adsorption sediments, always associated with other rare earths. Because they occur together and have similar chemical structures, separating rare earths is very time-consuming and cost-intensive.

At present most rare earths are obtained from opencast mining. Apart from the deposits in Southern China, all deposits contain radioactive substances e.g. uranium or thorium besides the rare earths. The ores also contain heavy metals. Consequently the mining and processing of rare earths leads to numerous environmental hazards if comprehensive environmental protection measures for protecting the groundwater, air and soil are not put in place. An overview of the most serious risks is shown in Figure 30.

The greatest potential environmental hazards are due to what are known as flotation tailings which come from concentrating the mined and then finely ground ores. They consist of a mixture of process chemicals, water and chemicals from the separation processes plus finely ground material and almost always also contain radioactive substances and heavy metals. The tailings are normally channelled into settling ponds which are either man-made reservoirs or natural water bodies (e.g. lakes). These settling ponds are surrounded by bunds for protection. The flotation tailings usually remain permanently in the settling ponds which gradually dry out due to natural evaporation if no water is added. The bund must remain stable for centuries so that the flotation tailings do not end up in the surrounding environment. It should be remembered that, depending on the site, the bunds are exposed to various risks such as e.g. overtopping from storm water and inadequate long-term stability due to construction faults or earthquakes. If the bund bursts as happened in Hungary in October 2010 in an aluminium oxide works, severe environmental damage can result with, in the case of rare earths, emissions of thorium, uranium, heavy metals, acids and fluorides. Other potential negative environmental effects due to the mining and further processing are additional emissions to the atmosphere, soil contamination, land consumption, etc.

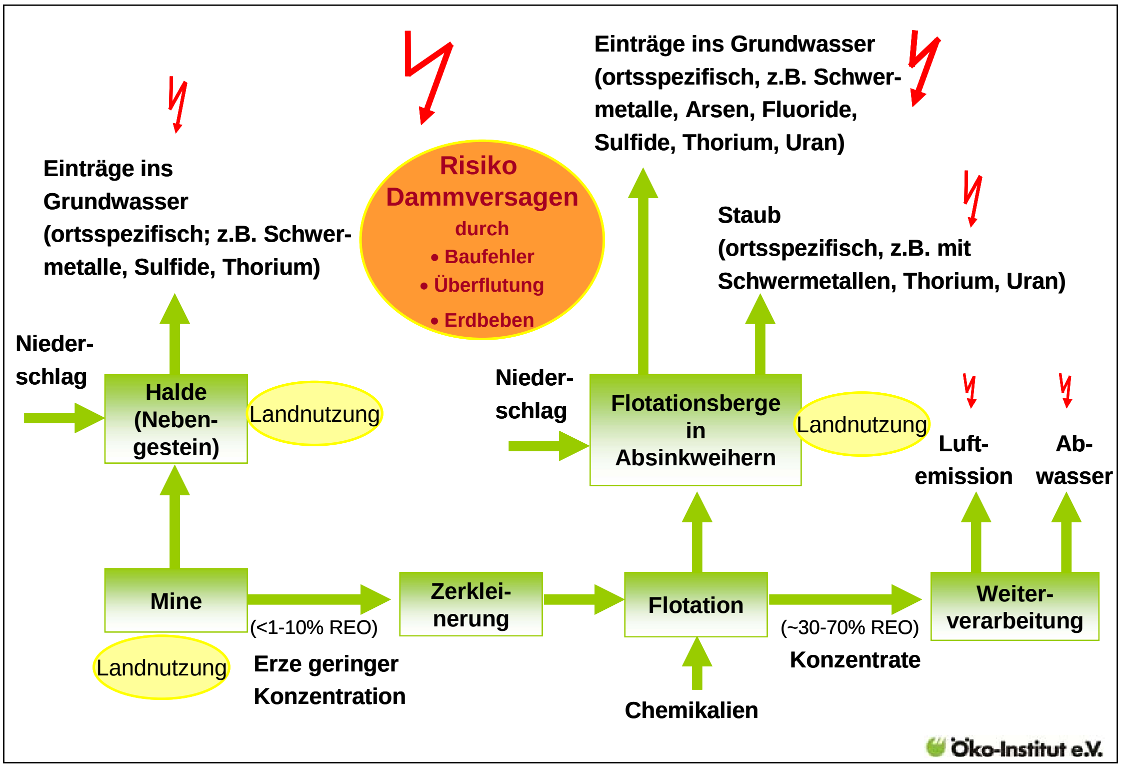



Figure 30 Risks of rare earth mining with inadequate environmental protection measures [Öko-Institut e.V. 2011]

On account of the massive environmental problems in China, the government has concluded plans for optimising and consolidating the rare earth industry for the next five years, including the closure of small mines.

### 8.3.8 Platinum group metals (PGM)

The two priority platinum group metals[10] platinum and palladium normally occur in association with the other platinum group metals ruthenium, osmium, rhodium and iridium as well as silver and gold [Hollemann Wiberg 2007].

The primary metal production of platinum was approx. 188 tonnes in 2010 of which 144 tonnes were mined in South Africa. The reserves-to-production ratio of platinum is 144 years for reserves of 27,000 tonnes [Öko-Institut e.V. 2009 and Johnson Matthey 2011].

Platinum is extracted both as a major metal (in South Africa) and as a minor metal in palladium / nickel mining (in the CIS). 76% of primary platinum extraction takes place in South Africa [Johnson Matthey 2011]. The ores here have a comparatively very low concentration of platinum. Infrastructure problems (e.g. power supply) and social issues (land use rights etc.) are of overriding importance.

[10] Ruthenium was added to the group of priority elements at the 1st expert workshop. In the course of the study it was downgraded to second priority again due to the findings.

In 2010 primary production of palladium was 227 tonnes, of which 116 tonnes were produced in Russia and 80 tonnes in South Africa [Johnson Matthey 2011]. Reserves total 26,000 tonnes which gives a calculated reserves-to-production ratio of 115 years [Öko-Institut e.V. 2009]. Palladium is always extracted as a minor metal from the natural platinum and nickel ores. Approx. 51% of the primary palladium is mined in Russia [Johnson Matthey 2011]. This site is known for its old processing plants and an unfavourable position north of the Arctic Circle. Production is associated with very high $SO_2$ emissions. Norilsk is the home of one of the world's largest PGM primary producers, linked to the production of nickel and copper. The city is the largest point source of $SO_2$ in the world due to the extraction of PGM and other metals. The area is badly acidified due to the sulphurous ores and inadequate waste gas purification. There are also problems with wastes and dust emissions. The isolated location is disadvantageous for the removal of sulphur or sulphuric acid, the standard products of waste gas purification.

Exploration and primary production of the platinum group metals are very time-consuming and capital-intensive. Global mining of PGM is focussed on a few large mining companies (e.g. Anglo Platinum, Norilsks Nickel) which have their own smelting and refining plants for turning the PGM into fine metal. The smaller mining companies usually only process the ores and deliver the PGM concentrates to specialised companies for refining [Hagelüken, Buchert, Stahl 2005].

Preparation of the finely ground ores is usually carried out using flotation. The precious metals along with copper, nickel and other non-ferrous metals are concentrated in multi-stage pyro-metallurgical processes and then separated from the non-ferrous metals. First a siliceous, iron-bearing slag is precipitated from the non-ferrous metal and precious metal-containing sulphide matte (green colour) in an electric arc furnace. This is followed by desulphurisation of the matte in Pierce-Smith or TBRC converters and the separation of iron as fayalite slag. This produces white-coloured low-iron matte. This matte is continually drawn off and poured into blocks which undergo controlled cooling over 2-5 days. This treatment brings about a phase separation. The PGMs are now concentrated in a fine crystal metallic Ni-Co-Fe phase with a yield of up to 98% which, after being ground, is separated from the low PGM sulphide Cu-Ni phase by magnetic separation. The non-ferrous metals are dissolved from the PGM-containing magnetic phase using pressure leaching with $H_2SO_4/O_2$. The remaining concentrate of PGM at 40% to 90% is the primary material for refining [Hagelüken, Buchert, Stahl 2005].

The environmental effects of extracting platinum group metals depend on the natural composition of the ores (the percentage varies between 5 and 10 grammes PGM per tonne of ore [Hagelüken, Buchert, Stahl 2005]), the location of the site, the age of the mine and the processing plant, the environmental policies of the country and the composition of the fuel mix.

### 8.3.9 Environmental relief through electro mobility (resource study)

Environmental relief also results from the discontinuation or reduction of conventional drives.

This sub-section will deal with the environmental pollution due to primary extraction of those metals used in the components which are no longer required in all-electric and fuel cell passenger vehicles. These components are the engine, fuel system, exhaust system and catalytic converter. The engine uses copper, aluminium, steel and ferrous materials in particular. As the exhaust system components are no longer necessary, savings of copper, steel and ferrous materials are made. Steel and ferrous materials used in the fuel system are also no longer required. Platinum and palladium are saved from the catalytic converter component.

For the estimate of $CO_2$ emissions associated with the material requirement, only the $CO_2$ emissions linked to the manufacture of the metals were used here. In 2020 this results in a saving of approx. 1.4 million tonnes of $CO_2$ equivalents; in 2030 the saving amounts to approx. 8.1 million tonnes of $CO_2$ equivalents (see Table 16). As already described in Section 8.2, the GWPs for 2020 and 2030 are kept constant for the calculation.

Table 16 Reduction in $CO_2$ emissions from primary metal extraction due to decreased amounts of metals in fuel cell and all-electric passenger vehicles in relation to the baseline scenario (calculations for global average passenger vehicle from information supplied by Daimler AG).

| | Kupfer | Platin | Palladium | Aluminium | Stahl |
|---|---|---|---|---|---|
| **Einsparung 2020** | | | | | |
| in Tonnen Material | ca. 4.500 | 4 | 5 | ca. 66.700 | ca. 250.400 |
| in Tonnen $CO_2$-Äquivalente | ca. 8.600 | ca. 70.000 | ca. 52.700 | ca. 826.000 | ca. 415.300 |
| **Einsparung 2030** | | | | | |
| in Tonnen Material | ca. 26.500 | 26 | 31 | ca. 394.000 | ca. 1.479.200 |
| in Tonnen $CO_2$-Äquivalente | ca. 51.000 | ca. 412.400 | ca. 311.400 | ca. 4.879.500 | ca. 2.453.200 |

Overall, it can be seen from the estimate that the order of magnitude of $CO_2$ relief due to reductions in material requirements for the components of the conventional powertrain dealt with in this project easily equal the order of magnitude for the additional $CO_2$ loading from the material requirements of the components used in electro mobility. As already stressed elsewhere, these results are not a comprehensive environmental balance sheet. Both the inputs for the production processes from the pure metals to the finished components (both for conventional and electro mobility components) and the production chain for the important component battery are excluded. The relevant comprehensive environmental balance sheets must be left for other projects. The potential savings from the important use phase of the electrical vehicles are discussed in detail in the main OPTUM project report.

# 9 Recycling status and prospects for the priority metals

An important prerequisite for fulfilling the future mobility concepts is to guarantee the medium and long-term resource availability of the special and precious metals for large-scale use in the components of future electric vehicles. The environmentally compatible and efficient recycling of these important materials is therefore a crucial requirement.

The demand for key metals will rise sharply with the market entry and increasing market penetration of electric vehicles, leading to price increases in these raw materials and therefore increased costs for electric and hybrid vehicles. Figure 31 shows the development of the primary extraction of the top priority high-tech metals identified for electro mobility. This illustrates the increasing exploitation over the last 30 years compared to the last 100 years. For completeness sake it should be mentioned here that, besides the material requirements for electro mobility, there is a whole series of competing applications which also make use of the elements in question; see Figure 32.

In addition to this, the primary production of some important raw materials for electro mobility such as rare earth elements (REE), platinum group metals, lithium and cobalt, etc. are extremely concentrated regionally. This means that the manufacturer is very dependent on these. Potential economic or politically destabilising events in the production regions can have detrimental effects on the security of the raw material supply and lead to considerable price fluctuations: see REE as a current example. Both within the automotive industry and elsewhere there is therefore a growing awareness of the possible risks associated with costs and failure of the supply of raw materials.

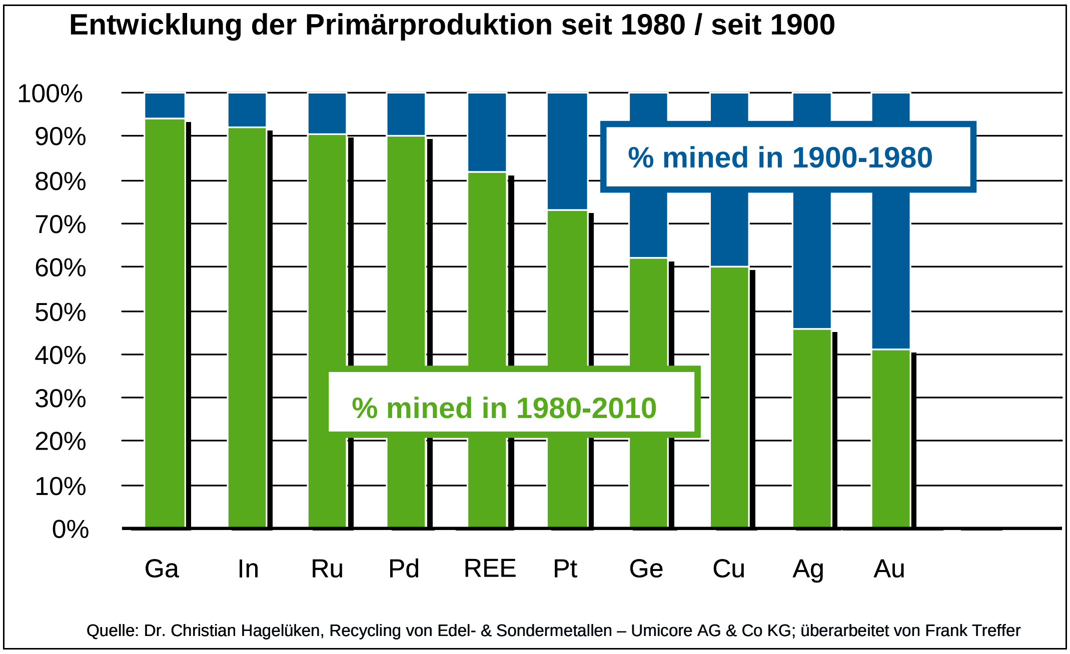



Figure 31 Percentage of high-tech metals classified as important by the OPTUM project extracted worldwide over the last three decades in comparison to total production since 1900

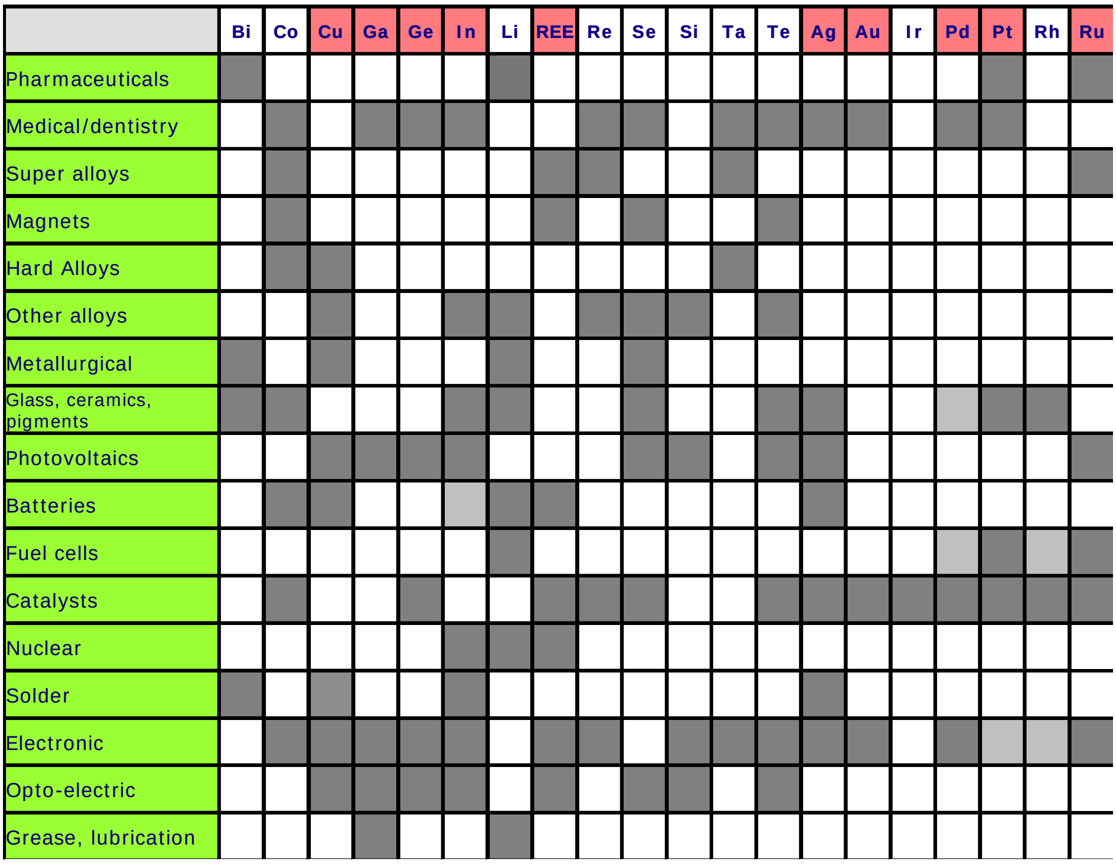



Figure 32 Competing applications for high-tech metals – the elements of importance for electro mobility are highlighted in red.

Recycling the materials already present in the economic cycle will definitely make an important contribution in helping to ease the future supply of raw materials. A not inconsiderable portion of the demand can be met by recycled material without having to depend solely on the natural resources. It is already apparent that increasingly costly processes are required to identify, develop and exploit natural deposits. This inevitably calls into question the profitability and environmental balance of new technologies. In Europe in particular – and Germany especially – there is a large and in future increasing "secondary supply" available due to the significant quantities of waste equipment which to date have not been exploited nearly enough.

<u>Recycling precious and special metals by Umicore</u>

Umicore AG is a leading global provider of metallurgical and chemical products and those containing precious metals with a staff of over 14,500 and an annual turnover of approx. EUR 6.94 billion in 2009. The company's headquarters is in Brussels. The German subsidiary Umicore AG & Co KG has wide-ranging expertise in the fields of catalysis, precious metals, recycling and surface technology. Umicore is one of the global market leaders in the field of catalytic converters. With the takeover of the Degussa precious metals business in 2003, Umicore's Precious Metals Refining division achieved the global leading position in the field of precious metals recycling.

In addition to all the precious metals, a large range of base and special metals are also recovered (20 metals in total) in large recycling plants with flexible capacities at the company's sites in Belgium and Brazil. The company combines industrial expertise in the production of modern products based on precious metals with over 125 years' of experience in the field of recycling. Umicore processes a broad range of secondary materials in one of the world's most modern recycling plants in Hoboken near Antwerp. Each year high yields of valuable metals are recovered from over 350,000 t of feedstock (catalytic converters, PCBs, mobile phones, intermediate industrial products and residues, slags, fly ash, etc.) using a complex pyro-metallurgical process (see Figure 33).

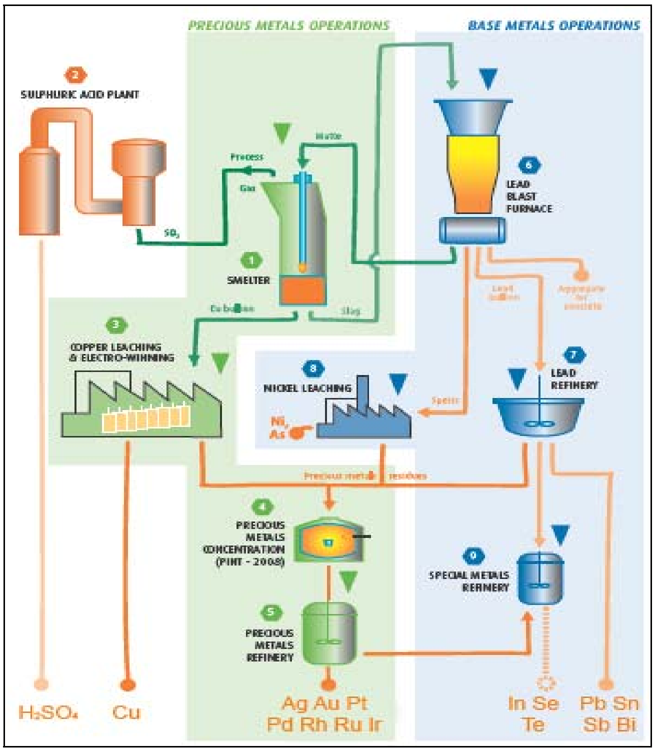



Figure 33 Process flow diagram for Umicore's integrated precious metal smelting works in Hoboken near Antwerp (Belgium)

The process management was originally optimised for the precious metals so that long cycle times <u>and</u> high precious metal yields were and are achieved. The throughput quotas can also be increased by the combined processing of a large range of complex materials containing precious metals. This also increases flexibility and the robustness towards contaminants. The copper contained in the melt binds the precious metals and is pelletised immediately after tapping and fed to a downstream electrolysis process where the precious metals are finally separated from the copper. The primary slag, on the other hand, undergoes a further blast furnace treatment in which lead and other base metals are separated and the remaining precious metal fraction recovered.

This also produces side stream material which is likewise reintroduced into the process cycle and can then undergo further processing. Nowadays a range of high quality special metals can be efficiently recycled besides the precious metals. A highly effective waste gas treatment plant which reliably meets current and future emissions standards, rounds off the environmental concept.

The pre-enriched concentrates are fed into special hydrometallurgical processes until the individual elements are recovered in a highly purified form. Many years of experience show that the combination of pre-treating the EOL components, specifying the feed stocks (see Figure 34), the sampling process (see Figure 35), pyro-metallurgy and hydrometallurgy and their overall optimisation forms an important success factor in a modern recycling process.

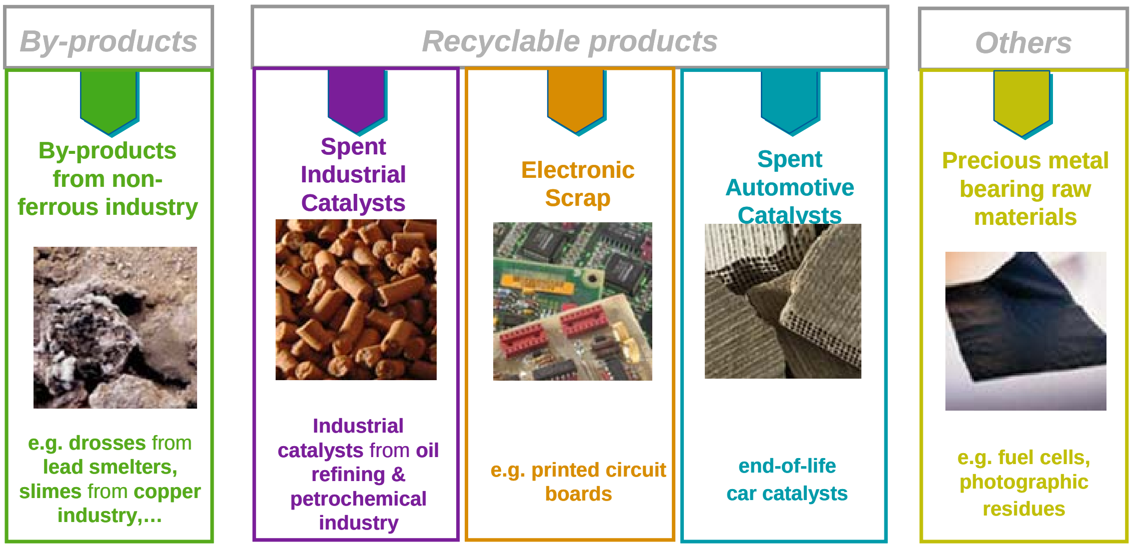



Figure 34 Over 200 different feed stocks illustrate the large range and flexibility of the Umicore process.

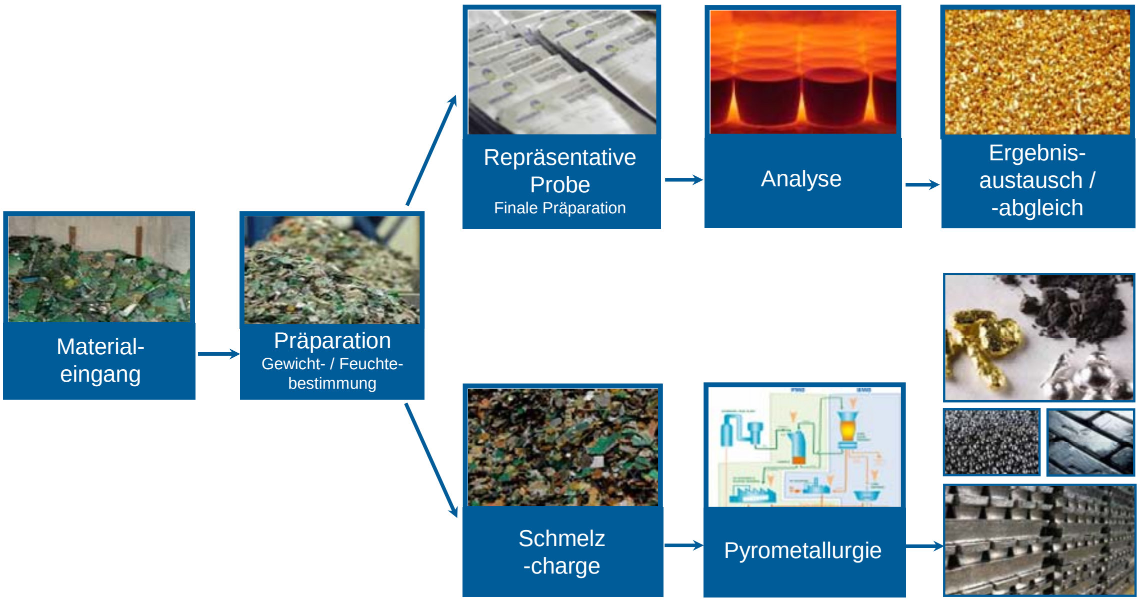



Figure 35 Principle material flow for recycling of (highly) valuable secondary materials

The metals recovered by this means are transferred into chemical (precursor) products at Umicore and used for the manufacture of new application products, thus completing the material cycle, see Figure 36.

In recent years a great deal of experience has been gathered in the fields of logistics, metal management, chemical analysis / sampling and metal recycling. This now provides a crucial basis for the future recycling of post-consumer applications of all kinds.

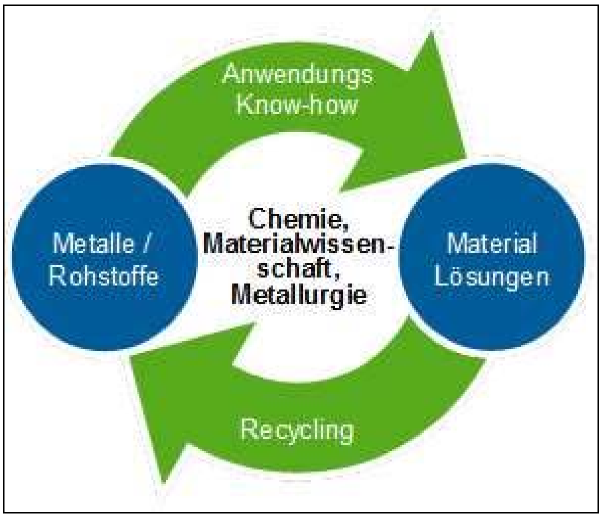



Figure 36 Umicore's principle of closed material cycles

Figure 37 shows Umicore's recycling plant in Hoboken which has been constructed and developed over time using an integrated approach. It combines various different processes in an integrated concept, starting with the preparation and preconcentration through recycling to refining.

Figure 37 Umicore’s integrated smelter in Hoboken, Antwerp. With a secondary material input of 350,000 t/year, it is the largest recycling plant of its kind in the world [Hagelüken, Treffer 2011]

Apart from the resource-saving aspects, a modern recycling concept also makes additional important contributions which will increase in value in the future and will ensure real sustainability in the product life cycles. The benefits of recycling are summarised briefly below:

- Reducing the environmental effects of mining
  - Less energy consumption/$CO_2$ (higher ore concentration; easier access)
  - Lower requirement for land and water
  - Smaller effect on the biosphere (rain forest, Arctic/Antarctic, marine mining, etc.)
- Reduction of pollution from emissions, land requirements from unnecessary primary extraction
- Reduction of geopolitical dependency on the producing countries and companies
- Support for ethical raw material supply (transparent supply chain)
- Reduction of supply risks from primary combined production, see Figure 38
- Stabilising the metal and raw material prices -> limiting fluctuations
  - Improving balance between supply & demand
  - Extending lifetime of primary resources, creating time until new mines are started
  - Restricting speculation (broader supply basis is less susceptible)

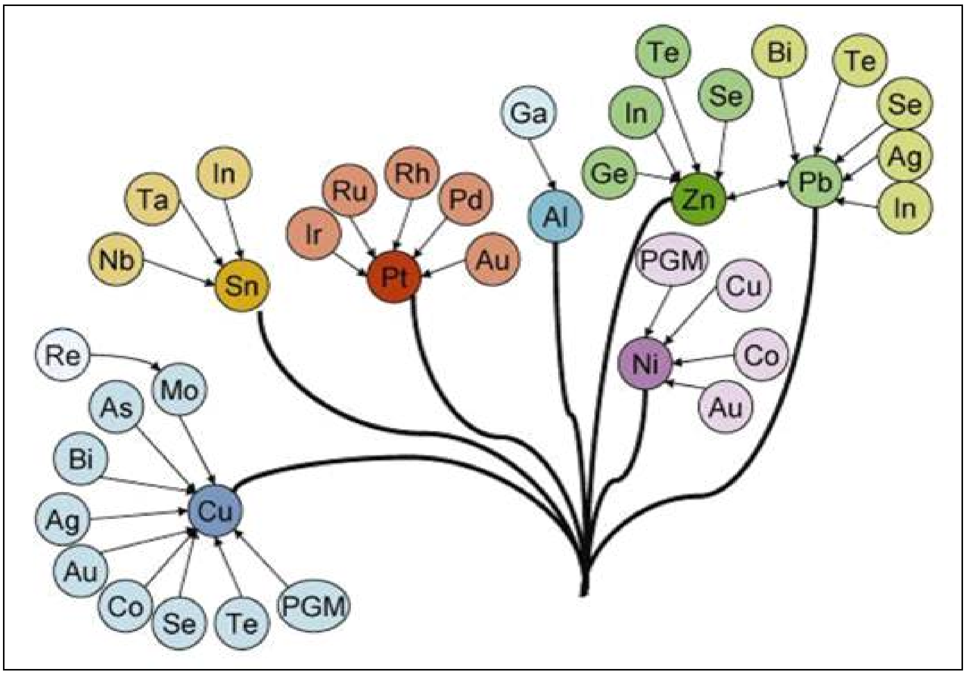



Figure 38 Combined production of high-tech metals. The figure shows the relationship of minor metals as by-products of major metals in primary extraction [Hagelüken, Meskers 2010]


Figure 39 Innovative Cu, Pb and Ni metallurgy from precious and special metals [Hagelüken, Treffer 2011]

This leads to the environmental aspects of recycling. Besides the purely economic benefits, modern recycling provides a high level of environmental relief. Only the material concentrations which can be attained from primary extraction are compared with the recycling rates. Platinum extraction has been chosen to illustrate this. For example, to obtain 1 kg of platinum metal from a South African mine requires approx. 150 t of ore to be mined and extracted from up to 1,000 m depth. The mined ore must then pass through the steps of grinding, flotation and finally pyro-metallurgical and hydrometallurgical processes. Besides the PGMs, the ores contain large amounts of copper and nickel plus notable quantities of chromium, iron, cobalt, bismuth, arsenic, selenium, tellurium, etc., normally as sulphide compounds, which require to be separated out. During the processing almost 400 t of tailings and slags are produced per kilogramme of PGM which have to be deposited. Besides causing environmental pollution and using land, this also clearly requires a large supply of energy. In comparison to this, consumer goods already contain much higher concentrations. Disused catalytic converters, for example, contain 0.5 kg PGM per tonne which can be recovered in high purity by recycling with considerably less effort. All the catalytic converter components and all the slags and waste water are treated and reused. Figure 40 underlines the necessity of recycling catalytic converters and of course other PGM-containing EOL products using the example of $SO_2$ emissions for the production of catalytic converters with primary and recycled PGM.

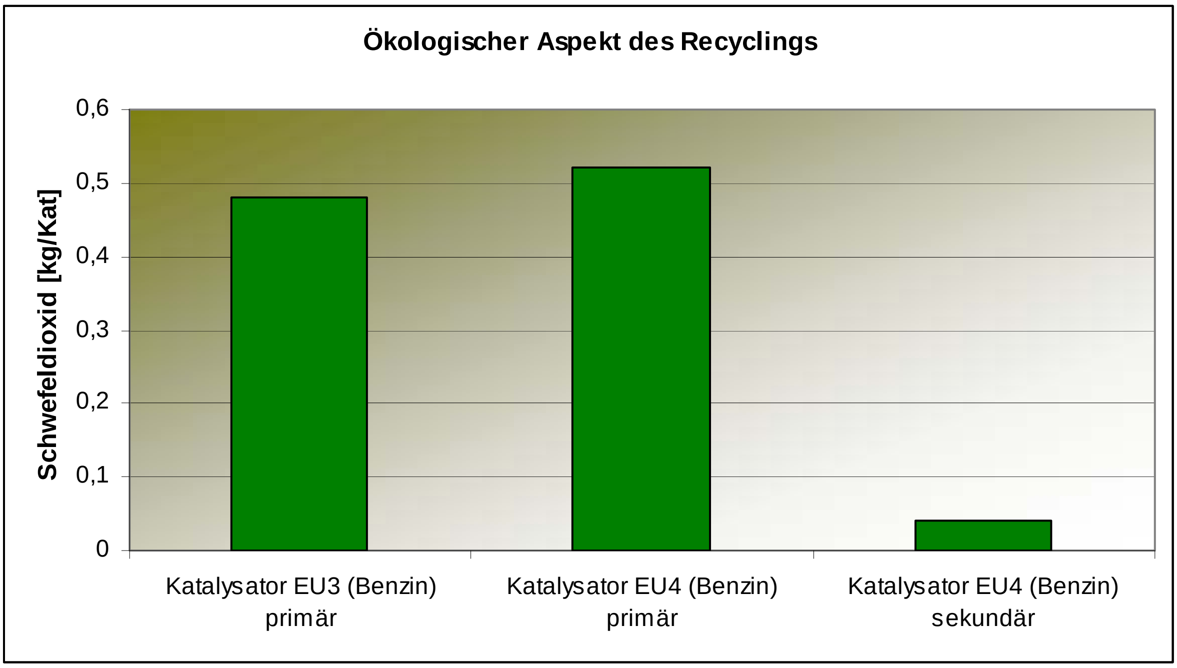



Figure 40 Comparison between the amounts of $SO_2$ pollution produced during the manufacture of catalytic converters from PGM from primary extraction compared to secondary PGM (urban mining) – figure adapted by F. Treffer; original source [Hagelüken et al. 2005]

It must of course be borne in mind that technical progress would not have been made without the primary extraction and that recycling cannot come near to replacing primary extraction – leastways not as long as the demand for high-tech metals continues to rise as steeply as it is currently doing. It is more a case of primary extraction and "urban mining" being viewed as complementary sources for the future supply of raw materials. Nevertheless, despite the optimisation potentials which still exist, particularly for the global collection systems, the example of the PGMs platinum and palladium already show just what an important contribution a modern recycling industry can make. Over half the total demand for these two metals on a global scale is met by secondary metals, i.e. by recycling palladium and platinum from industrial and automotive catalytic converters, scrapped jewellery, dental applications, electronic waste, etc. [Graedel et al. 2011]. An important factor which plays a significant part in efficient recycling is the tendency to very low concentrations of the high-tech metals in most applications and their components. It is often these elements which form the main material value of the devices. This trend has been apparent in the automotive field for a long time, where small electronic circuits (containing precious metals), electric motors (REE magnets) or gold-plated contacts are distributed over a large range of components in small amounts all over the vehicle. These elements would be irretrievably lost in the shredder fractions in the standard established recycling processes for vehicles.

Integrated recycling concepts are the only answer to ensure that valuable materials for the economic cycle and high recycling rates are maintained. Such recycling concepts must begin with the product design and development phases. Sustainable recycling at the end of the product cycle can be ensured as early as possible using recycling-friendly designs and combinations of materials and collection systems which suit the recycling process The following diagram aims to illustrate this statement. The recycling process of EOL products up to the recovered metals is shown in Figure 41. The example shown underlines the necessity of the processes involved being adapted to one other. It is not enough if a modern recycling process guarantees 95% or higher recovery rates if prior to this only 50% of the EOL products have been collected. For even with a really high assumed average sorting efficiency of 90% and pre-processing rate of 80%, only 34% will be achieved along the recycling chain as a whole.


Figure 41 Typical efficiency of high-tech metal recycling chain [Hagelüken, Treffer 2011]

European recycling plants are technically able to recover most metals with good yields. However, there are in fact significant deficiencies in a targeted collection which is adapted to the product and its component metals and suited to the subsequent recycling technology (for a more detailed discussion, see also [Öko-Institut e.V. 2009]).

A recycling chain of this kind would need to be developed with different process technology if the aim is to recover the high-tech metals where the quality of the recycled elements is the main goal in comparison with a concept for recycling bulk raw materials (e.g. steel and copper scrap), where the process is primarily optimised for volume. Not enough attention is paid to this important difference when recycling contracts are placed. Often "high-tech metal recyclers" are compared and evaluated against "bulk flow recyclers". This results in the award of contracts which end up causing significant damage to the economy and environment.

In Europe, for example, it is estimated that only 60% of the EOL electric equipment is sent to the available recycling processes, giving rise to a considerable loss to the European economy from secondary resources which are not used. Amongst the EOL components which are not collected, a large proportion of losses are due to what is known as "waste tourism". This is where valuable materials fall into the hands of "backyard businesses" which operate with the crudest methods and also cause high levels of pollution and risk to human health. These operators recover less than 30% of the valuable materials with the remainder being lost.

There are also considerable shortcomings in the case of old vehicles. In Germany, for example, only approx. 16% of de-registered vehicles are recycled. The remainder are not recorded in the recycling statistics. The official national recycling rate of over 85% does not address this problem and offers little help with the matter. This highlights the main challenge for the future. Future recycling must no longer be confined to recycling technology alone, but must develop an integrated treatment and evaluation of the whole recycling system. The factors which will determine success are:

- The basic recyclability of the materials
- Access to and identification of the components in the application
- Incentives for collection and recycling of EOL equipment
- Development and establishment of recycling chains for specific materials including suitable pre-treatment and preparation processes; see Figure 42.
- Management of the secondary material flow in terms of suitable recycling chains
- Development of recycling capacity with appropriate guarantee systems for the necessary investments


Figure 42 Summary of the most important pre-treatment and preparation processes

In what follows the important top-priority elements for electro mobility identified by the OPTUM project are investigated and evaluated in terms of their recyclability based on the recycling technology. This distinguishes between the recycling rates of post-consumer components i.e. including the steps prior to recycling (e.g. collection) and the assessment of the technical recovery of individual priority elements i.e. the technical feasibility.

Figure 43 shows the current overall recycling rates of the priority elements including all the contributory recycling steps along the specified recycling chains; cf. Figure 41.

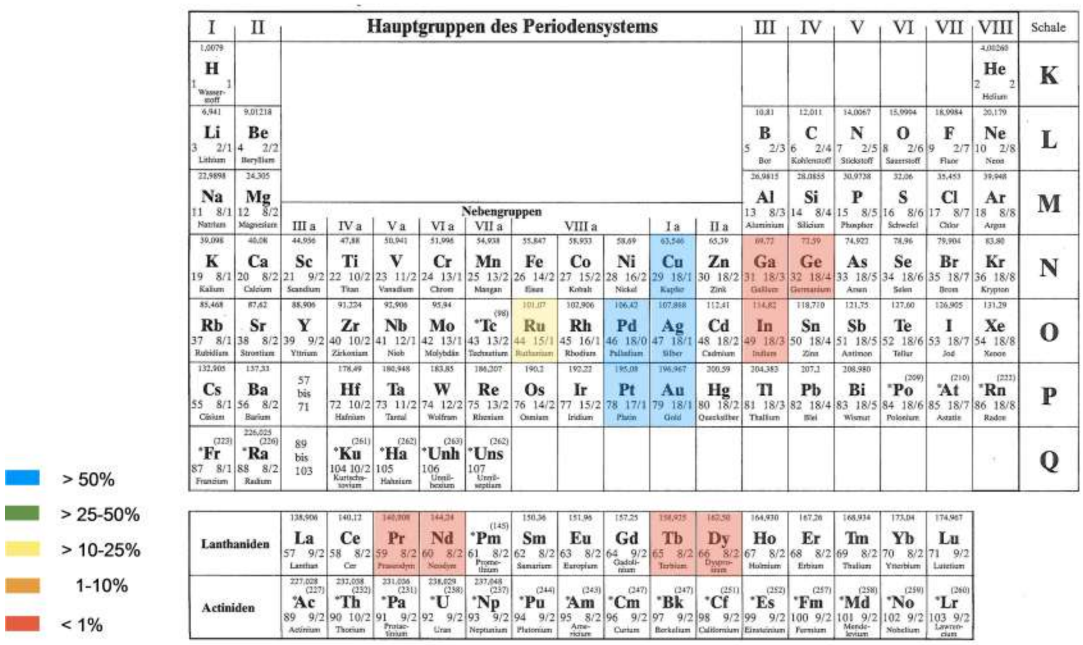



Figure 43 Post-consumer recycling rates of the important priority metals in electro mobility – current estimate, revised figure by F. Treffer, data source [Graedel et al. 2011]

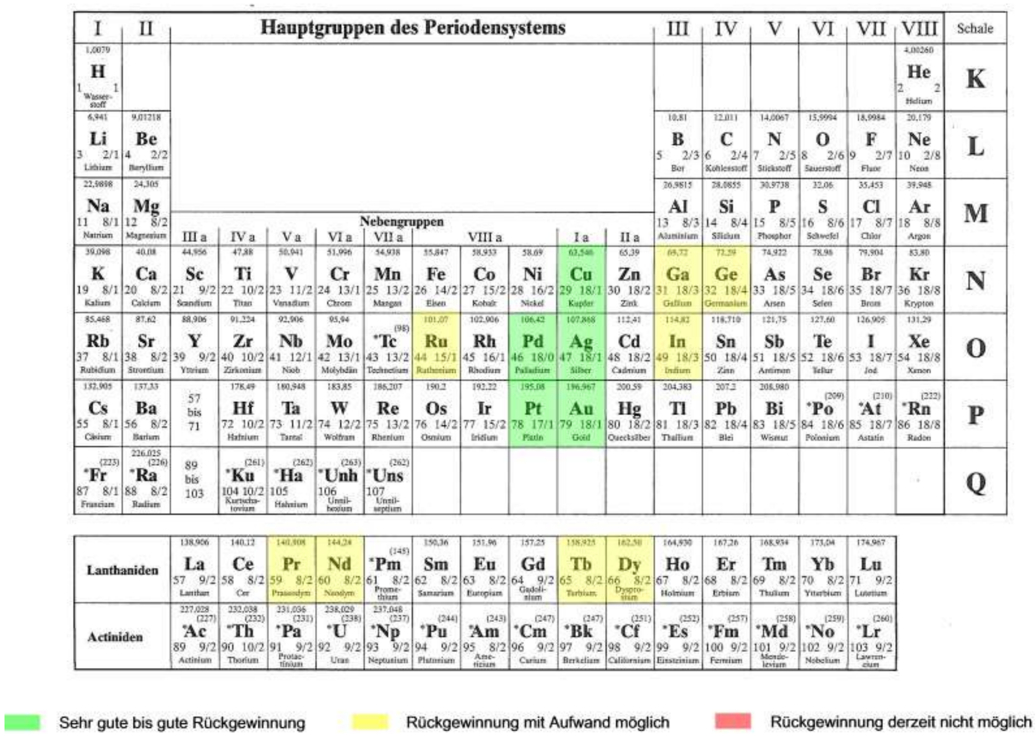



Figure 44 Estimate of recyclability of the relevant priority metals based on the recycling process presented – Umicore process

As shown graphically in the following figure, the recyclability of the top-priority elements (first priority elements) can be technically evaluated i.e. explained as follows:

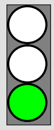
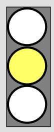
| **Element** (1st priority) | **Estimate of recyclability** | **Assessment** |
|---|---|---|
| Palladium<br>Silver<br>Platinum<br>Gold | Recycling precious metals presents no metallurgical problem. The most important requirement is appropriate pre-treatment of the EOL products so that the precious metals are actually removed for recycling / refining and are not lost in other fractions as a result of unsuitable processing. |  |
| Copper | Copper is used as a "collector" for precious metals in pyrometallurgical processes and can be completely recovered in high purity by leaching and electrolytic precipitation. | |
| Gallium<br>Germanium | At low concentrations there are virtually no opportunities for economic recycling. Like the rare earth elements (REE), recyclability increases with increasing concentration. In pyrometallurgical processes (Umicore; Hoboken) Ga and Ge are vaporised and collected in the fly ash of the treated waste gas stream. |  |
| Indium<br>Ruthenium | The mostly low concentrations in EOL products pose a challenge for recycling. Losses of In and Ru would be high if these elements, even in a pre-processed form, were to be introduced at the start of the recycling process. Better recovery rates are achieved for both if Ru is fed into the pyrometallurgical pre-concentration of precious metals (Umicore; Hoboken) or if In is fed into the lead process (Umicore; Hoboken). | |
| Praseodymium<br>Neodymium<br>Terbium<br>Dysprosium | As trace elements forming part of the mix in complex materials, rare earth elements usually pass into the slag where they are diluted to such an extent that recycling of the individual elements is not worthwhile. Recyclability is increased if high concentrations of REE are present in the product (see permanent magnets), or if the slag is enriched (see recycling of NiMH batteries; Umicore UHT). Recycling and pre-treatment processes for REE are currently being developed and some solutions are already available. | |

Figure 45 Estimate of recyclability of the priority elements

Due to many years of experience in the pre-treatment and recycling of PGM, all the precious metals classified as important for electro mobility including copper can be reliably and efficiently recovered, with the recycling rates of specific elements in the refining process being over 95% in some cases. As described above in detail, the total recycling rate depends on all the stages of the recycling chain so that the upstream stages such as collection, sorting, disassembly etc. are very important.

The recovery of gallium, germanium, indium, ruthenium and the rare earth elements praseodymium, neodymium, terbium and dysprosium is, in contrast, difficult or economically unviable without additional technical processes. This is where additional development efforts need to be made in the years ahead.

Despite everything, the opportunities for recovering these "yellow" elements from EOL products are really promising, particularly taking a holistic approach which integrates recycling-friendly design and return and collection systems with the pre-treatment steps (concentration) and the actual recycling and refining technology. Development efforts are required especially for the technical adaptation of processes i.e. along the whole life cycle chain of a product. Only in this way can all the specified elements be economically recycled in future. This development needs to focus on the pre-treatment processes which, more than all the other process stages, require greater attention and more efficient solutions due to the trend towards distributing the elements in small amounts throughout the individual components. This is confirmed by initial results from some development projects in particular on recycling Ga, In and the REEs.

# 10 Development in demand for metals for electro mobility in comparison to the total demand

The development in demand for the scenarios was described in detail in Section 7. The following section will consider the development in demand for all applications in comparison with the current primary production and the demand scenarios for electro mobility. The development in demand across all applications is related to 2015 for the rare earths (with the exception of 2014 for praseodymium) and to 2020 for indium and gallium. The differing observation periods result from the different sources available. The price trends for the 12 priority elements will also be considered.

## 10.1 Rare earths

The main application area for the rare earths neodymium, praseodymium and dysprosium (as metal alloys) is permanent magnets (neodymium iron boron magnets). Only very low percentages of REEs could be found in the magnet applications for electro mobility (passenger vehicles) in 2010. Numerous traditional magnet applications such as e.g. PCs, notebooks, medical applications, loudspeakers, electric motors for industry and other industrial applications are still dominant (cf. [Öko-Institut e.V. 20119]). At approx. 12.5% per year, the growth rates for magnet applications up to 2014 are higher than for other applications using rare earths (5-8% per year). The percentage use in magnets increases to approx. 80% for neodymium and 74% for praseodymium. This percentage could increase further by 2020 or 2030.

According to results from the OPTUM resources project and other studies by the Öko-Institut, electro mobility will reach significant percentages for the use of rare earths in magnets beyond 2020 or 2030. Wind power will also require increasing percentages in future. Both the electro mobility and wind power applications will be powerful future drivers of demand.

Based on current knowledge, the magnet applications will also remain the crucial drivers of growth for neodymium, praseodymium and dysprosium until 2020 or 2030. Only crucial innovations in the magnet or motor technologies could halt this trend.

### 10.1.1 Neodymium

Neodymium is used in magnets (approx. 77%), batteries[11] (approx. 12%), ceramics (approx. 3%), glass (approx. 2%), catalytic converters (approx. 1%) and other applications (approx. 5%) (see Figure 46).

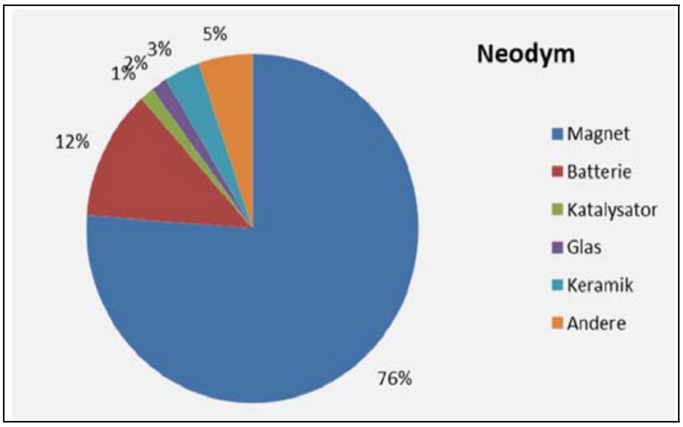



Figure 46 Fields of application for neodymium in 2010 (Öko-Institut calculation)

Electro Mobility (passenger vehicles) accounted for approx. 0.25% of neodymium used in all magnet applications in 2010 (Öko-Institut calculation). The wind power future technology had a percentage of approx. 2% of the magnet applications in 2010. Neodymium requirements show a rapid increase until 2015. This growth path should be considered critical in the context of fast-growing competing applications and the export restrictions from the main supplier China.

[11] It should be noted that in batteries neodymium is used as a misch metal (NiMH) and does not have to be separated during primary production.

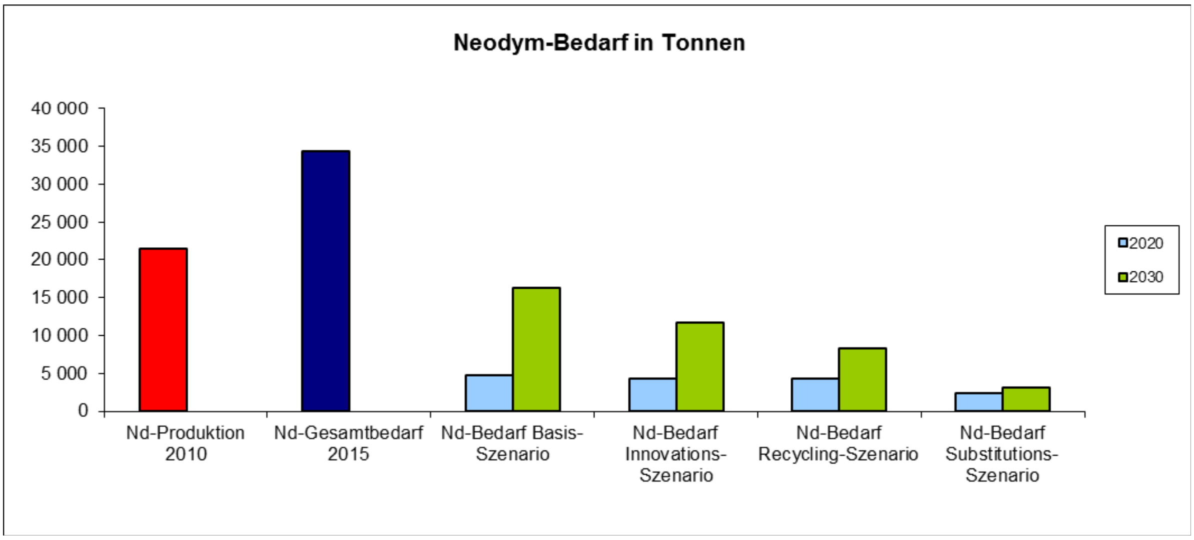



Figure 47 Total neodymium requirements in tonnes [IMCOA 2011, Öko-Institut e.V. 2011, Öko-Institut e.V. calculations]

The results of the project and other studies carried out by the Öko-Institut on rare earths and wind power indicate that a steep rise in the percentage of the total neodymium magnet applications can be expected. Calculations carried out by the project team show that the percentage of neodymium used in electro mobility could rise to 12% and 12-25% of magnet applications by 2020 and 2030 respectively.

The price of neodymium has risen steeply in recent years. Ten years ago the price level for a kilogramme of neodymium metal was around USD 15, falling to USD 6.40 / kg in 2003. Up to the start of 2010 the price fluctuated between USD 17 and 50 / kg neodymium. There was a price explosion in 2010 which continued in 2011. This price increase is due to the export restrictions on rare earths imposed by China where 97% of the rare earths are mined. The price reached a high of USD 500 / kg in late summer 2011. A slight drop in price then occurred in autumn 2011. The People's Republic of China subsequently suspended the production of rare earths temporarily in order to keep the price level up [Spiegel 2011]. Both China's raw materials policy and the on-going lack of competitors on the raw materials market for rare earths would suggest that the price level for neodymium will continue on a similarly high level, especially as the total demand is growing. However, accurate future price trends cannot be predicted.

### 10.1.2 Praseodymium

Praseodymium (see also Figure 48) is used in magnets (approx. 71%), batteries[12] (approx. 10%), polishing powder (approx. 6%), ceramics (approx. 5%), catalytic converters (approx. 3%), glass (approx. 1%) and other applications (approx. 4%).

12 It should be noted that in batteries praseodymium is used as a misch metal (NiMH) and does not have to be separated during primary production.

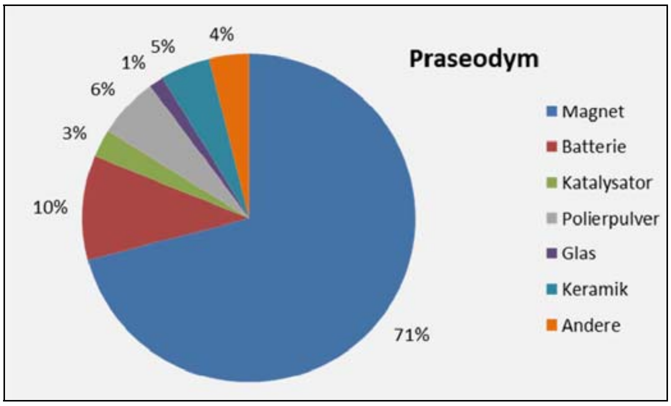



Figure 48 Fields of application for praseodymium (Öko-Institut calculation)

The percentage of praseodymium used in magnet applications in electro mobility (passenger vehicles) in 2010 was approx. 0.25% compared to all magnet applications (Öko-Institut calculation).

The total requirements for praseodymium will rise by approx. 50% from 2010 to 2014.

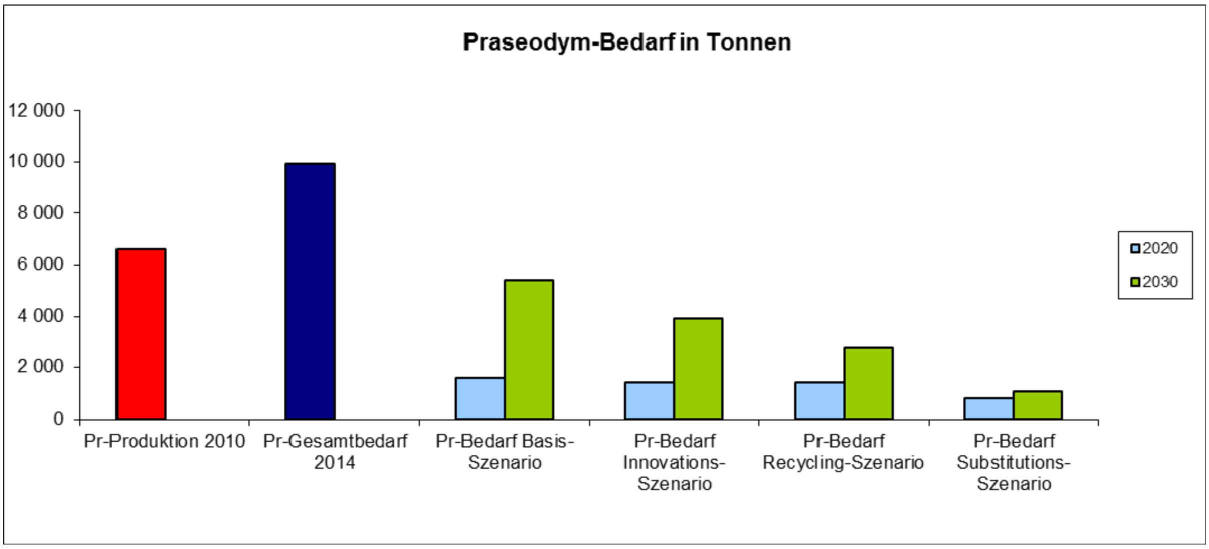



Figure 49 Total praseodymium requirements in tonnes [IMCOA 2011, Öko-Institut e.V. 2011, Öko-Institut e.V. calculations] [13]

Calculations carried out by the project team show that the percentage of praseodymium used in electro mobility could raise to 12% and 12-25% of neodymium magnet applications by 2020 and 2030 respectively.

[13] Total Pr requirement for 2014: reference was made to the "Study on Rare Earths and Their Recycling" and the mean of the values from Lynas 2010a and IMCOA/Kingsnorth calculated.

The development in the praseodymium price runs parallel to that for neodymium. A steep price increase has taken place for praseodymium (metal) in recent years. Ten years ago the price level for a kilogramme of praseodymium metal was around USD 9, falling to USD 6 / kg in 2002. At the start of 2010 the price fluctuated between USD 10 and a maximum of USD 50 / kg praseodymium. In 2010 the price of praseodymium also rose very steeply and this continued in 2011. The price reached a high of approx. USD 280 / kg in late summer 2011. A slight drop in price then occurred in autumn 2011 but this was less than for neodymium. Future price developments cannot be predicted; however China's raw materials policy and the on-going lack of competitors on the raw materials market for rare earths would indicate a comparable price level in the near future.

### 10.1.3 Dysprosium

All dysprosium is used in magnets. The current percentage used in electric vehicles is approx. 1.4% of all magnet applications (Öko-Institut calculations). The percentage of magnet applications for the future technology wind power is currently approx. 5%. Based on the Öko-Institut's estimates, the percentage of magnet applications for electro mobility alone could rise to 60% by 2020 and 65-90% by 2030.

Figure 50 shows the very high dysprosium requirement for the electro mobility sector.

Dysprosium requirements will grow very fast according to the scenario demand analyses in the OPTUM resources project.

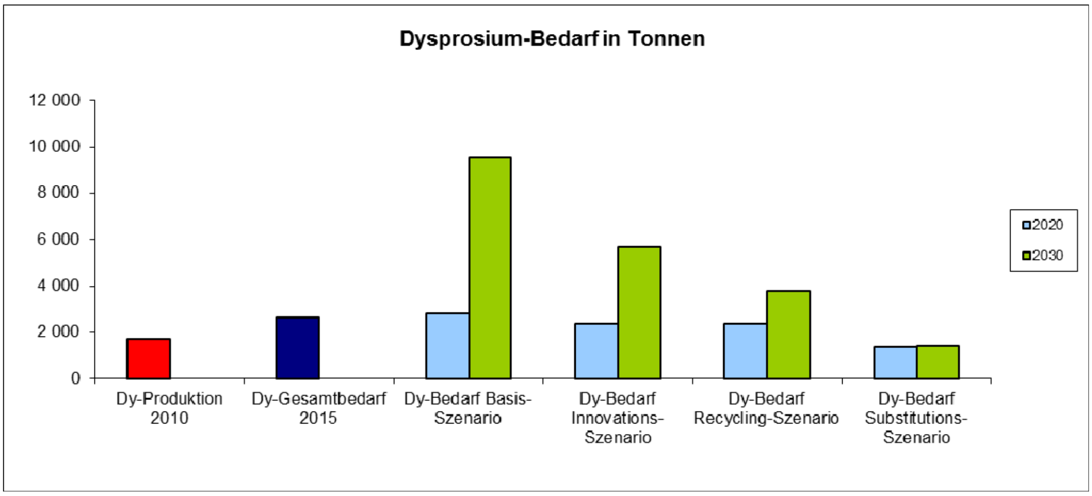



Figure 50 Total dysprosium requirements in tonnes [BGR 2011, Öko-Institut e.V. 2011, Öko-Institut e.V. calculations]

The development of the price of dysprosium (metal) shows the steepest rise of all the rare earths. From a dysprosium price of approx. USD 40 / kg 10 years ago and a subsequent drop in price to just under USD 30 / kg in 2003, the price rose continuously in the following years to approx. USD 150 by the end of 2009. The price of dysprosium also increased in

2010, but more than in the other rare earths. The price reached a high of USD 3,100 / kg in late summer 2011. Following this, the price of dysprosium dropped slightly in autumn 2011. However, the price remains at a very high level. The future price is expected to be at a similarly high level due to China's raw materials policy, the lack of supplies and the fast-growing demand.

### 10.1.4 Terbium

In 2010 approx. 89% of terbium was used in luminescent materials and approx. 11% in magnets. The percentage used in magnets for electric vehicles was approx. 5.7% of all magnet applications. Use in magnets is predicted to rise slightly to approx. 13% by 2014 (Öko-Institut calculation).

Figure 51 illustrates the additional demand for terbium from electrification of the automotive sector based on the different scenarios for 2020 and 2030.

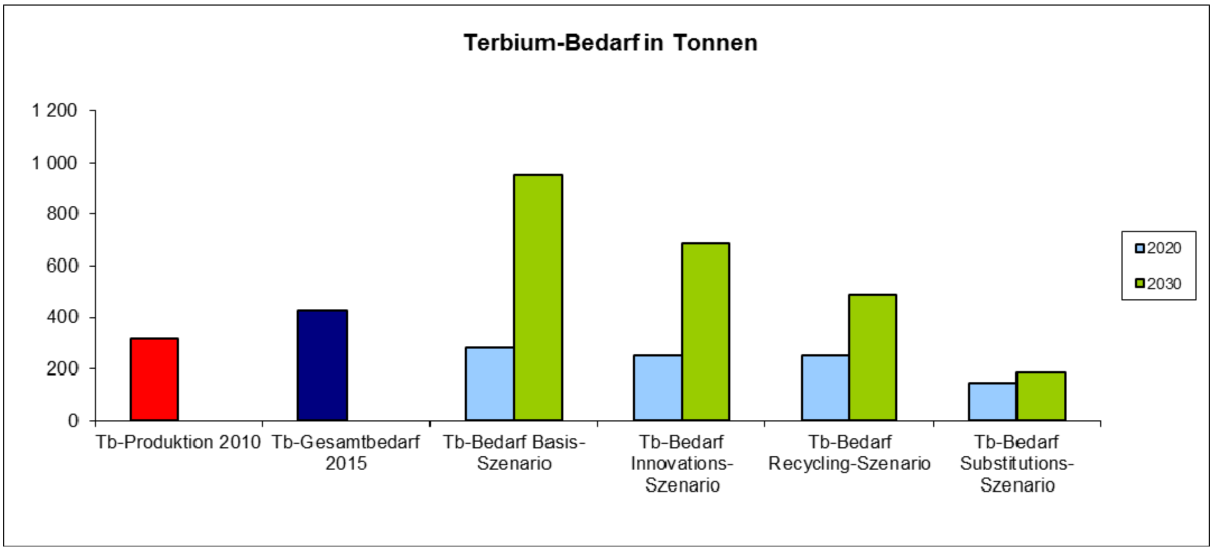



Figure 51 Terbium requirements in tonnes [BGR 2011, IMCOA 2011, Öko-Institut e.V. 2011, Öko-Institut e.V. calculations]

The price history of terbium (metal) shows a similar pattern to the other rare earths. Ten years ago the price level was approx. USD 300 / kg terbium. The price then dropped to slightly less than USD 180 / kg in 2003 and in the years following fluctuated between USD 400 and 900. A steep price increase took place at the start of 2010 as with the other rare earths. At the end of summer 2011 the price for a kilogramme of terbium was just under USD 5,000. The price of terbium then went on to drop slightly in autumn 2011. China's raw materials policy, the on-going lack of competitors on the supply market for rare earths and the steeply rising demand all point to continued high prices. However, future price trends cannot be predicted.

## 10.2 Gallium

The important fields of application for gallium are in integrated circuits, photovoltaics, optoelectronics such as e.g. LEDs or diodes and special alloys.

Figure 52 shows the gallium requirements across all applications for 2010, 2015 and 2020 for the different percentages of the fields of application.

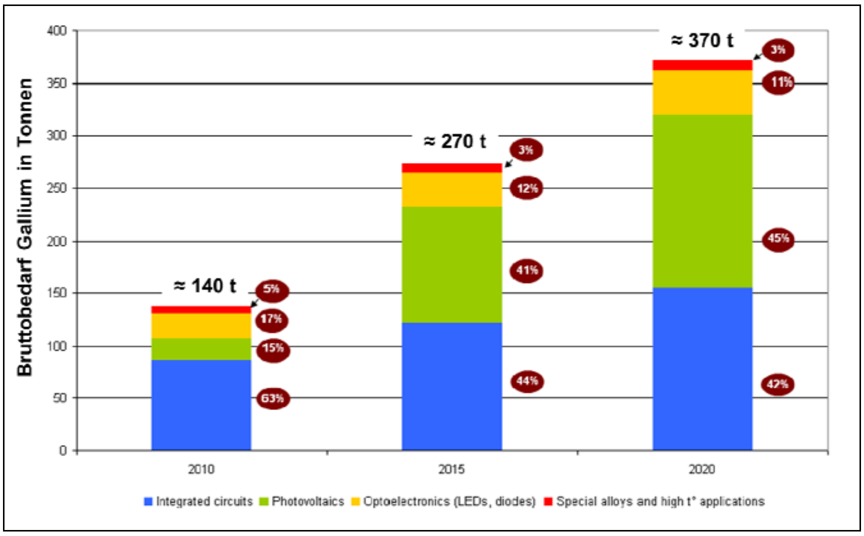



Figure 52 Gallium requirements by application for 2010, 2015 and 2020 [EU critical raw materials 2010]

A very high growth in demand of approx. 16% per annum is assumed up to 2020. The increase in demand up to 2030 is estimated at 14% p.a. Options are available for meeting this growing demand as the gallium potential from current global bauxite mining will not be exhausted by a long way. This will, however, require a timely incentive to optimise gallium extraction from bauxite as part of alumina production. Figure 53 shows the future requirements for gallium, first across all applications up to 2020 and second for the gallium requirements for electro mobility for the individual scenarios for 2020 and 2030.

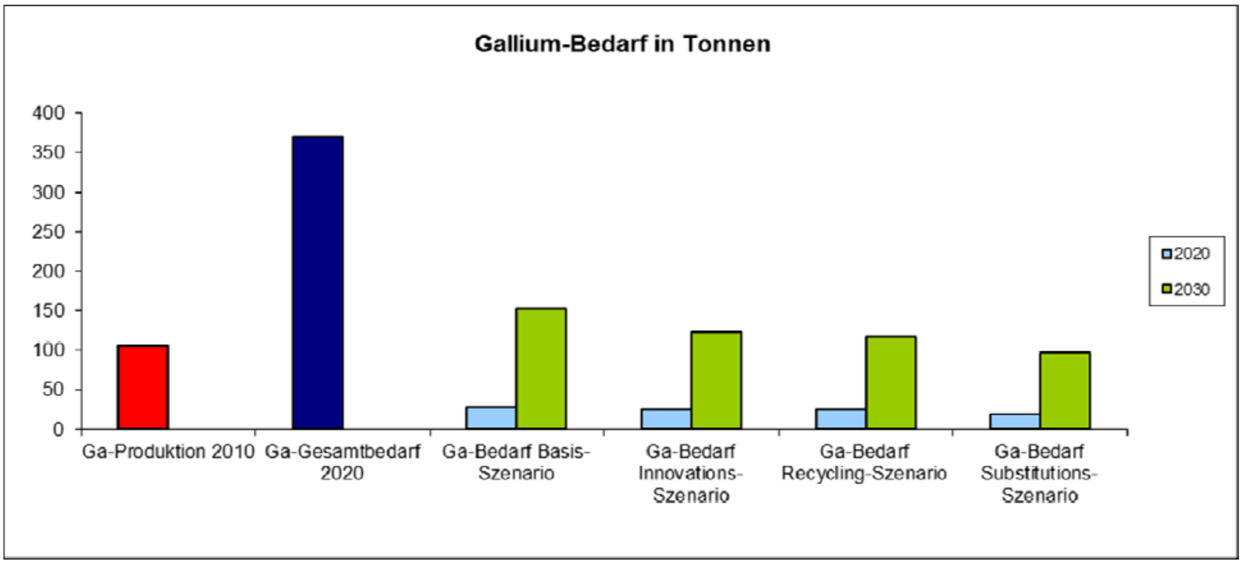



Figure 53 Gallium requirement in tonnes [USGS 2011, EU critical raw materials 2010, Öko-Institut e.V. calculations]

The price of gallium shows a completely different development compared to the rare earths. Ten years ago the price level of a kilogram of gallium was between USD 300 / kg and a short-lived peak of USD 2,000 / kg. The price stayed around USD 300 / kg gallium up until 2006. Over recent years there has been a slightly upward price trend to approx. USD 700-800 / kg. The future price trend cannot be predicted; however the fast growth in demand for gallium should be pointed out.

## 10.3 Indium

The main field of application of indium is in display technology which accounted for 83% in 2010. In addition, indium is used in photo-voltaics, alloys and semiconductors. The growth in demand for indium is estimated at 8.7% p.a. [EU critical raw materials 2010]. Growth rates of a similar order of magnitude might well occur up to 2030. The quantity of indium used for electro mobility has no significant quantitative effect. However, due to the very fast growth in demand from the field of photo-voltaics, there is keen competition in this sector. Any strains in the supply would therefore impact on the electro mobility sector.

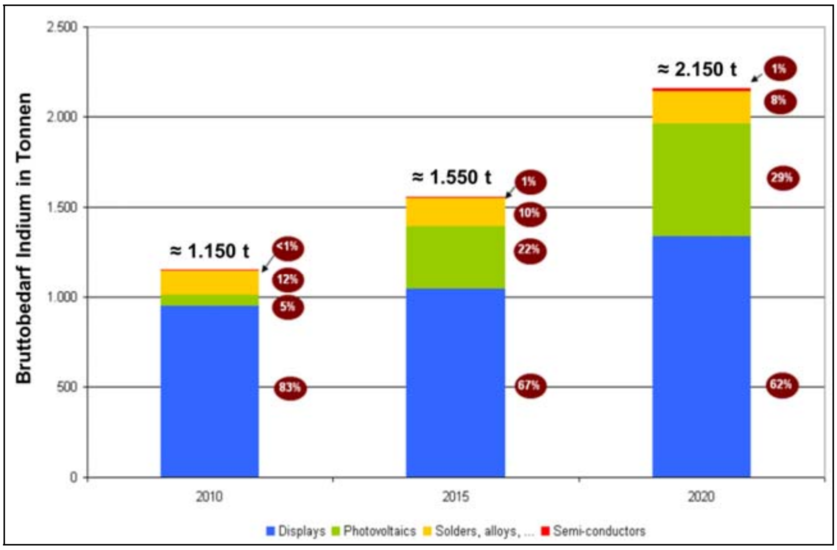



Figure 54 Indium requirements by application for 2010, 2015 and 2020 [EU critical raw materials 2010]

The price history of indium over recent years shows a rather mixed picture. Ten years ago the price for a kilogramme of indium was approx. USD 90. A sharp rise in price to over USD 1,000 / kg indium was recorded in the years 2005 and 2006. The price then fell to approx. USD 300 in 2009 and has been rising since then with periodic downturns. The price is currently approx. USD 700 per kilogramme of indium.

## 10.4 Copper

Copper has numerous fields of application. Besides the main field of application in transferring electrical energy[14] (approx. 26%), additional application sectors are in water supply, heat exchangers for household appliances, consumer products[15], mechanical components[16], data and signal transfer, architecture[17] and in drive engines for rail vehicles and ships and standard passenger vehicle cabling and electric motors [Fraunhofer ISI 2010].

The electrification of the passenger vehicle drive leads to an increase in demand for copper in the automotive sector. The annual growth in demand across all applications is estimated at 5.3% up to 2020 and 2030 [Fraunhofer ISI 2010]. While the market penetration by electro mobility does make a contribution to the growth in demand as the scenario results in this project have shown, the effect of electro mobility on the overall total demand for copper is only moderate due to the very broad range of applications of copper.

In 2002 the price of copper was USD 1.4 per kilogramme and this rose steadily to just under USD 8 per kilogramme by 2006. This price was maintained with fluctuations until summer

[14] In the form of high voltage underground cables, subsea cables, power cables in buildings etc.

[15] e.g. door handles, cookers, stoves, coins, jewellery, solder

[16] e.g. sheet metal, brass valves, bearing materials

[17] e.g. roofs, facades, gutters

2008. The steep drop in price initiated by the financial crisis led to a drop to USD 2.80 per kilogramme of copper. The copper price then recovered and, at the beginning of 2011, had reached USD 10 per kilogramme. The copper price is currently at USD 7.3 per kilogramme [Finanzen 2011] but the future price trend cannot be predicted.

## 10.5 Gold

The main field of application for industrial gold production, accounting for approx. 75%, is the manufacture of clocks and jewellery. In addition to dentistry, the food industry (gold leaf) and arts and crafts, gold is also used in electrical engineering and electronics, particularly in the IT and entertainment electronics industry plus in investment [Gold Infos 2011]. There are no up-to-date sources of information on the growth in demand of gold up to 2020 and 2030. Analysis of the demand trends for the past ten years indicates that demand has remained largely constant. Due to the advanced recycling structures for precious metals (incl. gold), a moderate growth in demand can be reduced in future in terms of the pressure on the primary resources by increased recycling e.g. of old jewellery, dental material and electronic equipment. Nevertheless, research on the development of demand and how the supply is to be met is important for gold because gold mining is linked to considerable environmental pollution.

Over the last 10 years the price of gold has shown a constant upward trend. This is partly connected to the increasing public-sector debt and the attendant weakening of the US dollar [Gold 2011]. Ten years ago the price of gold was approx. USD 9,000 / kilogramme. The continuing price rise over the last few years led to the all-time high of 1980 being exceeded in summer 2011 with a price of just under USD 52,000 / kilogramme [Metal Markets 2011]. It is not possible to predict how the price will develop in future.

## 10.6 Silver

Silver is primarily used in the jewellery and silverware industry (approx. 34%), electrical and electronic applications (approx. 24%), photography / mirrors (approx. 20%) and catalytic convertors (approx. 6%). A further 16% is attributable to other applications (solar panels, batteries, plasma screens) [EU critical raw material 2010]. The future demand for silver will grow by approx. 3.8% per annum until 2020 or 2030 [EU critical raw material 2010]. The rising demand for RFID tags and increasing use of solar plants will be major influences on the future demand for silver.

Over the last 10 years the price trend for silver has been one of almost continuous increases, with the exception of the price collapse at the end of 2007 (financial crisis). In 2001 the price of silver was approx. USD 130 per kilogramme. The price then increased steadily to approx. USD 640 per kilogramme by the end of 2007. The collapse in price due to the financial crisis allowed the price of silver to fall to just below USD 320 per kilogramme, after which it climbed steadily. In spring 2011 the silver price rose to almost the historical price ceiling in 1980 (USD 1,566 / kg) at USD 1,560 / kg. A slight drop in price in 2011 led to a current price of just under USD 1,030 per kilogramme of silver [Silver 2011]. It is not possible to predict how the price will develop in future.

## 10.7 Germanium

Germanium is primarily used in the fields of fibre optic systems (approx. 30%), infrared optics (approx. 25%), polymerisation catalysts (approx. 25%), components for electric and solar devices (approx. 15%) and other areas such as e.g. medical applications (approx. 5%) [EU critical raw materials 2010]. Future growth in demand must take account of an eightfold increase in the demand for fibre optic systems. Added to this are increasing demands for the other applications e.g. infrared devices in the automotive field [EU critical raw materials 2010]. The total growth in demand is estimated at approx. 5% per year to 2020 and 2030 (Öko-Institut calculation).

In general the data base for germanium is rather limited in comparison to the other metals. Information on germanium is often classified due to sensitive military applications (e.g. infrared devices). The British Geological Survey is due to publish a report at the beginning of 2012 which includes a detailed study of germanium carried out in cooperation with the BGR.

In 2004 the price of germanium was approx. USD 500 per kilogramme. The price rose steadily to just under USD 1,600 / kg by the summer of 2006. Following this it dropped again to just under USD 800 in 2010. Since the end of 2010 the price has risen constantly once more and is currently at the price level of summer 2006. It is difficult to predict how the price will develop in future. Both rising demands and an unreliable data base add to the difficulty of making an estimate.

## 10.8 Platinum group metals

The applications for platinum are, in addition to automotive catalytic converters (approx. 40%), jewellery (approx. 31%), industrial applications (approx. 21%) and investment (approx. 8%) [Johnson Matthey 2011]. Palladium is used primarily for automotive catalytic converters (approx. 5%), industrial applications (approx. 26%), investment (11%) and the jewellery industry (6%) [Johnson Matthey 2011].

The annual growth rates to 2030 are estimated for platinum and palladium at approx. 3% each (Öko-Institut calculation). The price trends for platinum and palladium need to be considered separately as they do not always run in parallel.

The price of platinum has shown large fluctuations in the last 10 years. In 2001 the price dropped to approx. USD 14,000 / kg of platinum. In the years thereafter the price rose continuously to a maximum of approx. USD 66,000 per kilogramme platinum by summer 2008. Due to the financial crisis a significant drop in price occurred at the end of 2008 (approx. USD 27,000 / kg). Since then the price of platinum has risen constantly with a small decline in autumn 2011. The platinum price is currently (as of October 2011) approx. USD 49,000 / kg [Johnson Matthey 2011a].

The price of palladium has also undergone fluctuations in the past. Between 1997 and January 2001 the price rose from USD 4,000 / kg to USD 35,000 / kg, falling again to a level of USD 8,000 by the end of 2002 [Hagelüken, Buchert, Stahl, 2005]. The price of palladium has never again exceeded that of platinum and reflects the platinum price trend at a lower level. The palladium price also rose until 2008 (approx. USD 15,000 / kg), afterwards falling markedly by the end of 2008 (approx. USD 5,600 / kg). Since then the price of palladium has risen constantly with a small period of decreased prices in the summer of 2010. There was a slight drop in price during autumn 2011 as with the other metals. Currently (as of October 2011) the price of palladium is at a level of approx. USD 20,000 per kilogramme of palladium [Johnson Matthey 2011a]. The future price trends of palladium and platinum cannot be predicted.

# 11 Summary and recommendations for action for resource efficiency in relation to electro mobility

The project team from the Öko-Institut, Umicore, Daimler AG and TU Clausthal, Institute of Mineral and Waste Processing, Waste Disposal and Geomechanics have drawn the following important conclusions from the comprehensive results of the project "Resource efficiency and resource policy of the electro mobility system" which are documented in the previous sections:

- The supply of **rare earths** – especially dysprosium – is particularly critical. Resource efficiency and technological substitution show the greatest potential for controlling supply bottlenecks in the medium term. Recycling is an important option to reduce shortages in the medium and long term, but is likely to have insignificant effects over the next few years due to the steadily increasing total demand and the long lifetime of the products.
- **Gallium** is also used in many applications apart from electric mobility (e.g. PV, LED). Significant increases in demand are to be expected. With a steep increase in demand and the lack of counter measures, the supply of gallium could become critical in the longer rather than shorter term (development of global extraction capacity for gallium as a by-product of the Bayer process [alumina extraction] and an actual start to post-consumer recycling).
- **Indium** is not critical in terms of electro mobility. **HOWEVER** there are many competing fields of application with high growth rates. Indium only occurs as a minor metal and a close eye must therefore be kept on it.
- **Germanium i**s not critical in terms of electro mobility. **HOWEVER** high growth rates could occur in other applications (e.g. fibre optic technology, LEDs) and basic

information is lacking for germanium (the "phantom" element) and its demand development.

- **The precious metals silver, gold, palladium and platinum** are also used in the components for electro mobility, with platinum of particular importance in fuel cell vehicles. On the other hand, the development of electro mobility in terms of all-electric vehicles can reduce the demand for platinum and palladium as catalytic converters are no longer required.
- **The current critical supply situation for some rare earths** is a cautionary example of the fact that bottlenecks can occur at least temporarily despite globally high geological reserves if geopolitical factors (mining almost exclusively in one country) correlate with a rapid growth in demand. Lessons for the future should be learned from this so that proactive countermeasures can be planned (by timely exploration and development of deposits, diversifying the supply, promoting recycling etc.).

The project team produced recommendations for action from the results and conclusions and these were presented to the expert participants for discussion at the concluding workshop. The recommendations met with general agreement. Nonetheless, important suggestions about the recommendations for action were made to the project team by the group of external experts and these have been incorporated in the following list of recommendations for action:

- **In view of the risk of a bottleneck in the supply of rare earths, different relief strategies need to be pursued simultaneously**
  - R&D into reduction of REs (esp. dysprosium) in magnets for e-motors and into RE-free e-motors
    →*Responsible: Government ministries for promotion programmes, OEMs (manufacturers of electric motors, magnet manufacturers) and the scientific community with regard to innovation*
  - Development of recycling technologies for permanent magnets from different applications
    → *Responsible: Government ministries for promotion programmes, the recycling industry and the scientific community*
  - Promotion of environmentally friendly primary production of REs (standards required)
    → *Responsible: German government and EU Commission via international negotiations, companies involved in rare earth mining*
- **Promotion of more environmentally compatible mining for the extraction of critical metals**
  - There is significant potential to make better use of natural resources by improving extraction rates in the primary production and processing of many metals (e.g. rare earths). For important minor metals such as indium, potential

also exists in the form of unused residues at mining sites some of which are now closed.

→ *Responsible: BGR and institutes involved in mining and processing which can prospect for mining residues and promote technical cooperation and knowhow transfer for optimised extraction*

- **Development of recycling strategies and technologies for the recycling of power electronics from EOL electric vehicles**
  - Recovery of copper, gallium, precious metals etc.
    → *Responsible: Government ministries for promotion programmes, the recycling industry and the scientific community*
- **General research needs**
  - Analysis of potential and recycling options for "conventional" electronic devices and other magnet applications in future passenger vehicles of all types in terms of precious and special metals incl. rare earths.

    → *Responsible: Government ministries for promotion programmes plus the recycling industry and OEMs (manufacturers of automotive electronics and magnets)*

- **Significant increases** are expected in the use of gallium, indium and germanium in other applications: it is currently not clear whether growth rates – and hence supply risks – resulting from technological revolutions such as LED technology or PV (post Fukushima) are still being underestimated.
  **The medium- and long-term effects on e-mobility need to be explored and solution strategies developed.**
  → *Responsible: Government ministries for promotion programmes*

In order to reach a broad audience and to stimulate important discussion, the project partners and the BMU intend to disseminate and present the project results to important groups of actors in a variety of ways, both at a national and international level.

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# Appendix

Appendix 1 List of participants at the 1st expert workshop on "Resources for electro mobility" in Berlin, 29.09.2010

| Name | Institution |
|---|---|
| Christian Kawohl | Aurubis AG |
| Mathias Samson | BMU Ref IG I 5 |
| Dr. Frank Lehnert | BMW AG |
| Martin Steinbild | Chemetall |
| Dr. Klaus Ruhland | Daimler AG |
| Sven Knoefel | Daimler AG |
| Dr. Eckhard Schüler-Hainsch | Daimler AG |
| Dr. Bernd Grieb | Fa. Magnequench |
| Dr.-Ing. Luis Tercero | Fraunhofer-Institut für System- und Innovationsforschung (ISI) |
| Dr.-Ing. Nils Nissen | Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration IZM |
| Tobias Klier | Friedrich-Alexander-Universität Erlangen-Nürnberg |
| Ingrid Ott | GGEMO |
| Heinz-Dieter Heibach | Hitachi |
| Axel Schober | I+ME ACTIA |
| Hans-Joachim Steinwachs | I+ME ACTIA |
| Stefan Seum | Öko-Institut e.V. |
| Dr. Matthias Buchert | Öko-Institut e.V. |
| Florian Hacker | Öko-Institut e.V. |
| Dr. Wolfgang Jenseit | Öko-Institut e.V. |
| Stefanie Dittrich | Öko-Institut e.V. |
| Dr. Thorsten Mausbach | Robert Bosch GmbH |
| Heiko Weller | Robert Bosch GmbH |
| Dr. Ulrich Bast | Siemens AG |
| Dr. Tina Dettmer | Technische Universität Braunschweig<br>Institut für Werkzeugmaschinen und Fertigungstechnik (IWF) |
| Kai Rasenack | Technische Universität Clausthal |

| Name | Institution |
|---|---|
| Prof. Dr.-Ing. Daniel Goldmann | Technische Universität Clausthal<br>Institut für Aufbereitung, Deponietechnik und Geomechanik |
| Prof. Dr. Arno Kwade | TU Braunschweig |
| Regina Kohlmeyer | UBA FG III 1.2 |
| Kristine Koch | UBA FG III 1.2 |
| Frank Treffer | Umicore AG & Co. KG |
| Prof. Dr. Armin Reller | Universität Augsburg |
| Dr. Rolf Blank | Vacuumschmelze GmbH & Co. KG |
| Nadine May | VDI / VDE |
| Franz Dorninger | Voest-Alpine |
| Dr. Dieter Schmid | Volkswagen AG |
| Dr. Marko Gernuks | Volkswagen AG |

Appendix 2 List of participants at the 2nd expert workshop on "Resources for electro mobility" in Berlin, 31.05.2011

| Name | Institution |
|---|---|
| Christian Kawohl | Aurubis AG |
| Markus Becker | BMU Ref IG I 5 |
| Mathias Samson | BMU Ref IG I 5 |
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| Dr. Klaus Ruhland | Daimler AG |
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| Dr. Bernd Grieb | Fa. Magnequench |
| Tobias Klier | Friedrich-Alexander-Universität Erlangen-Nürnberg |
| Heinz-Dieter Heibach | Hitachi |
| Axel Schober | I+ME ACTIA |

| Name | Institution |
|---|---|
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| Dr. Wolfgang Jenseit | Öko-Institut e.V. |
| Florian Hacker | Öko-Institut e.V. |
| Stefanie Dittrich | Öko-Institut e.V. |
| Dr. Alexandra Wilde | Robert Bosch GmbH |
| Dr. Thorsten Mausbach | Robert Bosch GmbH |
| Dr. Jens-Oliver Müller | Siemens AG |
| Kai Rasenack | Technische Universität Clausthal |
| Prof. Dr.-Ing. Daniel Goldmann | Technische Universität Clausthal<br>Institut für Aufbereitung, Deponietechnik und Geomechanik |
| Dr. Christoph Herrmann | TU Braunschweig |
| Patricia Egede | TU Braunschweig |
| Regina Kohlmeyer | UBA FG III 1.2 |
| Jan Kosmol | UBA FG III 2.2 |
| Frank Treffer | Umicore AG & Co. KG |
| Dr. Rolf Blank | Vacuumschmelze GmbH & Co. KG |
| Nadine May | VDI / VDE Innovation + Technik GmbH |
| Franz Dorninger | Voest-Alpine |
| Dr. Dieter Schmid | Volkswagen AG |
| Dr. Marko Gernuks | Volkswagen AG |

Appendix 3 List of participants at the final expert workshop on "Resources for electro mobility" in Berlin, 29.09.2011

| Name | Institution |
|---|---|
| Christian Kawohl | Aurubis AG |
| Markus Becker | BMU Ref IG I 5 |
| Mathias Samson | BMU Ref IG I 5 |
| Uwe Nestle | BMU Ref WA III 1 |

| Name | Institution |
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| Dr. Klaus Ruhland | Daimler AG |
| Sven Knoefel | Daimler AG |
| Dr. Eckhard Schüler-Hainsch | Daimler AG |
| Dr. Bernd Grieb | Fa. Magnequench |
| Axel Schober | I+ME ACTIA |
| Hans-Joachim Steinwachs | I+ME ACTIA |
| Volker Handke | IZT |
| Dr. Matthias Buchert | Öko-Institut e.V. |
| Dr. Wolfgang Jenseit | Öko-Institut e.V. |
| Florian Hacker | Öko-Institut e.V. |
| Stefanie Dittrich | Öko-Institut e.V. |
| Dr. Thorsten Mausbach | Robert Bosch GmbH |
| Dr. Jens-Oliver Müller | Siemens AG |
| Dr. Michael Oehlers | SolviCore GmbH& Co. KG |
| Kai Rasenack | Technische Universität Clausthal |
| Prof. Dr.-Ing. Daniel Goldmann | Technische Universität Clausthal<br>Institut für Aufbereitung, Deponietechnik und Geomechanik |
| Dr. Tina Dettmer | TU Braunschweig |
| Patricia Egede | TU Braunschweig |
| Regina Kohlmeyer | UBA FG III 1.2 |
| Jan Kosmol | UBA FG III 2.2 |
| Lars Mönch | UBA FG I 3.2 |
| Frank Treffer | Umicore AG & Co. KG |
| Dr. Rolf Blank | Vacuumschmelze GmbH & Co. KG |
| Dr. Randolf Schließer | VDI / VDE |
| Stella Konietzko | Volkswagen AG |
| Dr. Dieter Schmid | Volkswagen AG |
| Dr. Marko Gernuks | Volkswagen AG |