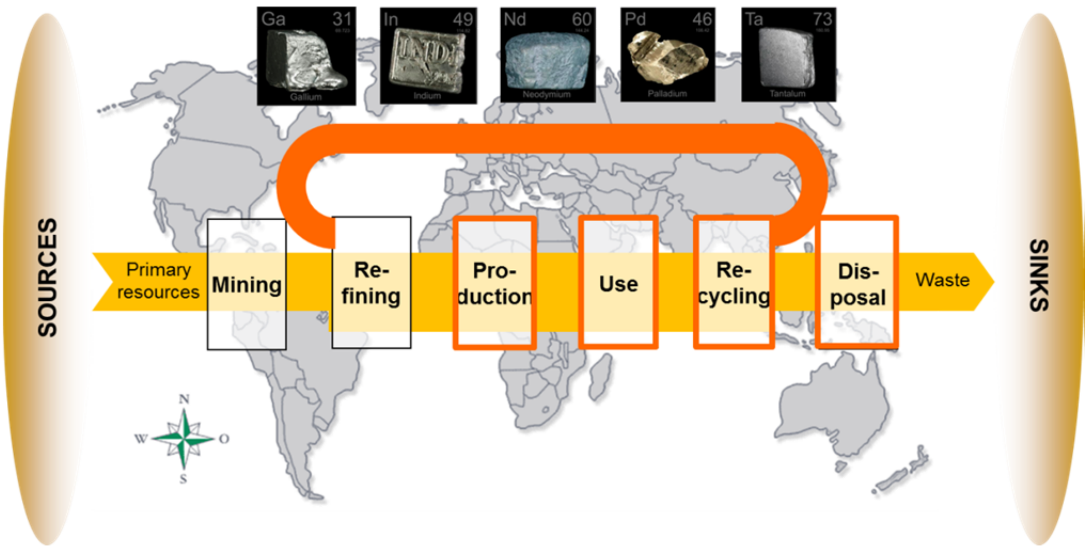
Scarce technology metals - applications, criticalities and intervention options



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Summary

The present report, which was commissioned by the Swiss Federal Office for the Environment (FOEN), provides a synthesis of existing information on applications, criticalities and intervention options towards a more sustainable governance of scarce technology metals in the context of Switzerland.

Switzerland has no primary production of scarce technology metals. Rather, these metals enter the country in the form of raw materials or semi-finished and finished products. Because of their very specific properties, scarce technology metals are generally difficult to substitute - unless society would be ready to accept less 'sophisticated' services. Accordingly, it is generally expected that emerging technologies will significantly increase the demand for scarce metals in the near future. As a consequence, a demand competition between technologies might arise (energy- (e.g. PV) vs. ICT applications), which would increase the pressure on scarce metals supply, but also could drive the development towards a minimisation of scarce metal requirements or substitution.

According to recent studies, the following scarce metals or metals families appear to have a particularly high supply risk or to be 'critical': antimony, beryllium, cobalt, gallium, germanium, indium, niobium, platinum group metals (PGM), rare earth elements (REE), tantalum and tungsten. However, this result has to be interpreted with care, since the scopes and methodologies of the studies addressed differ from each other and the criticality of a metal is subject to high temporal dynamics, as a consequence of e.g. altering geopolitical conditions.

A separate evaluation of scarce metals criticality for Switzerland makes sense insofar as raw material supply restrictions might have other impacts on the economy than those identified in the above mentioned studies for the European Union and the United States. In particular, as it is expected that the major share of potentially critical metals enters Switzerland (indirectly) through (semi-finished) products, the impacts of scarce technology metals supply restrictions on their availability should be further investigated.

Besides e.g. geopolitical or economic factors, the criticality of scarce metals is determined by the environmental impacts associated with their supply. Particularly high environmental impacts are generated during the primary production of precious metals such as gold and PGMs.

In the future, the environmental impacts associated with primary production of scarce technology metals are expected to increase either due to a shift to other resource types (as it is the case e.g. for lithium), decreasing ore grades (as it is the case for e.g. gold) or mining at greater depths. Australian studies, in particular, argue for higher impacts, since they are rather pessimistic that technological developments in mining will counterbalance higher material throughput with lower ore grades.

For the secondary production of scarce metals from EoL products, significantly lower environmental impacts compared to the primary production have been reported for precious metals such as gold and palladium in a recent life cycle assessment of the Swiss WEEE collection and recycling systems. How far this also will be true for the secondary production of other scarce metals from EoL products will depend on the specific collection, pre-processing and recovery processes. Provided that data on such processes are available, this will have to be investigated in future LCA research projects.

In view of reducing the environmental impacts of scarce metals supply the producers will play a very important role, in particular through product design and the procurement of raw materials or semi-finished products for which scarce metals are required. In any case, a reduction of environmental impacts related to scarce metals supply to the minimum will require the application of a life cycle perspective to identify the "hot-spots" and to allow for appropriate interventions. This should include the consideration of possible rebound effects induced by the consumption of a great number of environmentally optimised products.

In existing studies and reports addressing scarce metals supply risks and criticalities, different interventions towards a more sustainable governance of scarce metals have implicitly or explicitly been proposed. In this study, typical intervention domains addressed were integrated into a generic framework towards a sustainable governance of scarce metals, which consists of three levels: 1. Knowledge provision, 2. Possible interventions along the scarce metals life cycle and 3. Institutional setting. Taking into account that every scarce metal has its own demand and supply 'history' and that different societal levels (inter alia consumer, company, business sector, state, international community), with their particular possibilities and limitations are addressed, this generic framework of possible interventions will have to be prioritized for every scarce metal or scarce metals family. First steps in this direction have been undertaken on the occasion of an expert workshop.

Establishing a simple hierarchy of most effective interventions for a specific scarce metal or scarce metals family however appears to be difficult, not least because the scarce metals life cycle typically transgresses the boundaries of traditional political entities and involves many actors with limited information and communication on this subject. A main issue to be considered when establishing intervention priorities will therefore consist in identifying possibilities to motivate and integrate actors along the life cycle, not least in the recycling chain.

Within any political entity the possibilities for interventions will depend on its specific natural, societal and techno-economic conditions. For an economically well-developed political entity without any significant primary mineral resources and limited emerging technology production capacities like Switzerland, the most obvious direct interventions along the life cycle phase will be related to the production, use, recycling and disposal life cycle phases, accompanied by measures related to knowledge provision (e.g. retracing scarce metals in the supply chain, identification of substitution options, providing data on anthropogenic scarce metals stocks and flows, developing (eco-)efficient pre-processing and recovery processes) and the institutional setting. Although the impact of these interventions on a global scale may be limited, contributing to supply security, avoiding dissipation of scarce metals and generating less specific environmental impacts than primary production are considered to be sufficient reasons to support their consequent implementation.

While for some scarce metals recycling technologies are available and EoL recycling rates are comparatively high, for many scarce metals such as gallium, germanium, indium, osmium REE, tantalum or tellurium EoL recycling rates are below 1%. Increasing the EoL recycling rates requires a good accessibility of the scarce metals, a high EoL collection rate, and efficient pre-processing - and recovery processes. While in Switzerland the collection rates of e.g. WEEE are comparatively high, pre-processing and recovery of most scarce metals except some precious metals are very low. Indeed, for several critical scarce metals such as lithium, REE or tantalum are not yet available or will never be economic for thermodynamic reasons.

Compared to base metals, scarce metals are mostly used at very low concentrations. Product design could greatly improve EoL recycling rates by designing products in which scarce metals can be easily localized and accessed. In particular, this means easy disassembly of parts containing scarce metals and, if scarce metals are part of very compact blends (e.g. composites, alloys or compounds) and/or extremely thinned out (e.g. dopants), the concentration of these functionalities in easily removable building components. The use of easily removable components could be promoted by specific recovery targets for certain elements, as well as the installation of a proper pre-treatment infrastructure allowing to feed them into optimized recovery operations (electro, hydro- and/or pyrometallurgical processes).

An increase of EoL recycling rates for scarce metals allows, in particular, to avoid a dissipation of scarce metals into other materials (as tramp elements e.g. in base metals) or into the environment (e.g. via landfilling of slags), which will mostly be thermodynamically irreversible, and to take advantage of the most often lower environmental impacts of recycling compared to primary production (for example, the primary production of REE is associated with the emission of radioactive isotopes, which would not be the case for their recovery from e.g. WEEE).

Besides EoL recycling, whenever possible the recycling of production scrap should be given a high priority, as it is to be expected that it generally has a higher recycling potential (scarce metals concentrations, homogeneity, amounts) than EoL scrap.

Zusammenfassung

Der vorliegende Bericht, der im Auftrag des schweizerischen Bundesamtes für Umwelt (BAFU) erstellt wurde, fasst die heute verfügbaren Informationen über Anwendungsbereiche und die Kritikalität von seltenen technischen Metallen und über Interventionsmöglichkeiten für einen nachhaltigeren Umgang mit solchen Metallen in der Schweiz zusammen.

In der Schweiz gibt es keine Primärproduktion seltener Technologiemetalle. Vielmehr werden diese Metalle entweder als Rohstoffe oder aber in Form von Fertig- oder Halbfertigprodukten eingeführt. Aufgrund ihrer sehr spezifischen Eigenschaften lassen sich seltene Metalle in der Regel schwer substituieren, denn dies würde eine gesellschaftliche Akzeptanz für weniger anspruchsvolle Dienstleistungen voraussetzen. Es wird deshalb allgemein davon ausgegangen, dass die Nachfrage nach seltenen Metallen aufgrund neuer Technologien in naher Zukunft deutlich zunehmen wird. Als Folge davon könnte ein Nachfragewettbewerb zwischen verschiedenen Technologien (z. B. zwischen Energieanwendungen wie Photovoltaik und IKT-Anwendungen) entstehen. Dies wiederum könnte die Versorgungsengpässe für seltene Metalle verschärfen oder aber Entwicklungen begünstigen, die zu einer Verringerung des Bedarfs an solchen Metallen oder zu ihrer Substituierung führen.

Laut aktuellen Studien, die in diesem Bericht erörtert werden, sind die folgenden Metalle bzw. Metallfamilien hinsichtlich Versorgungsrisiko bzw. Auswirkungen eines Versorgungsunterbruchs als besonders 'kritisch' zu beurteilen:: Antimon, Beryllium, Cobalt, Gallium, Germanium, Indium, Niob, Platinmetalle, Seltenerdeelemente (SEE), Tantal und Wolfram. Dieser Befund ist indessen mit Zurückhaltung zu interpretieren, da sich die betrachteten Studien in Zweck und Methodik unterscheiden und die Kritikalität eines Metalls eine ausgeprägte zeitliche Dynamik aufweist, beispielsweise infolge Veränderung der geopolitischen Rahmenbedingungen.

Eine spezifisch auf die Schweiz bezogene Beurteilung der Kritikalität seltener Metalle ist insofern sinnvoll, als eine eingeschränkte Rohstoffverfügbarkeit weitere wirtschaftliche Auswirkungen haben könnte, die in den erwähnten, auf die EU und die USA fokussierten Studien nicht aufgezeigt werden. Da der grösste Teil der potenziell kritischen Metalle (indirekt) über (Halb-)Fertigprodukte in die Schweiz gelangen dürfte, ist eine vertiefte Untersuchung der Folgen eines Versorgungsengpasses seltener technischer Metalle auf die Verfügbarkeit dieser Produkte besonders angezeigt.

Die Kritikalität seltener Metalle hängt nicht nur von geopolitischen oder wirtschaftlichen Faktoren, sondern auch von Umweltauswirkungen im Zusammenhang mit ihrer Förderung ab. Besonders schwerwiegende Umweltauswirkungen entstehen bei der Primärproduktion von Edelmetallen wie Gold und Platinmetalle.

Infolge einer Verschiebung hin zu anderen Ressourcentypen (wie z. B. bei Lithium), abnehmender Erzgehalte (wie etwa bei Gold) oder des Abbaus in immer grösserer Tiefe ist in Zukunft mit einer Zunahme der Umweltauswirkungen der Primärproduktion seltener technischer Metalle zu rechnen. Grössere Umweltauswirkungen werden insbesondere von australischen Studien vorausgesagt, da diese die Wahrscheinlichkeit, dass die Weiterentwicklung der Bergbautechnologie den durch tiefere Erzgehalte bedingten höheren Materialdurchsatz wettmachen kann, eher pessimistisch einschätzen.

Eine kürzlich erstellte Ökobilanz der schweizerischen Sammel- und Verwertungssysteme für Elektro- und Elektronikgeräteabfall (waste electrical and electronical equipment, WEEE) hat für Edemetalle wie Gold und

Palladium gezeigt, dass die Umweltauswirkungen der Sekundärproduktion von seltenen Metallen durch Rückgewinnung aus Altprodukten im Vergleich zur Primärproduktion signifikant geringer sind. Inwiefern dies auch für die Rückgewinnung anderer seltener Metalle aus Altprodukten gilt, hängt von den jeweiligen Sammel-, Vorverarbeitungs- und Rückgewinnungsverfahren ab. Vorausgesetzt, dass Daten zu den spezifischen Verfahren verfügbar sind, wäre dies im Rahmen weiterer Ökobilanzen genauer zu untersuchen.

Eine Reduktion der Umweltauswirkungen durch Versorgung mit seltenen Metallen wird wesentlich von den Anstrengungen der Produzenten beim Produktedesign und der Beschaffung von Rohmaterialien oder Halbfertigprodukten abhängen. Im Hinblick auf eine Reduktion der Umweltauswirkungen auf ein Minimum ist in jedem Fall eine Betrachtungsweise des gesamten Lebenszyklus erforderlich, damit die Hot-spots identifiziert werden können und angemessene Interventionen möglich sind. Dabei sind auch die möglichen Rebound-Effekte zu berücksichtigen, die durch den Verbrauch einer grossen Zahl ökologisch optimierter Produkte entstehen können.

Bisherige Untersuchungen und Berichte über Versorgungsrisiken und -kritikalität im Zusammenhang mit seltenen Metallen schlagen implizit oder explizit verschiedene Massnahmen zur Förderung eines nachhaltigeren Umgangs mit seltenen Metallen vor. Die typischen angesprochenen Interventionsbereiche wurden in einem übergeordneten Rahmen für einen nachhaltigeren Umgang mit seltenen Metallen zusammengefasst. Dieser übergeordnete Rahmen umfasst drei Ebenen: 1. Bereitstellung von relevantem Wissen, 2. Mögliche Interventionen entlang des Lebenszyklus seltener Metalle, und 3. Institutioneller Rahmen. Da jedes seltene Metall seine eigene Nachfrage- und Angebotsgeschichte hat und verschiedene Ebenen der Gesellschaft (Verbraucherinnen und Verbraucher, Unternehmen, Branche, Staat, internationale Gemeinschaft) mit unterschiedlichen Handlungsspielräumen angesprochen werden, erfordert dieser übergeordnete Rahmen für mögliche Interventionen eine gesonderte Priorisierung für jedes einzelne seltene Metall beziehungsweise für jede einzelne Gruppe von Metallen. Erste Schritte dazu wurden im Rahmen eines Sachverständigenworkshops gemacht.

Allerdings dürfte es schwierig sein, eine einfache Hierarchie der wirksamsten Interventionen im Hinblick auf ein spezifisches seltenes Metall oder eine Gruppe von Metallen zu erstellen, dies nicht zuletzt deshalb, weil der Lebenszyklus seltener Metalle üblicherweise die Grenzen traditioneller politischer Einheiten sprengt und eine grosse Zahl von Akteuren betrifft, die nur beschränkte Informationen zu diesem Thema besitzen. Ein wichtiges Element bei der Priorisierung der Interventionen ist daher die Identifizierung von Möglichkeiten, Akteure entlang des gesamten Lebenszyklus und insbesondere auch der Recyclingkette zu motivieren und einzubinden.

Ausschlaggebend für die Interventionsmöglichkeiten innerhalb einer politischen Einheit sind deren natürlichen, gesellschaftlichen und technoökonomischen Umstände. Für eine wirtschaftlich hoch entwickelte politische Einheit wie die Schweiz, die keine nennenswerten primären Mineralvorkommen und nur beschränkte Produktionskapazitäten für aufstrebende Technologien besitzt, dürften sich die augenfälligsten direkten Interventionen entlang des Lebenszyklus auf die Phasen der Produktion, der Verwendung, des Recyclings und der Entsorgung beziehen. Ergänzend dazu wären Massnahmen zur Wissensbeschaffung (z. B. Rückverfolgung von seltenen Metallen entlang der Zulieferketten, Identifikation von Substitutionsmöglichkeiten, Bereitstellung von Daten über anthropogene Vorräte und Flüsse von seltenen Metallen, Entwicklung (öko-)effizienter Vorverarbeitungs- und Rückgewinnungsverfahren) und auf dem Gebiet des institutionellen Rahmens in Betracht zu ziehen. Selbst wenn die Wirkungen dieser Massnahmen im globalen Massstab beschränkt sein dürfte, so sind doch ihr Beitrag zur Verbesserung der Versorgungssicherheit und zur Vermeidung der Dissipation von seltenen Metallen und die im Vergleich zur Primärproduktion weniger spezifischen Umweltprobleme Gründe genug, um diese Massnahmen konsequent umzusetzen.

Für einige seltene Metalle sind bereits Rückgewinnungstechnologien verfügbar, und die Recyclingraten sind vergleichsweise hoch. Bei zahlreichen seltenen Metallen wie Gallium, Germanium, Indium, Osmium, SEE, Tantal oder Tellur jedoch betragen die Recyclingraten weniger als 1 %. Voraussetzungen für eine Erhöhung der Recyclingquote sind eine gute Zugänglichkeit der seltenen Metalle, eine hohe Sammelquote von Altgeräten und -anwendungen sowie effiziente Vorverarbeitungs- und Rückgewinnungsprozesse. Die Sammelquoten für WEEE sind in der Schweiz zwar vergleichsweise hoch, der Anteil der Vorverarbeitung und Rückgewinnung ist für die meisten seltenen Metalle mit Ausnahme einiger Edelmetalle jedoch sehr gering. Tatsächlich sind für gewisse kritische seltene Metalle wie Lithium, SEE oder Tantal noch keine Rückgewinnungstechnologien vorhanden, beziehungsweise die Rückgewinnung wird aus Gründen der Thermodynamik nie wirtschaftlich sein.

Verglichen mit Basismetallen werden seltene Metalle mehrheitlich nur in sehr geringen Konzentrationen verwendet. Durch ein Produktedesign, welches eine einfache Ortung und einen problemlosen Zugang zu seltenen Metallen ermöglicht, liessen sich die Recyclingraten signifikant steigern. Dies bedeutet namentlich, dass Komponenten, die seltene Metalle enthalten, problemlos ausgebaut werden können und dass sehr kompakte Mischungen (Verbundstoffe, Legierungen oder Verbindungen) und/oder extrem dünne Schichten mit seltenen Metallen (z. B. als Dotierungsstoffe) in leicht auszubauenden Bauteilen konzentriert werden. Der Einsatz leicht abtrennbarer Komponenten liesse sich durch spezifische Rückgewinnungsziele für gewisse Elemente sowie durch den Aufbau einer geeigneten Vorverarbeitungsinfrastruktur fördern, die eine Weiterverarbeitung in optimierten Rückgewinnungsbetrieben (elektro-, hydro- und/oder pyrometallurgische Verfahren) erlauben.

Durch eine Steigerung der Recyclingrate für seltene Metalle liesse sich insbesondere die Dissipation seltener Metalle in andere Materialien (z. B. als unerwünschte Begleitelemente in Basismetallen) oder in die Umwelt (z. B. aus Schlackendeponien) vermeiden, da diese Vorgänge mehrheitlich thermodynamisch irreversibel sind. Ein weiterer Vorteil besteht darin, dass die Umweltauswirkungen des Recyclings im Vergleich zur Primärproduktion meistens geringer sind (bei der Primärproduktion von SEE beispielsweise werden radioaktive Isotopen freigesetzt, die bei der Rückgewinnung dieser Elemente aus WEEE usw. nicht anfallen).

Neben dem Recycling von Altgeräten und -anwendungen ist wo immer möglich auch der Wiederverwertung von Produktionsabfällen grosse Priorität beizumessen, da diese im Vergleich zu Altgeräten und -anwendungen ein grösseres Recyclingpotenzial aufweisen dürften (Konzentrationen von seltenen Metallen, Homogenität, Mengen).

Résumé

Le présent rapport, commandé par l'Office fédéral suisse de l'environnement (OFEV), synthétise les informations disponibles concernant les applications des métaux rares utilisés dans la haute technologie, les points critiques et les interventions possibles pour gérer plus durablement ces éléments dans le contexte helvétique.

A l'heure actuelle, la Suisse ne produit pas de métaux rares primaires. Les métaux rares sont importés sous la forme de matériaux bruts ou de produits semi-finis ou finis qui répondent à la demande. Dotés de propriétés très spécifiques, ces métaux sont généralement difficiles à remplacer – à moins que la société ne se satisfasse de services moins « sophistiqués ». Plusieurs scénarios analysés indiquent que les technologies émergentes devraient accroître significativement la consommation de métaux rares dans un proche avenir. Différents domaines techniques pourraient alors entrer en compétition (p. ex. applications énergétiques, telles que photovoltaïques, vs technologies de l'information et de la communication), ce qui accentuerait la pression sur l'approvisionnement, mais pousserait peut-être aussi à limiter le recours aux métaux rares ou à les remplacer.

D'après certaines études récentes évoquées dans le rapport, les métaux ou familles de métaux rares antimoine, béryllium, cobalt, gallium, germanium, indium, niobium, platinoïdes, terres rares, tantale et tungstène risquent de subir de gros problèmes d'approvisionnement, voire de devenir « critiques ». Mais cette conclusion doit être interprétée prudemment, car le cadre et les méthodes mises en œuvre varient d'une étude à l'autre. De plus, le caractère critique d'un métal, sujet à des dynamiques très variables dans le temps, peut évoluer rapidement, par exemple, en fonction de la situation géopolitique.

Le problème doit être évalué spécifiquement dans le cas de la Suisse, car la limitation de la fourniture d'un de ces matériaux pourrait avoir d'autres conséquences sur l'économie helvétique que celles identifiées dans les études mentionnées précédemment, qui portent sur l'Union européenne et sur les Etats-Unis. Comme il faut s'attendre à ce que la plus grande partie des métaux potentiellement critiques entrent en Suisse (indirectement) dans des produits (semi-finis), il s'agit d'étudier en détail les effets des restrictions d'approvisionnement en métaux rares utilisés dans la haute technologie.

Outre les facteurs géopolitiques et économiques, le caractère critique des métaux rares est déterminé par l'impact sur l'environnement lié à leur fourniture, qui est très lourd dans le cas de la production primaire de métaux précieux à but technique comme l'or et les platinoïdes.

On s'attend à ce que l'impact environnemental lié à la production primaire de métaux rares utilisés dans la haute technologie croisse avec le passage à d'autres types de ressources (c'est notamment le cas pour le lithium), avec la baisse de teneur des gisements (p. ex. d'or) ou avec l'accroissement de la profondeur des mines. Des études australiennes, en particulier, arguent que les effets sur l'environnement s'intensifieront, car il est peu probable que les progrès techniques dans le domaine minier compensent l'augmentation des quantités extraites en raison de la baisse de teneur des gisements.

Une évaluation récente des cycles de vie, réalisée par des filières suisses de collecte et de valorisation des déchets d'appareils électriques et électroniques, indique que la production secondaire des métaux précieux comme l'or et le palladium à partir de produits en fin de vie a un impact environnemental significativement moindre que leur production primaire. C'est peut-être aussi le cas pour d'autres métaux rares, mais cela dé-

pend des collectes, des traitements préalables et des méthodes de récupération. Il y aura lieu de l'étudier en analysant le cycle de vie de ces éléments – pour autant que des données utilisables soient disponibles.

La diminution des répercussions écologiques de l'approvisionnement en métaux rares est tributaire d'importantes décisions prises par les fabricants, qui touchent en particulier à la conception de leurs produits et à l'acquisition des matériaux bruts et des produits semi-finis nécessitant des métaux rares. Pour les restreindre au minimum, il faut raisonner en termes de cycle de vie pour identifier les "hot spots" et pouvoir intervenir de manière appropriée. Les éventuels effets de rebond consécutifs à la consommation de produits en grand nombre, fussent-ils optimisés dans une perspective écologique, doivent aussi être pris en considération.

Les études et les rapports examinant les risques et les points critiques liés à l'approvisionnement en métaux rares proposent implicitement ou explicitement diverses opérations pour les gérer dans une perspective plus durable. Dans la présente étude, les principaux axes d'intervention envisageables ont été regroupés en une démarche générale en trois étapes: 1/ acquérir et intégrer les connaissances appropriées, 2/ identifier et incorporer des interventions spécifiques tout au long du cycle de vie, 3/ instaurer un cadre institutionnel approprié. Cette démarche devra être hiérarchisée en fonction des métaux rares ou des familles de métaux rares, car chacun d'entre eux a sa propre demande, son propre historique de diffusion et implique différents segments de la société (consommateurs, entreprises, milieu des affaires, Etat, communauté internationale, etc.) avec leurs possibilités et leurs limitations. La première avancée dans cette direction a été réalisée lors d'un atelier d'experts.

Il semble toutefois difficile de hiérarchiser simplement, à l'aune de leur efficacité, les interventions portant sur un métal rare ou sur une famille de métaux rares spécifique, notamment parce que leur cycle de vie franchit habituellement les limites des entités politiques traditionnelles et implique de nombreux protagonistes disposant d'informations et de contacts limités. Pour y parvenir, il est donc essentiel d'identifier les possibilités de motiver et d'associer ceux qui interviennent tout au long du cycle de vie et surtout dans la chaîne de recyclage de ces matériaux.

Les possibilités d'intervention offertes dans une entité politique dépendent du contexte naturel, sociétal et technico-économique. Lorsque l'une d'entre elles est, comme la Suisse, bien développée économiquement mais dépourvue de ressources notables en minéraux primaires et de grandes capacités de production technique, les interventions directes les plus évidentes dans le cycle de vie porteront sur les phases de production, d'utilisation, de recyclage et de mise en décharge et elles comprendront des mesures ayant trait aux connaissances (p. ex. retracement des métaux le long des chaînes d'approvisionnement, identification des possibilités de substitution, acquisition de données concernant les stocks et les flux de métaux rares dus aux activités humaines, développement de méthodes de prétraitement et de récupération (écologiquement) efficaces) et au cadre institutionnel. L'incidence de ces interventions à l'échelle mondiale est certes modeste, mais elles contribuent à la sécurité de l'approvisionnement, évitent l'éparpillement des métaux rares et réduisent la charge sur l'environnement par rapport à la production primaire, autant de raisons suffisantes pour les mettre en œuvre systématiquement.

Des techniques de recyclage permettant d'atteindre des taux de récupération élevés dans les produits usagés sont disponibles pour quelques métaux rares, mais la proportion est inférieure à 1 % pour de nombreux métaux rares comme le gallium, le germanium, l'indium, l'osmium, les terres rares, le tantale ou le tellure. Pour l'augmenter, il faut pouvoir isoler ces métaux, collecter une bonne part des produits en fin de vie en contenant et mettre en œuvre des procédés efficaces de prétraitement et de récupération. En Suisse, si le taux de collecte des déchets d'équipements électriques et électroniques est relativement élevé, les performances du prétraitement et de la récupération de la plupart des métaux rares, sauf quelques métaux précieux, sont quant à elles très faibles. Il n'existe pas encore de procédé de récupération applicable pour certains métaux rares critiques comme le lithium, les terres rares ou le tantale, ou alors leur rentabilité ne sera jamais assurée pour des raisons dues à la thermodynamique.

Contrairement aux métaux courants, les métaux rares sont le plus souvent appliqués en concentrations minimes. Leur récupération pourrait être bien meilleure si on concevait des produits dans lesquels ils seraient faciles à localiser et à isoler. Cela demande en particulier que les composants en renfermant soient simples à démonter et que, lorsque ces métaux entrent dans des mélanges très compacts (p. ex. alliages, matériaux composites ou composés) ou sont extrêmement dilués (p. ex. dopants), ils soient regroupés dans des composants aisés à retirer. On peut favoriser cela en assignant des buts spécifiques à la récupération d'éléments donnés et en mettant sur pied une infrastructure de prétraitement dédiée, qui faciliterait l'optimalisation des opérations de récupération (processus électriques, hydrométallurgiques ou pyrométallurgiques).

En augmentant le taux de récupération des métaux rares dans les produits usagés, on évite leur éparpillement dans d'autres matériaux (p. ex. comme impuretés dans des métaux courants) ou dans l'environnement (p. ex. via les mâchefers mis en décharge), souvent irréversible pour des raisons thermodynamiques, et on profite du fait que le recyclage exerce habituellement un impact écologique moindre que la production primaire (p. ex., la production primaire de terres rares s'accompagne d'émissions radioactives émanant d'isotopes, qui sont absentes de la récupération dans les déchets d'appareils électriques et électroniques).

On devrait accorder la priorité au recyclage des déchets de fabrication, car on s'attend à ce qu'il présente généralement un potentiel supérieur à la récupération dans les produits en fin de vie (teneur élevée en métaux rares, homogénéité, quantité).

Riassunto

Il presente rapporto, commissionato dall'Ufficio federale dell'ambiente (UFAM), fornisce una sintesi delle informazioni disponibili in merito ad applicazioni, criticità e possibili interventi per una gestione più sostenibile dei metalli rari nel contesto svizzero.

Attualmente la Svizzera non ha una produzione primaria di metalli rari. Tali metalli entrano invece nel Paese come materie prime o come prodotti finiti e semifiniti per garantire la fornitura dei servizi richiesti. A causa delle loro proprietà molto specifiche, i metalli rari sono generalmente difficili da sostituire, a meno che la società non sia pronta ad accettare servizi meno «sofisticati». Sulla base dell'analisi di diversi scenari si prevede che nel prossimo futuro le tecnologie emergenti determineranno un aumento significativo della domanda di metalli rari. I fabbisogni delle diverse tecnologie potrebbero farle entrare in competizione (applicazioni energetiche, ad es. fotovoltaiche, in concorrenza con le applicazioni TIC), con conseguente aumento della pressione sulla catena di approvvigionamento di questi metalli. D'altra parte, l'aumento della domanda potrebbe anche determinare una dinamica che tenda a ridurre al minimo il fabbisogno di metalli rari o a sostituirli.

Secondo i recenti studi esaminati in questo rapporto, i metalli rari che presentano un elevato rischio di approvvigionamento o una «criticità» sono i seguenti: antimonio, berillio, cobalto, gallio, germanio, indio, niobio, MGP, terre rare, tantalio e tungsteno. I dati che ne risultano vanno però interpretati con cautela, sia perché gli studi in questione differiscono nei campi di applicazione e nei metodi utilizzati, sia perché la criticità di un metallo è soggetta a forti dinamiche temporali e di conseguenza può cambiare con rapidità, ad esempio per un'alterazione delle condizioni geopolitiche.

Una valutazione separata della criticità dei metalli rari per la Svizzera appare opportuna nella misura in cui eventuali restrizioni nell'approvvigionamento di materie prime potrebbero determinare impatti economici diversi da quelli identificati nei sopraccitati studi per l'Unione europea e gli Stati Uniti. In particolare, considerato che la maggior parte dei metalli potenzialmente critici entrerebbe (indirettamente) in Svizzera attraverso i prodotti (semifiniti), andrebbero esaminati in modo approfondito i possibili effetti che le restrizioni di approvvigionamento dei metalli rari provocherebbero sulla disponibilità degli stessi prodotti.

Oltre che dai fattori geopolitici ed economici, la criticità dei metalli rari è determinata anche dall'impatto ambientale dell'approvvigionamento. Particolarmente elevato è l'impatto ambientale derivante dalla produzione primaria di metalli preziosi come oro e MGP.

Per il futuro è previsto un aumento dell'impatto ambientale legato alla produzione primaria di metalli rari, sia per il passaggio a risorse di altro tipo (come ad es. nel caso del litio), sia per il peggioramento della qualità dei minerali (come ad es. nel caso dell'oro) e per l'estrazione a maggiori profondità. La tesi dell'impatto più elevato è sostenuta in particolare dagli studi australiani, caratterizzati da un certo pessimismo riguardo alla possibilità che i progressi tecnologici nel settore minerario possano compensare il maggior volume di produzione di materiale qualitativamente inferiore.

Per quanto concerne la produzione secondaria di metalli rari ottenuti da prodotti a fine vita, nell'ambito di una recente valutazione del ciclo di vita nei sistemi svizzeri di raccolta e riciclaggio dei RAEE sono stati registrati, per metalli preziosi come oro e palladio, impatti ambientali significativamente inferiori rispetto a quelli della produzione primaria. In che misura ciò sia vero anche per la produzione secondaria di altri metalli rari

ottenuti da prodotti a fine vita dipende dagli specifici processi di raccolta, pretrattamento e recupero. Qualora disponibili, i dati su questi processi dovranno essere esaminati in futuri progetti di ricerca LCA.

Nell'ottica di una riduzione dell'impatto ambientale legato all'approvvigionamento di metalli rari, i produttori dovranno prendere decisioni importanti, soprattutto per quanto riguarda la progettazione dei prodotti e il rifornimento di materie prime o di prodotti semifiniti che richiedono metalli rari. Per ridurre al minimo l'impatto ambientale dell'approvvigionamento di tali metalli sarà necessario adottare una del ciclo di vita. Tale prospettiva dovrebbe anche tenere conto dei possibili effetti di rimbalzo dovuti al consumo di un gran numero di prodotti ottimizzati dal punto di vista ambientale.

Negli studi e nei rapporti che hanno finora esaminato i rischi e le criticità dell'approvvigionamento di metalli rari sono stati implicitamente o esplicitamente proposti diversi interventi per una gestione più sostenibile dei metalli in questione. Nel presente rapporto i tipici settori d'intervento sono stati integrati in un quadro globale con l'obiettivo di realizzare una gestione sostenibile dei metalli rari a tre livelli: 1. fornire e integrare conoscenze rilevanti, 2. identificare e attuare interventi specifici lungo il ciclo di vita dei metalli rari, 3. creare un quadro istituzionale adeguato. L'applicazione di questo quadro globale richiederà almeno due specifiche. Occorrerà tenere presente da un lato che ogni metallo raro ha una sua «storia» per domanda e approvvigionamento e che dall'altro sono coinvolti diversi livelli sociali (tra cui consumatore, società, settore commerciale, Stato e comunità internazionale) con possibilità e limitazioni proprie. Ne consegue che per ogni metallo raro o famiglia di metalli rari si dovranno stabilire delle priorità nell'ambito del quadro globale dei possibili settori d'intervento. I primi passi in questa direzione sono già stati compiuti in occasione di un seminario di esperti.

Stabilire una semplice gerarchia degli interventi più efficaci per uno specifico metallo raro o una specifica famiglia di metalli rari appare comunque difficile, non da ultimo perché il ciclo di vita dei metalli rari in genere trascende i limiti delle tradizionali entità politiche e coinvolge molti soggetti con carenza di informazioni e comunicazioni sull'argomento. Nel definire le priorità d'intervento bisognerà quindi dare particolare importanza all'identificazione di soluzioni che consentano di motivare e integrare le diverse parti interessate lungo il ciclo di vita, non ultimi i soggetti della catena del riciclo.

Per qualsiasi entità politica le possibilità d'intervento dipenderanno dalle specifiche condizioni naturali, sociali e tecnico-economiche. Nel caso di un'entità politica come la Svizzera, caratterizzata da un elevato sviluppo economico ma priva di risorse minerali primarie significative e con limitate capacità produttive a tecnologia emergente, gli interventi diretti più ovvi lungo il ciclo di vita sono quelli legati alle fasi di produzione, utilizzo, riciclaggio e smaltimento, con misure di accompagnamento inerenti alla fornitura di conoscenze (ad es. Rintracciare i metalli rari lungo catena di approvvigionamento, identificazione di soluzioni alternative, fornitura di dati su riserve e flussi antropogenici di metalli rari, sviluppo di processi di pretrattamento e recupero (eco)efficienti) e al quadro istituzionale. Nonostante il loro limitato impatto a livello globale, tali interventi contribuiscono alla sicurezza dell'approvvigionamento, prevengono la dispersione di metalli rari e producono impatti ambientali meno specifici rispetto a quelli della produzione primaria. Vi sono perciò motivi sufficienti per sostenerne l'attuazione.

Mentre per alcuni metalli rari presenti in prodotti a fine vita sono già disponibili tecnologie che consentono tassi di riciclaggio relativamente elevati, per molti metalli rari come gallio, germanio, indio, osmio, terre rare, tantalio e tellurio si registrano tassi inferiori all'uno per cento. L'aumento dei tassi di riciclaggio dei prodotti a fine vita richiede una buona accessibilità ai metalli rari, un elevato tasso di raccolta al termine del ciclo vitale e processi di pretrattamento e recupero efficienti. In Svizzera i tassi di raccolta, ad esempio quelli dei RAEE, sono elevati, ma per la maggior parte dei metalli rari, eccetto alcuni metalli preziosi, i livelli di pretrattamento e recupero risultano estremamente bassi. In effetti, per metalli rari critici come litio, terre rare e tantalio i necessari processi non sono ancora disponibili o non saranno mai economicamente vantaggiosi per motivi di termodinamica.

Rispetto ai metalli comuni, quelli rari sono generalmente utilizzati in concentrazioni molto basse. I tassi di riciclaggio dei prodotti a fine vita potrebbero migliorare in modo significativo se si progettassero prodotti con un contenuto di metalli rari facilmente localizzabile e accessibile. In particolare ciò consentirebbe una facile estrazione delle parti contenenti metalli rari e, laddove tali metalli facciano parte di miscele molto compatte (ad es. compositi, leghe e composti) e/o siano estremamente diluiti (ad es. droganti), la concentrazione delle loro funzionalità in componenti facilmente rimovibili. L'impiego di questi componenti potrebbe essere favorito dalla definizione di obiettivi di recupero specifici per determinati elementi e dall'installazione di una infrastruttura di pretrattamento tale da consentire operazioni di recupero ottimizzate (processi elettro-, idro- e/o pirometallurgici).

Un aumento dei tassi di riciclaggio dei prodotti a fine vita permetterà non solo di evitare la dispersione dei metalli rari in altri materiali (come impurità, ad es. nei metalli comuni) o nell'ambiente (ad es. attraverso la messa in discarica di scorie), che sarebbe per lo più irreversibile dal punto di vista termodinamico, ma anche di beneficiare di un impatto ambientale quasi sempre inferiore rispetto a quello della produzione primaria (ad es. la produzione primaria di terre rare è associata all'emissione di isotopi radioattivi, mentre il recupero delle stesse, ad es. da RAEE, non comporta un simile fenomeno).

Oltre a favorire il riciclaggio dei prodotti a fine vita, se possibile bisognerebbe dare un'elevata priorità al riciclaggio degli scarti di produzione. Si ritiene infatti che questi scarti abbiano, generalmente, un potenziale di riciclaggio (concentrazioni di metalli rari, omogeneità, quantità) superiore a quello dei prodotti a fine vita.

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Abbreviations

ATO	Antimony-Tin-Oxide
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
EC	European Commission
EEE	Electrical and Electronic Equipment
EoL	End-of-life
EU	European Union
FPD	Flat Panel Display
GWP	Global Warming Potential
HFR	Halogenated flame retardants
ICT	Information- and Communication Technologies
ITO	Indium tin oxide or tin-doped indium oxide
LED	Light Emitting Diode
LCD	Liquid Crystal Display
MIPS	Material Intensity per Service Unit
OLED	Organic LED (also AMOLED = Active Matrix OLED)
PGMs	Platinum Group Metals
PV	Photovoltaics
R&D	Research and Development
REE	Rare Earth Elements
REO	Rare Earth Oxides
RFID	Radio Frequency Identification
SOFC	Solid Oxide Fuel Cell
SFA	Substance Flow Analysis
TMR	Total Material Requirement
UNEP	United Nations Environment Programme
WEEE	Waste electrical and electronic equipment
WLED	White Light Emitting Diode
w/o	without
XtL	Umbrella term of Biomass to Liquid (BtL) -, Coal to Liquid (CtL) - and Gas to Liquid (GtL) technologies

1 Introduction

The present report, which was commissioned by the Swiss Federal Office for the Environment (FOEN), aims at providing a synthesis of existing reports related to the criticality of scarce technology metals. In particular, the guiding questions summarised in Table 1-1: and tentatively grouped in five categories were intended to be addressed.

Table 1-1: Guiding questions intended to be addressed in the present report

Scarce technology metals applications
- In which products and functions/parts are scarce technology metals used?
- What amounts are used for which products in Switzerland?
- Which amounts of scarce technology metals does Switzerland consume per annum (DMC and DMO)?
- Which technological developments will have to be considered? For what time period?
The 'criticality' of scarce technology metals
- Which scarce technology metals are to be considered critical?
- For which scarce technology metals is there a need for action because of disproportionate environmental impacts (raw materials extraction) and resource overuse?
- For which critical technology metals could a supply restriction induce additional environmental impacts?
- Which are the life cycle phases of a scarce technology metal with the greatest environmental impacts?
- Which are the life cycle phases, in which the most important decisions regarding sustainability (ecology, economic availability, efficiency, etc.) are made?
Invervention options for a more sustainable scarce metals governance
- What are possible interventions for a more sustainable governance of scarce metals?
Recycling and product design opportunities
- What can recycling and product materials design contribute to a sustainable use of scarce technology metals?

The concepts of 'scarce' or 'critical' metals found in the literature may significantly differ from study to study. In this report, we will apply the following definitions:

- The term 'technology metal' denotes a metal which is used for "high-tech" and "clean-tech" products[1] expected to play a crucial role in the coming decades (see e.g. (Hagelüken and Meskers 2010)).
- A technology metal is labelled '(geochemically) scarce' when it occurs in the earth crust at (average) concentrations below 0.01% w/w (Skinner 1979, Wäger et al. 2010).
- A technology metal is labelled 'critical' when the risks of a supply shortage and its impacts on the economy are higher compared to most of the other raw materials (see e.g. (European Commission 2010)).

The geochemically scarce metals cover a wide range of elements in the periodic table of the elements, including elements such as gallium, germanium, indium, lithium, the platinum group metals (iridium, osmium, palladium, platinum, rhodium and ruthenium), the rare earth elements (scandium, yttrium, lanthanum and the lanthanides) and tantalum (see Figure 1-1).

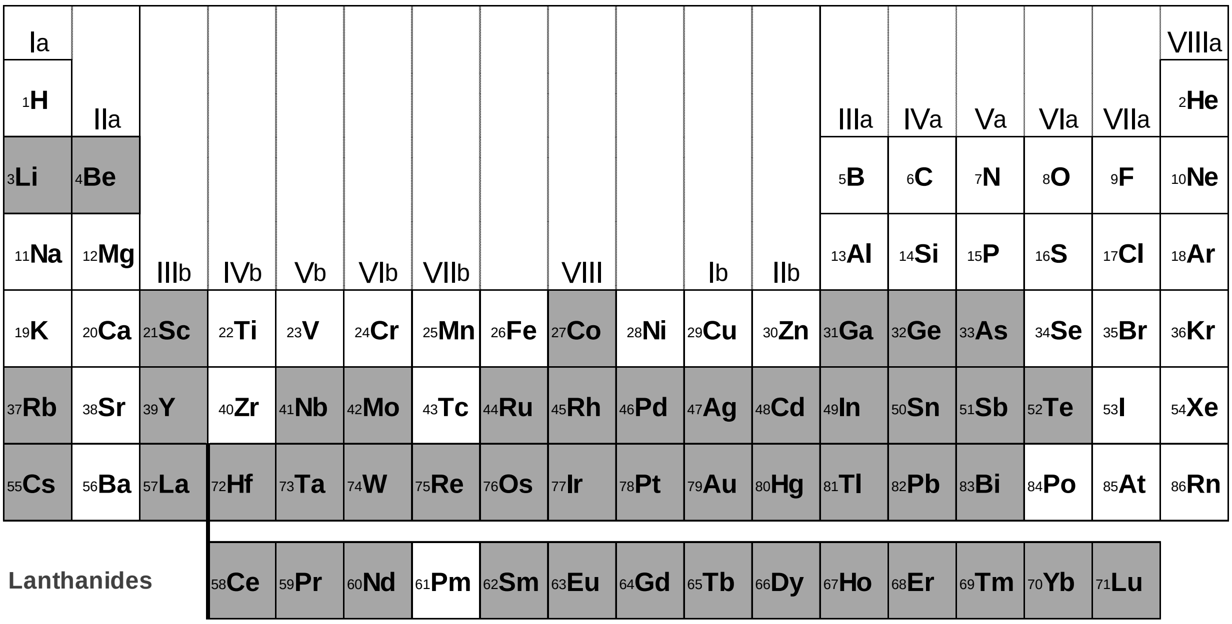

Figure 1-1: Geochemically scarce metals in the periodic table of the elements according to (Skinner 1979, Binder 2009); radioactive elements were not considered

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[1] The term 'clean technology' stands for an economically competitive and productive technology that uses less material and/or energy, generates less waste, and causes less environmental damage than the alternatives (www.businessdictionary.com). According to (http://knol.google.com/k/cleantech#), the concept of clean technologies (cleantech) embraces a diverse range of products, services, and processes across industry verticals that are inherently designed to provide superior performance at lower costs, greatly reduce or eliminate negative ecological impact and improve the productive and responsible use of natural resources.

It is important to keep in mind that 'criticality' is a relative rather than an absolute concept and that it typically only gives a static view of the situation, as it does not consider that the supply risks for some raw materials might change relatively rapidly (European Commission 2010); (National Research Council 2008).

The notion of 'strategic metals', if used at all, will be strictly applied for metals applied for military purposes. This corresponds to the approach proposed by the ad hoc working group on defining critical raw materials chaired by the European Commission (European Commission 2010).

The present report consists of six chapters. In chapter 2, which follows to the introduction, he occurrence of scarce technology metals in existing and future technologies and applications is addressed. Chapter 3 presents the outcome of recent studies addressing the criticality of scarce technology metals and explores the environmental dimension of criticality. Chapter 4 identifies possible interventions allowing for a more sustainable governance of scarce technology metals. In chapter 5, specific intervention options on the level of material design and recycling are discussed. Finally, in the concluding chapter, tentative answers to the guiding questions presented in the introduction are given.

2 Scarce technology metals applications

2.1 Existing applications

The application of scarce technology metals in existing products and technologies is widespread. Table 2-1 gives an overview of such applications for some selected scarce technology metals.

Table 2-1: Products and technologies, in which potentially critical metals are used (according to (Hagelüken and Meskers 2010)); REE: Rare Earth Elements

	Bismuth	Cobalt	Gallium	Germanium	Gold	Indium	Iridium	Lithium	Palladium	Platinum	REE	Rhenium	Selenium	Rhodium	Ruthenium	Silver	Tantalum	Tellurium
Pharmaceuticals	■							■		■					■			
Medical/dentistry		■	■	■	■	■			■	■		■	■			■	■	■
Superalloys		■									■	■			■		■	
Magnets		■									■		■					■
Hard Alloys		■						■									■	
Other alloys						■		■				■	■					■
Metallurgical [a]	■							■					■					
Glass, ceramics, pigments [b]	■	■				■			■	■			■	■	■	■		■
Photovoltaics			■	■		■							■			■		■
Batteries		■				■		■			■					■		
Fuel cells								■	■	■				■	■			
Catalysts		■		■	■	■	■		■	■	■	■	■	■	■	■		■
Nuclear						■		■			■							
Solder	■					■										■		
Electronics		■	■	■	■	■			■	■	■	■		■	■	■	■	■
Opto-electronics			■	■		■					■		■					■
Grease, lubrication			■					■										

[a] Additives in, e.g., smelting, plating. b Includes indium tin oxide (ITO) layers on glass REE: Rare Earth Elements

Up to now, the need for scarce technology metals in Switzerland has not been systematically addressed in existing studies. In a survey conducted among its members, Swissmem investigated how far the Swiss industry applies critical raw materials as defined in (European Commission 2010) (see section 3.1) The main insights of the survey were that about 75% of the member companies directly or indirectly (i.e. in semi-finished products) apply at least one of the critical raw materials, that the most often applied raw materials applied in these companies were chromium (74%), molybdenum (69%), magnesium (60%), tungsten (57%), graphite (53%) and cobalt (48%) and the least often applied raw materials were germanium, fluorspar, indium and antimony (Binder 2009)

According to (Weber et al. 2010), Switzerland's minerals primary production restricted to gypsum and anhydrite as well as salt in 2008. Regarding secondary production, only little data is presently available for the recycling of scarce technology metals in Switzerland and on their occurrence in emerging technologies such as Electrical and Electronic Equipment (EEE) applications (see (Chancerel et al. 2009), (Müller and

Widmer 2008)). In general, it appears that in Switzerland the secondary production of scarce metals such as e.g. gallium, indium, REE or tantalum is as insignificant as the primary production, and that the main share of critical technology metals in the Swiss anthropogenic stocks and flows most probably stems from the import of semi-finished and finished products.

Table 2-2: Production of Mineral Raw Material in Switzerland (Weber et al. 2010)

		2004	2005	2006	2007	2008
Non-Ferrous Metals	Al	44'538	44'800	12'000	0	0
Gypsum and Anhydrite	CaSO4 (2H2O)	300'000	300'000	300'000	300'000	300'000
Salt	NaCl	486'000	539'000	525'000	341'000	300'000

For EEE, (Müller and Widmer 2008) estimated the concentrations of different materials, including a few scarce technology metals (copper, cadmium, gold, indium, mercury, palladium and silver) in the categories large household appliances (LHA), small household appliances (SHA), information and communication technologies (ICT) and consumer electronics (CE) as well as lighting equipment (LE). For their investigation, they classified the materials into either bulk-, valuable- or hazardous materials (see Table 2-3).

Table 2-3: Materials considered in the study of (Müller and Widmer 2008) (scarce technology metals in italics)

Bulk materials:	aluminium, *copper*, glass, iron plastics
Valuable materials:	gold, indium, palladium, silver
Hazardous materials':	*Cadmium*, lead, leaded glass, *mercury* , plastics containing halogenated flame retardants,

As shown in Table 2-4

Table 2-4 , the material composition of the different categories is dominated by bulk materials such as glass, iron and plastics. Valuable and hazardous materials such as gold or mercury, respectively, are only found in very small quantities. An exception is the category ICT/CE, where leaded glass and plastics containing halogenated flame retardants from the group of hazardous materials account for over 30% of the mass.

The bulk materials comprise 60-90% of the total weight. The share of valuable materials is very small with a maximum of approximately 0.003% by weight in ICT/UE. The hazardous materials also contribute very little except for ICT/UE where mainly due to leaded glass and to some extent plastics containing halogenated flame retardants the share is up to 40%.

Table 2-4: **Composition in % of total weight according to (Müller and Widmer 2008)**

Material	large household appliances (LHA)	small household appliances (SHA)	information and communication technologies (ICT) and consumer electronics (CE)	lighting equipment (LE)
Aluminum	14	9.3	5.0	14
Cadmium	0.014	8.3E-03	0.018	n.a.
Copper	12	17	4.0	0.22
Glass	0.017	0.16	0.30	77
Gold	6.7E-07	6.1E-07	2.4E-04	n.a.
Indium	0	0	5.0E-04	5.0E-04
Iron	43	29	36	n.a.
Lead	1.6	0.57	0.29	n.a.
Leaded glass	0	0	19	0
Mercury	3.8E-05	1.9E-05	7.0E-05	0.020
Palladium	3.0E-07	2.4E-07	6.0E-05	n.a.
Silver	7.7E-06	7.0E-06	1.2E-03	n.a.
Plastics (w/o HFR)	19	37	12	n.a.
Plastics (w HFR)	0.29	0.75	18	3.7
Other	10	6.9	5.7	5.0

HFR: Halogenated flame retardants n.a.: data not available

It is worthwhile to note that the Swiss e-waste recycling system is, according to its documented mass balance, efficiently recovering gold but dissipates almost all of the indium (see Figure 2-1 and Figure 2-2). Currently batch tests are conducted to confirm this conclusion with detailed analysis of all output fractions at a major Swiss e-waste recycler.

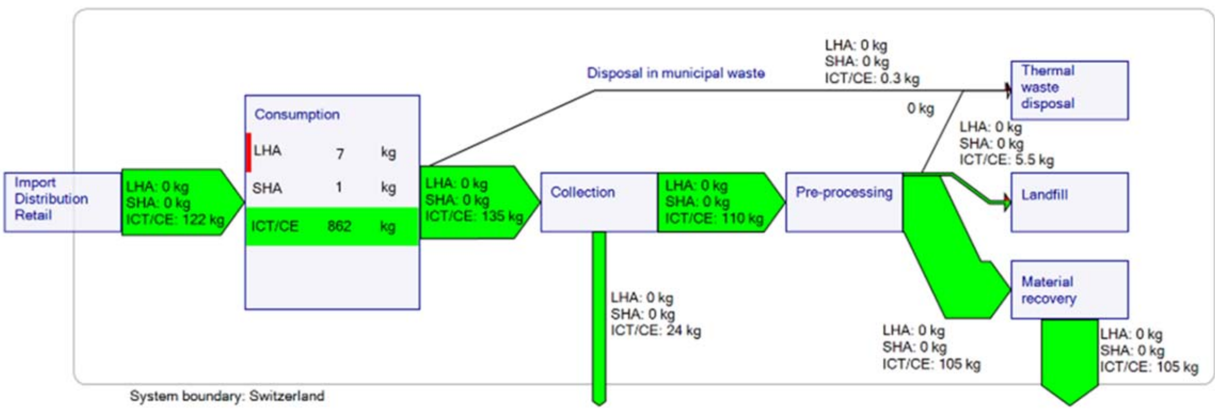

Figure 2-1: **Gold flows in Switzerland linked to specific EEE categories for 2006 (Müller and Widmer 2008)**

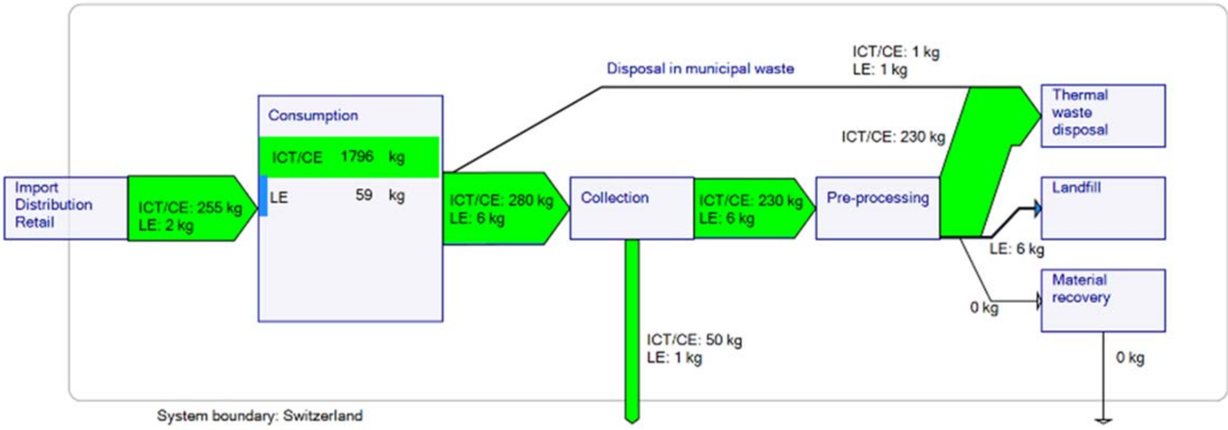

Figure 2-2: Indium flows in Switzerland linked to specific EEE categories for 2006 (Müller and Widmer 2008)

2.2 Technological developments

Because many scarce metals addressed in Figure 1-1 are considered to be essential for emerging technologies, their demand in the coming years is expected to increase rather than to decline. In a comprehensive study, (Angerer et al. 2009) applied a bottom-up methodology based on a technological and economic innovation analysis for 32 selected emerging technologies to derive possible future technology metal needs. According to (Angerer et al. 2009), the global supply of several technology metals in the year 2030 is expected to significantly exceed their global production in the year 2006 (see Table 2-5).

Table 2-5: Demand indicators (total metal demand from selected emerging technologies/ metals production in 2006) for selected technology metals in the years 2006 and 2030 according to (Angerer et al., 2009) and (Elsner et al. 2010)

	Demand indicator 2006	Demand indicator 2030	Future technology responsible for demand increase
Gallium	0.18[1)]	3.97[1)]	Thin-film photovoltaics, Integrated circuits, WLED
Indium	0.40[1)]	3.29[1)]	Displays, Thin-film photovoltaics
Scandium (REE)	0	2.31[1)]	Fuel cells (SOFC), Alloying element for aluminium
Germanium	0.28[1)]	2.20[1)]	Glass fiber cables, IR optical technologies
Neodymium (REE)	0.23[1)]	1.66[1)]	Permanent magnets, Laser technology
Platinum (PGM)	0	1.35[1)]	Fuel cells, Catalysis
Tantalum	0.40[1)]	1.02[1)]	Micro capacitors, Medical technology
Silver	0.28[1)]	0.83[1)]	RFID, Lead free solders
Tin	0.57[1)]	0.71[1)]	Lead free solders, Transparent electrodes
Cobalt	0.21[1)]	0.43[1)]	Lithium ion accumulators, XtL technologies
Palladium (PGM)	0.09[1)]	0.29[1)]	Catalysis, Seawater desalination
Titanium	0.08	0.29	Seawater desalination, implants
Copper	0.09	0.24	Efficient electro motors, RFID
Selenium	0	0.08[1)]	Thin film photovoltaics, Alloy element
Ruthenium (PGM)	0	0.03	Dye-sensitized solar cells, Titanium alloy element
Niobium	0.01	0.03	Micro capacitors, Ferroalloys
Yttrium (REE)	0	0.01	High temperature superconductivity, Laser technology
Antimony	<0.01	<0.01	ATO, Micro capacitors
Chromium	<0.01	<0.01	Seawater desalination, Marine technologies

[1)] Recalculated on the basis of newer production data by (Elsner et al. 2010)

As a matter of course, such projections are associated with big uncertainties regarding, in particular, the effective diffusion rates of emerging technologies and their material composition; the latter will also be a function of materials innovations - including e.g. a substitution of critical elements. Nevertheless, from the perspective of the prevention principle, such possible future realities will help to reflect and identify potential negative impacts of technological developments and to specify and discuss intervention options.

The perspective of about 25 years as applied by e.g. (Angerer et al. 2009) or (Thielmann et al. 2010) appears to make sense for a bottom up assessment of technology evolution. However, it has to be kept in mind that with such an approach disruptive technologies will be out of scope, although such technologies could induce revolutionary changes and reshape the need for scarce technology metals.

2.2.1 Focus 1: Display technologies

In a recent study, (Benedetti and Zumbühl 2010) modelled the stocks and flows of the metals mercury and indium in Switzerland related to display technologies for the time period of 2000 to 2030. Current Flat Panel Display (FPD) technologies require mercury containing backlight units i.e. cold cathode fluorescent lamps (CCFL–LCD) for certain types of liquid crystal displays (LCD) and indium for transparent conductors (indium tin oxide, ITO). However, FPDs based on different display technologies (such as Plasma, Light Emitting Diodes (LED-LCD), and Organic LED (OLED) will rapidly succeed each other (see Figure 2-3). These new FPDs contain varying amounts of indium but no mercury. According to the authors of the study, the mercury stocks and flows stemming from CCFL-LCDs will presumably reach its peak in 2013, with 36 kg per year (see Figure 2-4) and diminish to nil within a decade. The total mercury load from FPD disposal between 2000 and 2030 is expected to add up to 388 kg. Annual indium loads are assumed to peak at 115 kg and will presumably start to decrease from 2017 on, if OLED displays manage to replace LCDs in the market (see Figure 2-4). The total indium load from FPD disposal between 2000 and 2030 is expected to amount to2'065 kg of indium.

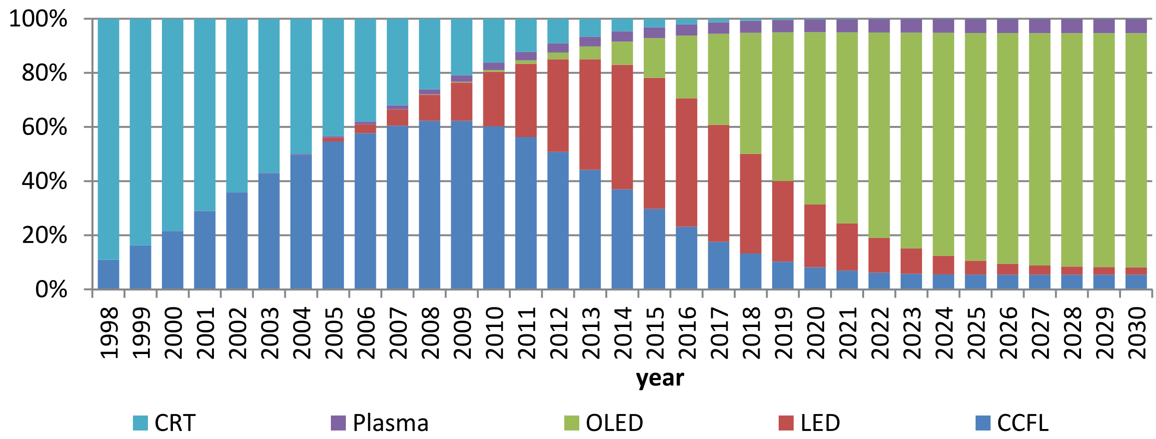

Figure 2-3: Development of the market penetration of display technologies between 2000 and 2030 (Benedetti and Zumbühl 2010)

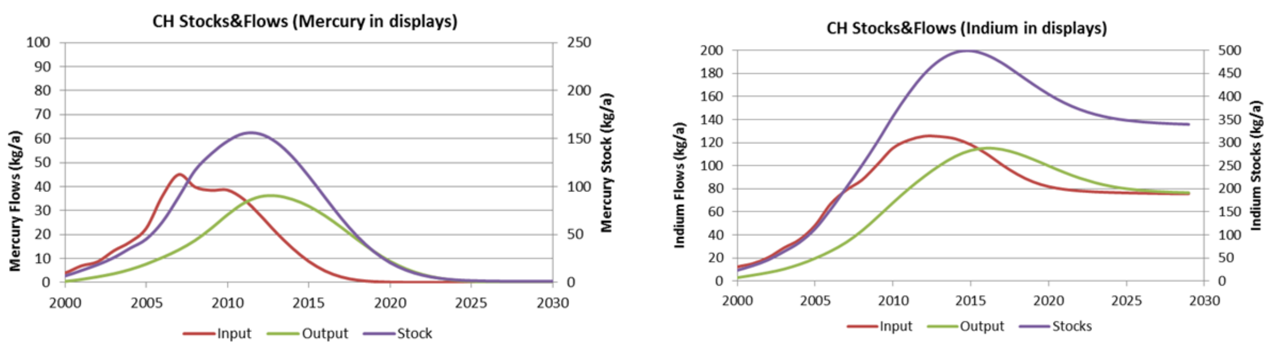

Figure 2-4: Development of mercury - (left diagram) and indium (right diagram) stocks and flows induced by Flat Panel Displays (Benedetti and Zumbühl 2010)

Due to the steep sales increase, flat panel displays (FPD) are replacing the cathode ray tube (CRT) displays (see Figure 2-3). As a consequence, it becomes increasingly difficult to find markets for the leaded glass from CRTs and the risk to dissipate lead in 'down-cycle' applications increases. The issue of dissipation is even more pronounced with indium, which the Swiss recycling system is currently unable to recover (see section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

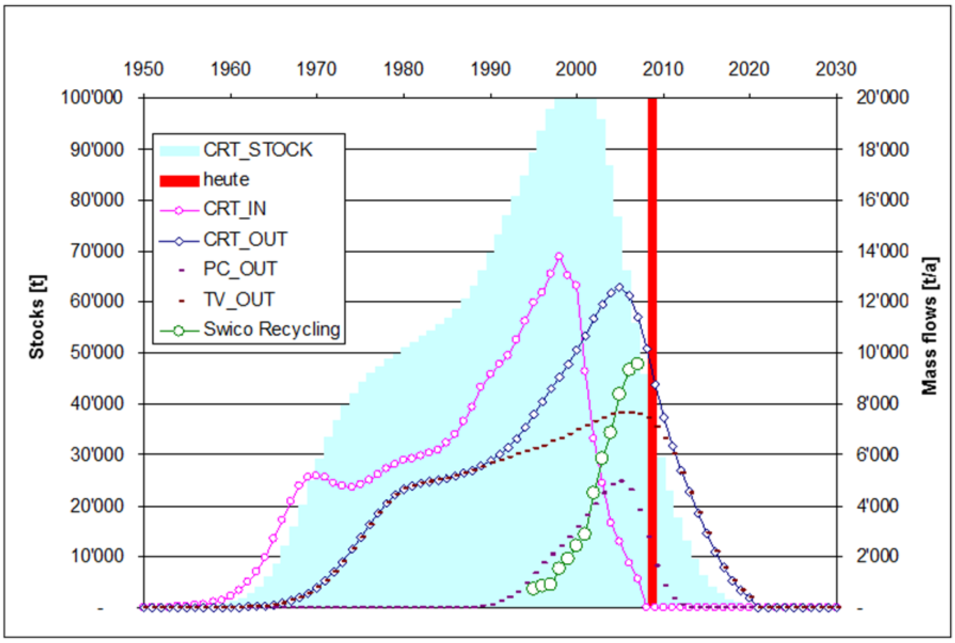

Figure 2-5: Development of CRT stocks and flows in Switzerland ((Widmer 2009))

A possible mitigation strategy to avoid dissipation would consist in an intermediate storage of End-of-Life (EoL) equipment or relevant components to bridge the time until market prices and/or technologies would allow for a recovery of the metals contained in these parts. In a report published for SWICO Recycling data of (Benedetti and Zumbühl 2010) was used to estimate volumes and costs of storing the indium containing parts of FPD (Faulstich et al. 2010). With current technologies, the FPD would have to be dismantled manually, which adds significantly to the costs of such a solution; however, the potential material and value recovery also increases significantly due to the high purity of the resulting fractions. The market value of the peak recoverable indium from FPD in Switzerland (to be reached in 2017 at 115kg/a) would amount to USD66'000[2]. This amount will most likely not trigger investments in indium recovery technologies, and additional payments will be required into the foreseeable future. Assuming that indium prices increase and technologies advance, storage might be a practicable solution.

Table 2-6 shows the required storage volumes for 2012, 2016 and 2020, if all EoL flat panel displays would be dismantled and the LCD and OLED panels stocked.

Table 2-6: Volume estimates for an intermediate storage of FPD in Switzerland (Swico recycling report, unpublished)

[2] Indium price according to www.mineralprices.com; October 26, 2010: USD576

	LCD-Panels 2012			2016		2020	
	[m³/pcs]	[pcs]	[m³]	[pcs]	[m³]	[pcs]	[m³]
PC FPD Monitors*	0.00036	479'000	172	597'000	215	711'000	256
TV FPD**	0.00352	158'000	556	474'000	1'668	706'000	2'485
Laptops***	0.00018	465'000	84	876'000	158	1'293'000	233
TOTAL			812		2'041		2'974

* width 30cm, length 40cm, height 3mm

** average size 36": width 44cm, length 80cm, height 1cm

*** width 20cm, length 30cm, height 3mm

The total volume to be expected reaches about 15'000 m^3 in 2020, which would fit in a storehouse of 10m height and covering an area of 1'800 m^2 (incl. 20%). Assuming an annual rental cost of 80 CHF/m^2 and an upscale of the rented storage area according to the need, this accumulates to approx. 0.8 Mio. CHF for the next decade. This would offset the respective, cumulated incineration costs of 0.9 Mio CHF[3]. Additional returns from secondary raw material sales from dismantled fractions could improve this balance even further.

2.2.2 Focus 2: Lithium batteries

Modelling stocks and flows for even longer time periods is associated with many more uncertainties, making predictions a rather impossible undertaking. Nevertheless, for elements which cannot easily be substituted due to exceptional properties, a dynamic model still might give very valuable insights. This appears to be the case for e.g. lithium, which is expected to play a key role in rechargeable (secondary) batteries for traction uses, in particular because it is the lightest metal and has the highest electrochemical potential, which allows for exceptionally high volumetric and gravimetric energy storage capacity compared to other metals (see Figure 2-6).

[3] Incineration of the FPD modules is current practice! assumption: specific weight of FPD 300 kg/m^3, incineration costs CHF200

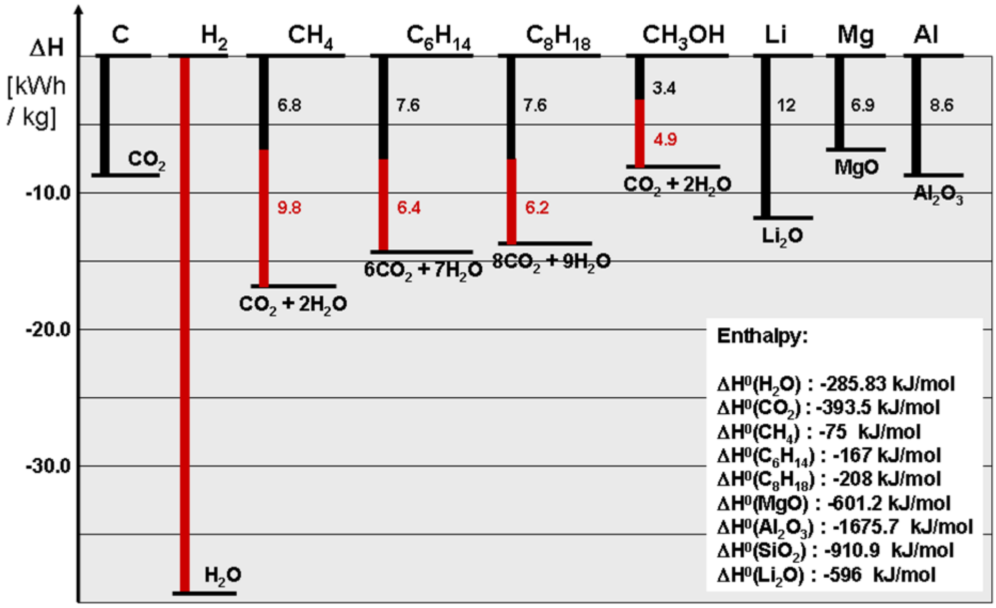

Figure 2-6: Specific enthalpies for various energy carriers

In a recent master thesis (Carles 2010), the global lithium stocks and flows were modelled to determine the depletion of the natural lithium resources and the importance of recycling for four scenarios, covering a time period of almost two centuries:

- The lithium flow distribution between the four sources: brines, ores, sea water and EoL equipment (recycling) depends only on the optimisation of the total energy requirements for the extraction and refining processes (Base case scenario).
- The extraction from the lihium rich brines is limited to 20kt/a[4] for strategic, political, economic, environmental or social reasons (OLiEC[5] scenario).
- A protectionist approach is adopted by some countries subsidising 20kt/a lithium extraction from sea water even if the process is uneconomic and very energy intense (South Korean scenario).
- A major investment is done in lithium recycling plants imposing a certain recycling target (Swiss scenario).

The results of the simulations showed, amongst others, that the scenario with the most important flows of secondary lithium is not, as one could have expected, the 'Swiss scenario', which aims at enforcing recycling, but the OLiEC scenario, because recycling appears to be the second best option to produce lithium after brines from an energy perspective (see Figure 2-7).

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4 20kt/a is the current global production rate of lithium

5 Fictitious Organisation of the Lithium Exporting Countries, named in analogy to OPEC.

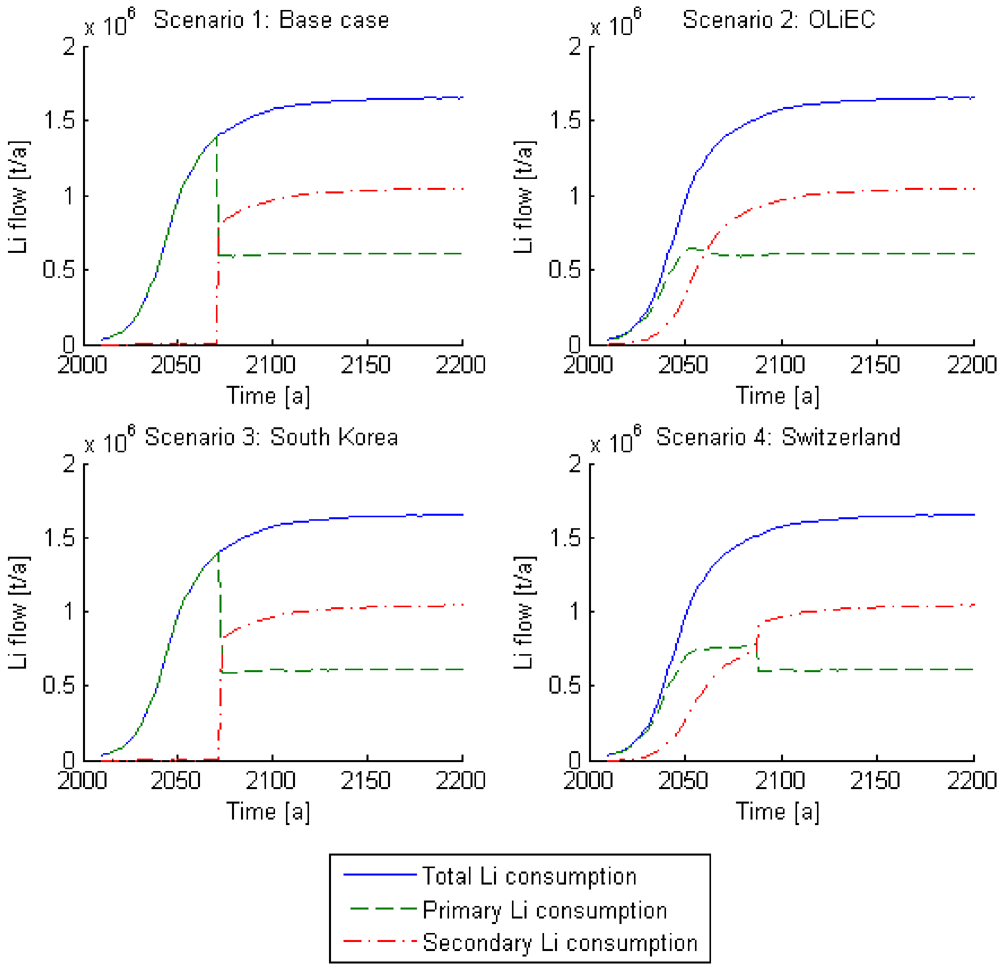

Figure 2-7: Primary and secondary lithium in the consumption for the four scenarios (Carles 2010)

According to (Grosse 2010), a sustainable development in a world of finite resources is only possible with two types of delinking: first a fundamental delinking between the creation of added value and the raw material consumption, which is translated into a stabilization or even a decrease in raw material consumption; second a relative delinking between the consumption of total raw material and the consumption of primary raw material, i.e. an increase of the recycling rate. By considering that recycling is not sufficient but has to be combined with stabilized or decreasing raw material consumption, (Grosse 2010) wonders if it is useful to recycle during the periods of exponential growth, as it only allows to gain a couple of years of consumption, whilst recycling during a stabilized consumption period allows to slow down the consumption by a proportionality factor.

3 The 'criticality' of technology metals

In the past few years, several research projects and working groups have addressed potential supply risks and 'criticalities' of scarce technology metals. Following, recent studies addressing potential scarce metals supply risks and criticalities with regard to (i) specific emerging technologies and (ii) different political contexts (the United States of America and the European Union) will be presented and discussed with regard to their scope, the evaluation methodologies applied and their main outcomes (see also the overview in Annex I). The studies were selected with the intention to give a representative overview of existing comprehensive evaluations on the criticality of scarce metals. Reports on criticalities issued on a national level e.g. in Austria, France or the UK (see (Commission of the European Communities 2008), annex 8) were not considered.

In Table 3-1 the outcomes of the supply risk and criticality studies presented below are summarised, with the metals most often mentioned to be critical marked in red. For the interpretation of the results it has to be kept in mind that criticality assessments are always made from the perspective of a particular system (e.g., company, sector, country, global society) with specific supply risks and impacts of supply disruption (Schüler et al. 2011).

Table 3-1: Metals for which supply risks or criticalities were identified in selected, comprehensive studies

	United States (NRC, 2008)	European Union (EC, 2010)	Electronics		Green technologies (Buchert et al., 2009)	Clean energy technologies (DOE, 2010)
			(Behrendt et al., 2007)	(Elsner et al., 2010)		
Antimony						
Beryllium						
Cobalt						
Gallium						
Germanium						
Gold						
Indium						
Lithium						
Niobium						
PGMs	Pd,Pt,Rh		Ir,Pd,Pt,Rh,Ru		Pd,Pt	
REE				Nd, Dy, Pr, Tb		Dy,Eu,Nd,Tb
Rhenium						
Tantalum						
Tellurium						
Tin						
Tungsten						

In orange and italics: Metals identified to be critical or to have an elevated supply risk in more than two study.

3.1 Minerals and raw materials criticalities in different political contexts

a) Minerals criticality in a U.S. context

The Committee on Critical Mineral Impacts on the U.S. Economy (National Research Council 2008) assessed the degree of criticality of selected nonfuel minerals with a matrix methodology (see Figure 3-1). According to the Committee, to be critical a mineral must be both essential in use (represented by the vertical axis of the matrix) and subject to supply restriction (the horizontal axis of the matrix).

To evaluate potential supply restrictions (the horizontal axis), the Committee considered two time scales of interest and defined short- to medium term , and long-term criteria for availability and reliability of supply (National Research Council 2008). In the short to medium term (a few months to a few years, but less than a decade), availability and reliability of supply can be assessed using a variety of market-specific factors for supply risk such as worldwide mineral reserve-to-production ratios, world-by-product-production, U.S. secondary production (through scrap and recycling), import dependence or the degree to which production is concentrated in a small number of companies or countries. Over the long-term (more than about 10 years), availability is a function of geologic, technical, environmental and social, political, and economic factors for primary availability, and technical, environmental and social, political and economic factors for secondary availability. According to (National Research Council 2008), a balanced interpretation of all of these factors in terms of examination of supply risk is highly dependent on good domestic and global data on nonfuel minerals and mineral markets and comprehensive and reliable analysis of such data.

For the assessment of importance of minerals in use (vertical axis), the committee evaluated the degree of importance (or impact of supply disruption) for each important application or end use of a specific mineral in the context of the US Economy. Here, the evaluation is based on the judgment of the committee and considers questions such as: What is the technical substitution potential in a particular end use? If a technical substitution is possible, what are the economic consequences? (National Research Council 2008).

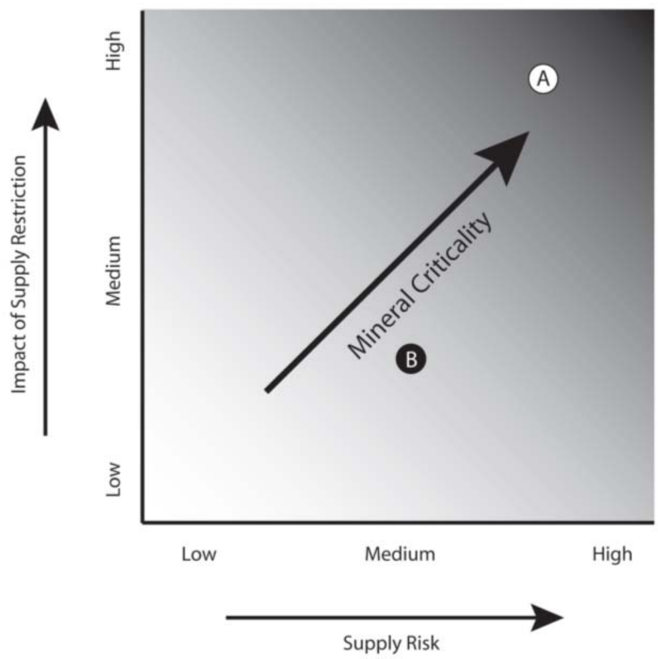

Figure 3-1: Criticality matrix according to (National Research Council 2008). The degree of criticality increases as one moves from the lower-left to the upper-right corner of the figure. In this example, mineral A is more critical than mineral B.

The Committee applied the criticality matrix to 11 minerals/mineral groups: copper, gallium, indium, lithium, manganese, niobium, platinum group metals (metals palladium, platinum and rhodium), rare earth elements, tantalum, titanium, and vanadium. According to the evaluation, the most critical nonfuel minerals are the platinum group metals, rare earth elements, indium, manganese and niobium (see Figure 3-10 and Figure 3-2).

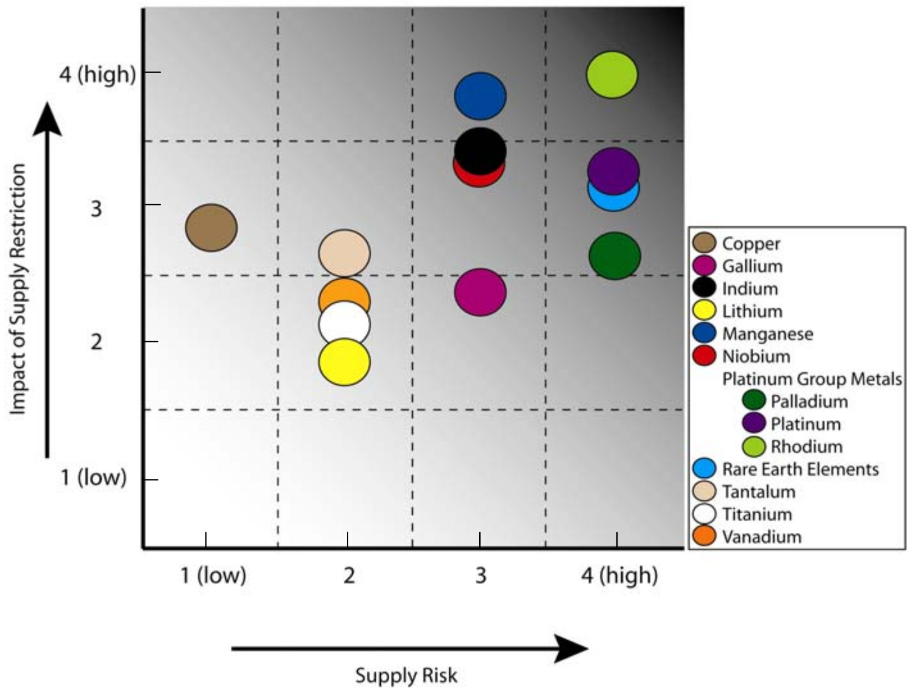

Figure 3-2: Criticality of the nonfuel minerals evaluated by (National Research Council 2008)

b) Minerals criticality in a European Union context

In a recent report the ad hoc working group on defining critical raw materials, which is a subgroup of the Raw Materials Supply group chaired by the European Commission, evaluated the criticality of 41 selected non-energy raw materials (European Commission 2010). The ad hoc working group classifies a raw material as 'critical' when the risks of supply shortage and their impacts on the economy are higher compared to most of the other raw materials. Hereby, the ad hoc working group considers two types of risks:

i. the 'supply risk', which takes into account the political-economic stability of the producing countries, the level of concentration of production, the potential for substitution and the recycling rate; and

ii. the 'environmental country risk' which addresses the risk that measures might be taken by countries with weak environmental performance in order to protect the environment and, in doing so, endanger the supply of raw materials to the European Union (EU).

According to the methodology applied by (European Commission 2010), either high supply risk or environmental country risk is sufficient to qualify a raw material for criticality, provided that its economic importance is above a defined threshold (see Figure 3-3).

The authors of the study claim that they apply an innovative and pragmatic approach to determine criticality, in particular because it

- considers three main aggregated indicators or dimensions, which are calculated for each raw material, namely (i) the economic importance of the considered raw material, (ii) its supply risk (for instance restrictive measures from resource-rich countries) and (iii) an environmental country risk assessing the potential for environmental measures that may restrain access to deposits or the supply of raw materials.

- takes into account the *substitutability* between raw materials, i.e. the potential for substitution of a restricted raw material by another one that is not faced with similar restrictions. In case of easy substitutability, the supply risk is adjusted downward.
- deals with both primary and *secondary raw materials*, the latter being considered as similar to an indigenous European resource. It symmetrically addresses risks on imports and risks on access to European deposits.
- introduces a *logical* way to aggregate indicators. For instance the economic importance is calculated by adding the value–added of user sectors weighted by their relative share in the overall use of the raw material. This contrasts with some other studies where the different values of indicators are apparently simply added up without any underlying rationale.
- makes use of widely *recognised* indexes. For instance it applies a Herfindahl-Hirschman index[6] (HHI) to aggregate risks in order to take into account the concentration of risks. The supply risk is indeed all the more important when the countries represent a higher share of worldwide production or exportation.
- presents a *transparent* methodology. The applied methodology allows direct assessment of the relative contribution of the different factors to criticality thus facilitating the justification for policy recommendations.

To assess the economic importance EI_i of a raw material, its main uses were broken down and the value added of the economic sector that has this raw material as an input was attributed to each of them. The study introduces the concept of "megasectors" to approximate value added chains. In this approach the usual NACE[7] codes have been regrouped or broken down with a view to describing value-added chains. All results were scaled to fit in the range from 0 to 10, with higher scores indicating higher economic importance.

The assessment of the supply risk SR_i included the following elements, which were finally aggregated into one supply risk indicator:

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[6] The Herfindahl-Hirschmann Index (HHI) is widely applied in competition and anti-trust proceedings or assessments. Increases in the HHI indicate a decrease in competition and an increase of market power, whereas decreases indicate the opposite. In the study of the ad hoc group, increases in the HHI indicate a higher supply risk which will be all the more difficult to overcome if the risky countries are responsible for a large part of worldwide production.

[7] NACE stands for 'Nomenclature statistique des activités économiques dans la Communauté européenne'

- an estimation of how stable the producing countries are. This is done by using the Worldwide Governance Indicators (WGIc) provided by the World Bank8 and aggregating them into an HHI based on the share of the country (c) in the world production data (Sic);
- the extent to which a raw material i may be substituted, which was estimated by experts to lie between easily and completely substitutable at no additional cost (value: 0) and not substitutable (value: 1).
- the extent to which raw material needs are met by recycling, quantified as the ratio of recycling from old scrap9 to European consumption.

All results were scaled so that the values of SRi lie between 0 and 10, with higher values indicating high supply risk

The assessment of the environmental country risk EM_i was done in analogy to the assessment of the supply risk by replacing the HHI calculated on the basis of World Governance Indicators with an HHI calculated on the basis of environmental performance indexes[10]. All results were scaled so that the values of EM_i lie between 0 and 10, with higher values indicating high environmental country risk.

Figure 3-3 shows the results of the evaluation of criticality from the supply risk perspective. The ad hoc working group considers the sub-cluster of 14 raw materials positioned in the top right corner of the figure, which are of high economic importance and have a high supply risk, to be most critical. Their high supply risk is mainly due to the fact that a high share of the worldwide production comes from China (antimony, fluorspar, gallium, germanium, graphite, indium, magnesium, rare earths, tungsten), Russia (PGM), the Democratic Republic of Congo (cobalt, tantalum) and Brazil (niobium and tantalum) (see Figure 3-4). The ad hoc working group emphasizes that production concentration, in many cases, is compounded by low substitutability and low recycling rates (European Commission 2010).

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[8] see http://info.worldbank.org/governance/wgi/sc_country.asp

[9] 'old scrap' refers to raw material which has been recycled at the end of the life product from products in which it is incorporated, whereas 'new scrap' refers to scrap resulting from the processing of raw material from primary sources.

[10] see http://epi.yale.edu/

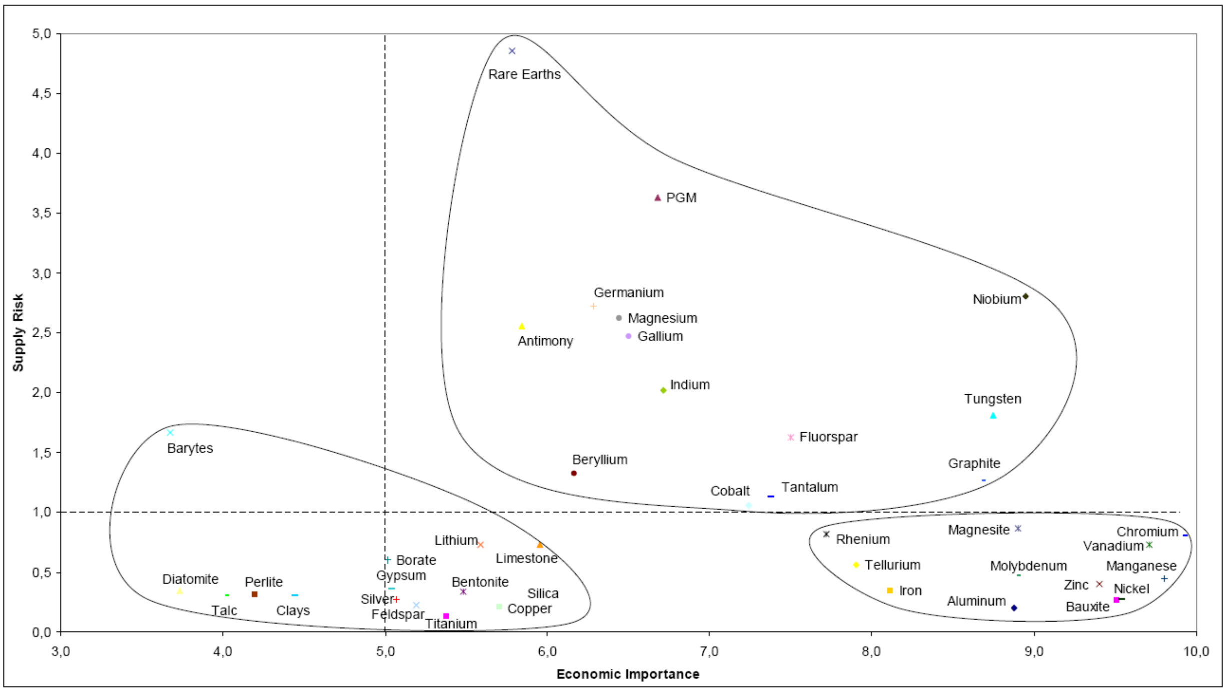


Figure 3-3: Criticality of raw materials evaluated by the ad hoc working group on defining critical raw materials of the EC according to (European Commission 2010)

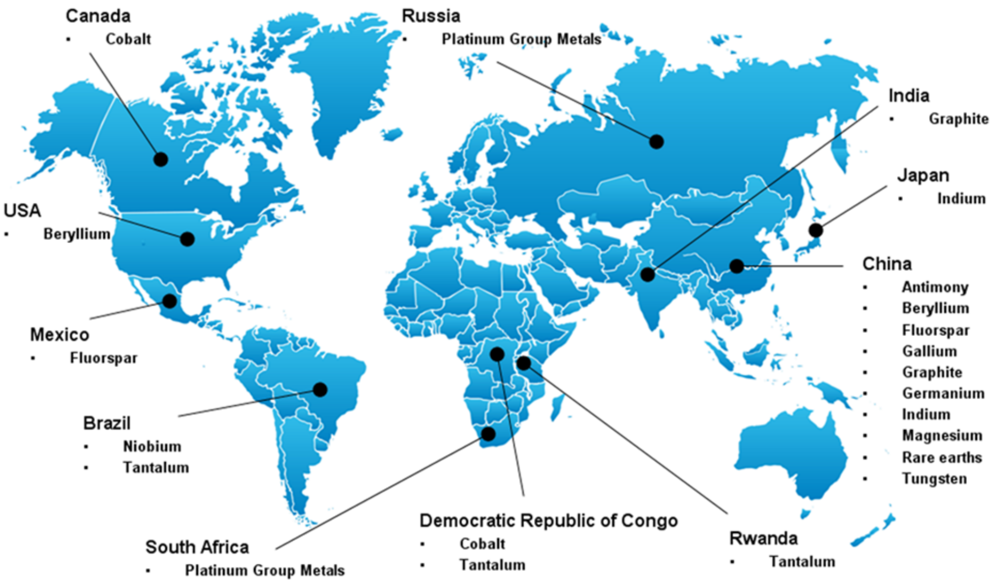


Figure 3-4: Production concentration of critical raw materials (http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm)

The evaluation of economically important raw materials from their environmental country risk perspective (see Figure 3-5) showed that there is a subgroup of materials with high environmental country risk (i.e. over a threshold set at 1.2). In ascending order: PGMs, tungsten, graphite, fluorspar, indium, beryllium, niobium, gallium, magnesium, antimony, germanium and REE. Compared to the criticality evaluation according to the supply risk (see Figure 3-3), no materials would need to be added to the list of critical raw materials on the basis solely of high environmental country risks (European Commission 2010).

Figure 3-5: Ranking of economically important raw materials according to their environmental country risk (National Research Council 2008, European Commission 2010, Wäger et al. 2010)

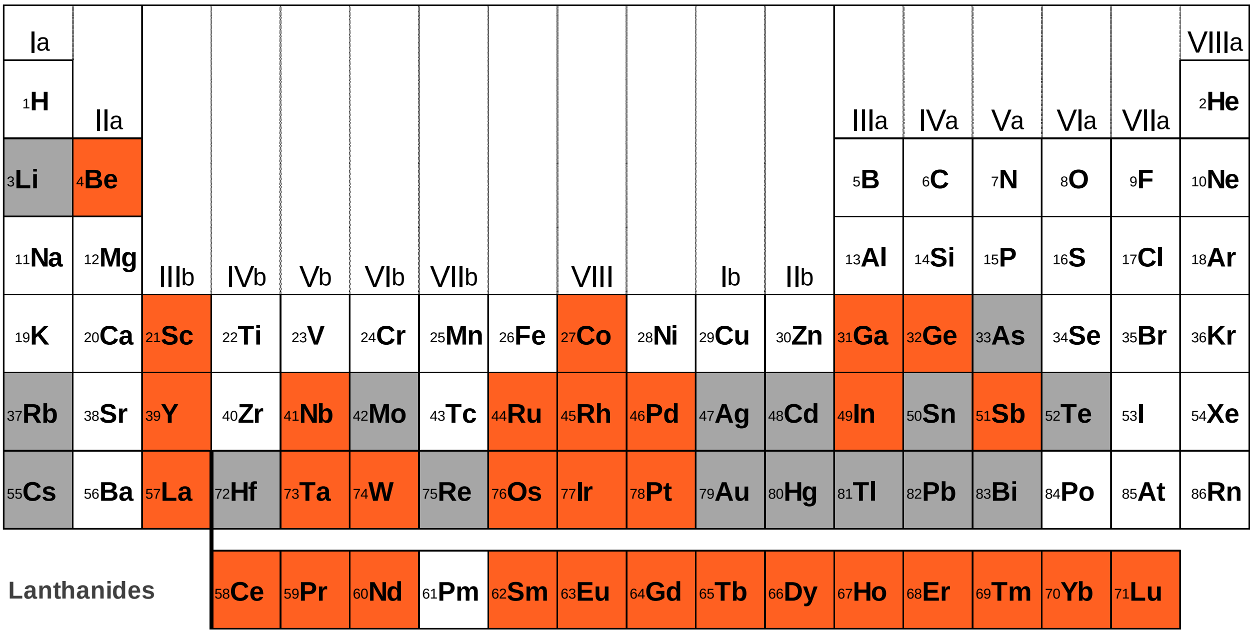


Figure 3-6: Scarce metals considered to be critical for the European Union (grey shaded elements: geochemically scarce metals; red coloured elements: critical according to (European Commission 2010)); radioactive elements were not considered.

3.2 Studies evaluating scarce metals criticality with a focus on specific technologies

a) The criticality of metals for future sustainable technologies

In a study commissioned by the United Nations Environmental Programme (UNEP), (Buchert et al. 2009) investigated 'green minor metals', i.e. metals essential for future sustainable technologies. (Buchert et al.

2009) evaluated the following metals, which they allocated to four major 'future sustainable technology' application clusters:

- indium, ruthenium and tantalum (EEE Technologies),
- gallium, germanium and tellurium (photovoltaic technologies),
- cobalt and lithium (battery technologies) and
- palladium, platinum, REE (catalysts).

The 'green minor' metals and 'future sustainable' technologies considered by (Buchert et al. 2009) are summarised in Figure 3-10.

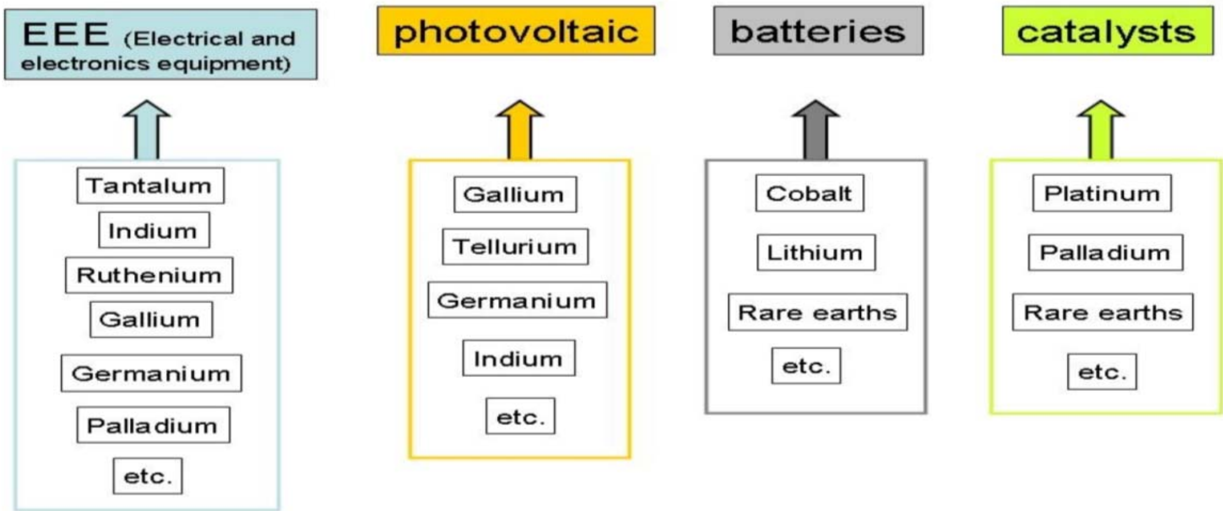


Figure 3-7: Application cluster and corresponding green minor metals according to (Buchert et al. 2009)

The objectives of the study of (Buchert et al. 2009) were (i) to make an in-depth analysis of the global availability and expectations for the development of the 'critical metals' demand, supply and prices, (ii) to comprehensively analyse their recycling potential and to identify gaps, and (iii) to explore favourable framework conditions, proposed course of actions, policies, incentives, funds, instruments, models etc. to predict and monitor the availability of critical metals.

In order to prioritise the different metals with a focus on the attribute 'critical', (Buchert et al. 2009) applied different sub-criteria related to demand growth, supply risks and recycling restrictions (see

Table 3-2).

Table 3-2: Sub-criteria for the evaluation 'green minor metals' according to (Buchert et al. 2009)

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

Depending on the number of sub-criteria fulfilled, supply risks and recycling restrictions were classified as low, moderate or serious, and demand growth as slow, moderate or rapid. Under consideration of the classification results, the metals were prioritised with regard to a timeline as 'critical' in a short-term perspective (next 5 years), in a mid-term perspective (until ca. 2020) or in a long-term perspective (2050).

The results of the prioritisation of these metals along the timeline are summarized in Table 3-3.

Table 3-3: Prioritisation of metals evaluated by (Buchert et al. 2009) with regard to the timeline

Timeline and associated criteria	Metal
Short-term (< 5 years) Rapid demand growth Serious supply risks Moderate recycling restrictions	- Tellurium - Indium - Gallium
Mid-term (until 2020) Rapid demand growth and Serious recycling restrictions or Moderate supply risks Moderate recycling restrictions	- Rare Earth Elements - Lithium - Tantalum - Palladium - Platinum - Ruthenium
Long-term (until 2050) Moderate demand growth Moderate supply risks Moderate recycling restrictions	- Germanium - Cobalt

b) *The criticality of metals for clean energy technologies*

The U.S. Department of Energy (U.S. DOE) evaluated the criticality of cobalt, gallium, germanium, indium, lithium, tellurium as well as of nine rare earth elements with regard to four selected clean energy technologies (wind turbines, electric vehicles, photovoltaics, and energy-efficient lighting) (U.S. DOE 2010b) Basically, it applied the same methodology as (National Research Council 2008), with the main difference that the "Impact of Supply Disruption" was reoriented to become "Importance to Clean Energy", (ii) the attributes used to characterize "Supply Risk" were adjusted and (iii) the assessments were completed separately for both short- and medium-term criticality, as these two time horizons have different supply and demand profiles and also different policy options. The evaluation of the U.S. DOE resulted in the following most critical elements: dysprosium, europium, indium, neodymium, terbium and yttrium in the short term, and all these elements except indium in the medium term (see Figure 3-8 and Figure 3-9). The U.S. DOE explicitly states that its report addresses neither the material needs of the entire economy, nor the entire energy sector nor even all clean energy technologies (U.S. DOE 2010b).

In a recent report, (Hatch 2011) evaluated a set of projections for the future supply the rare-earth metals identified to be most critical by the U.S. DOE. According to their evaluation, the following five elements are at greatest risk, in order of descending risk: 1. Dysprosium, 2. Yttrium, 3. Terbium, 4. Europium and 5. Neodymium.

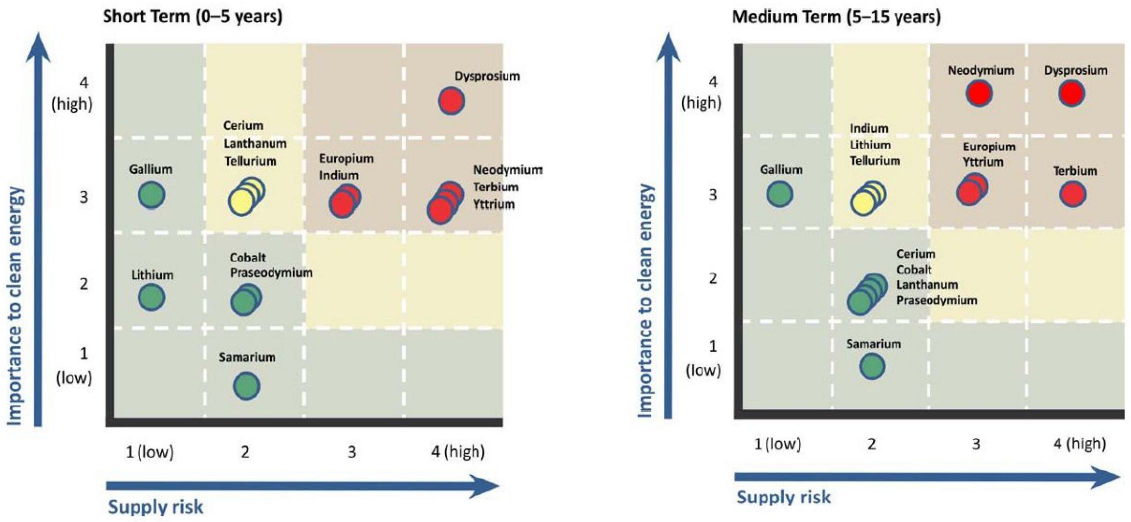


Figure 3-8: Short- term (figure left) and medium-term (figure right) criticality according to (U.S. DOE 2010b)

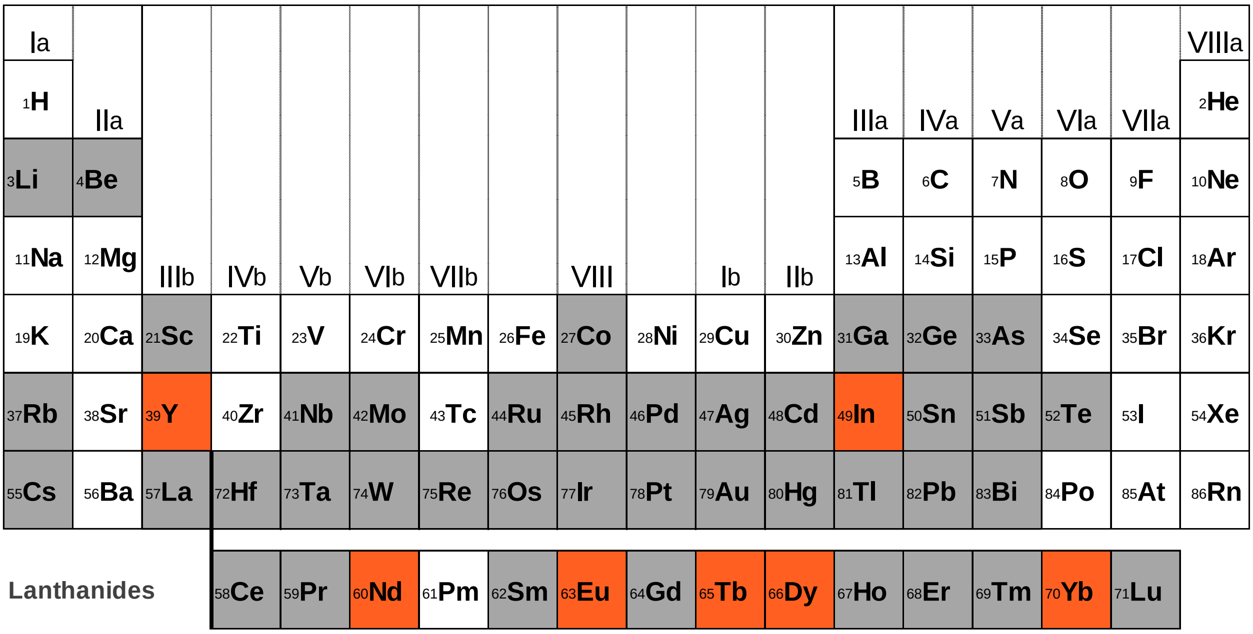


Figure 3-9: **Scarce metals considered to be critical in the short – and medium term for clean energy technologies (grey shaded elements: geochemically scarce metals; red coloured elements: critical according to (U.S. DOE 2010b)); radioactive elements were not considered.**

c) Potential supply risks for selected metals used in ICT

In a contribution for the publication series 'Commodity Top News' of the German Federal Institute for Geosciences and Raw Materials (BGR), (Elsner et al. 2010) showed in which industry sectors the scarce metals gallium, indium, scandium, germanium, neodymium and tantalum are applied, where they are extracted, which are the known stocks and how the supply situation could change until the year 2030. The metals evaluated had previously been identified in a comprehensive study by (Angerer et al. 2009) to be subject to a significant increase in demand from future technologies in the year 2030 compared to 2006 (for more details see section 2.2). According to (Elsner et al. 2010), an enhanced supply risk exists for germanium and neodymium, in particular. For germanium the authors recommend an investigation of the recycling potential and of the potential of germanium and other scarce elements in worldwide raw materials deposits (in Germany for example in domestic and imported coal). For neodymium and other REE (in particular dysprosium, terbium and praseodymium), for which the authors expect the supply restriction to persist until the year 2030 even if the large-scale project Kvanefjeld in Greenland is realized, it is not clear at the moment, how the provision gap will be closed (Elsner et al. 2010).

d) The 'rarity' of metals used in ICT

In a study primarily focused on coltan extraction in the Democratic Republic of Congo, (Behrendt et al. 2007) provided an overview of metals used in electrical and electronic equipment (see Figure 3-10) and evaluated what they called the 'rarity' of the identified metals. The study focused on metals rather than on minerals, amongst others because minerals are rarely used in the manufacturing of products and processes or because chemical and substance lists and databases usually only refer to the pure forms of substances (Behrendt et al. 2007).

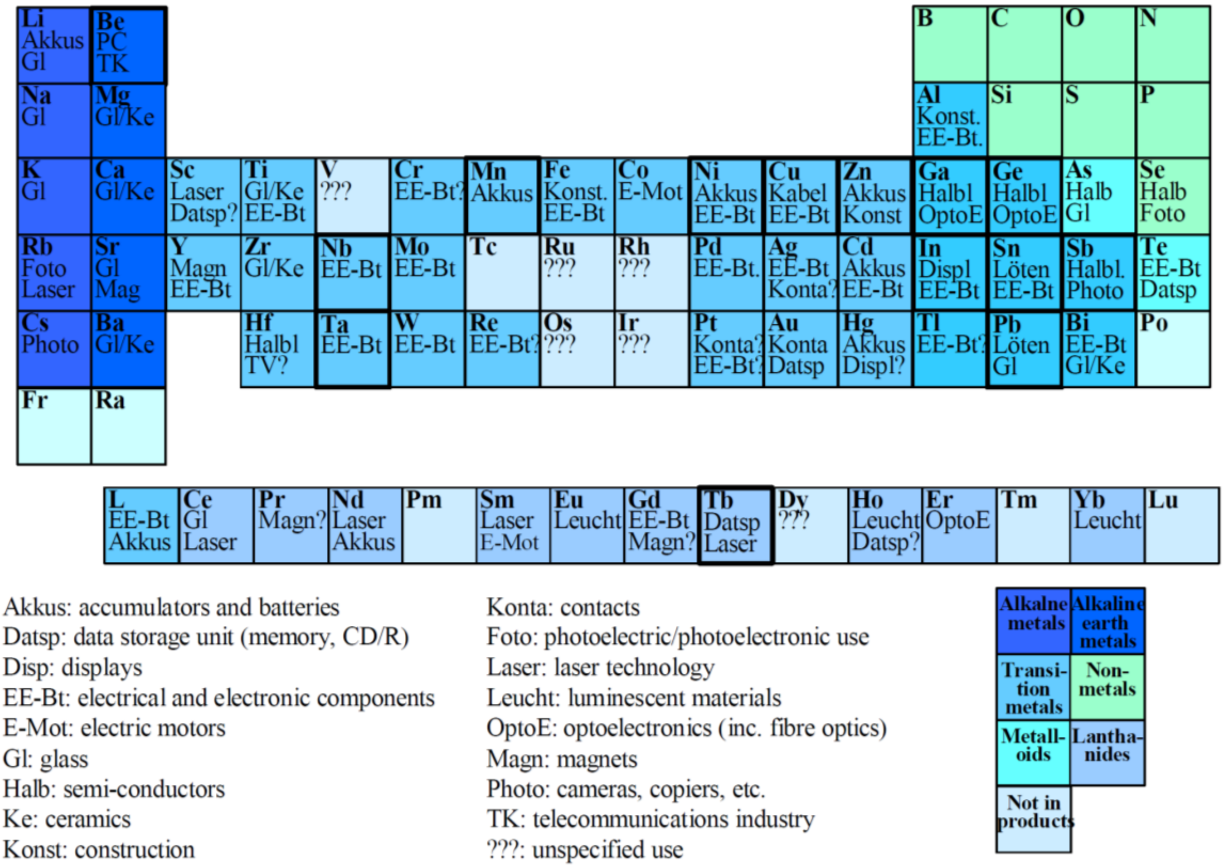


Figure 3-10: Use of metals in electrical and electronic equipment (EEE) (Behrendt et al. 2007)

For the evaluation of the 'rarity' of metals used in electrical and electronic equipment (EEE), (Behrendt et al. 2007) applied the following criteria:

- Price: metal prices of more than US $500 per kilogram;
- Price increase: a rise in the price of metals in excess of 100% in the period from 2001 to 2004;
- Scarcity of reserves: reserves lasting under 25 years, based on production figures for 2004;
- Scarcity of reserve bases: reserve bases lasting under 50 years, based on production figures for 2004;
- Concentration of reserves: concentration of known reserves primarily in one (> 50%) or two countries (> 65%,);
- Concentration in supply and value chain or high concentration of reserves: a high concentration in the supply and value chain, and a high concentration of reserves (>65%)

The criteria applied by (Behrendt et al. 2007) were intended to consider different time-frames: While concentrations in the supply chain, trade stability and an increase in prices are more short-term issues, their reference to reserves reflects more of a medium-term perspective.

The more criteria were fulfilled, the 'rarer' a metal was estimated to be. According to this evaluation, indium (5 criteria) and antimony (4 criteria) were found to be the rarest metals, followed by cobalt, gold, iridium, palladium, platinum, rhenium, rhodium, ruthenium, tin and zinc (3 criteria). For some metals such as beryllium, germanium, gallium, scandium, hafnium, rubidium and caesium, either no production data or no reserve estimates were found, so that they possibly could comply with more criteria. According to (Behrendt et al. 2007), it is possible that some of the metals in the platinum group would also have to be classified as fulfilling an extra one or two criteria; however little information on reserves is available for specific platinum metals.

4 The environmental dimension of 'criticality'

As shown by the ad hoc group on defining critical raw materials (European Commission 2010), the Committee on Critical Mineral Impacts on the U.S. Economy (National Research Council 2008) and (Wäger et al. 2010), the supply of scarce technology metals is of a multifactorial nature (see Figure 4-1).

Figure 4-1: **Factors affecting scarce technology metals supply**

4.1 Life cycle environmental impacts of scarce metals supply

Besides other factors, the environmental impacts of scarce metals provisioning in different phases of the life cycle may have an important influence on their supply security and hence on their criticality (see e.g. the environmental country risk indicator of the ad hoc working group on defining critical raw materials (European Commission 2010) or (Wäger et al. 2010)).

According to (UNEP 2010a), environmental impacts of metals are related mostly to the mining, extraction and refining stages (see Figure 4-2). These stages are very energy intensive and can be the cause of substantial air, water and soil pollution (see e.g. (Althaus and Classen 2005, Classen et al. 2007, Norgate et al. 2007). Typically, the environmental impacts from primary production are particularly high for underground mining and/or when extracting metals from sulphide ores ((Classen and Althaus 2005); for metals extracted from sulphide ores see Figure 6-1 in section 6.1).

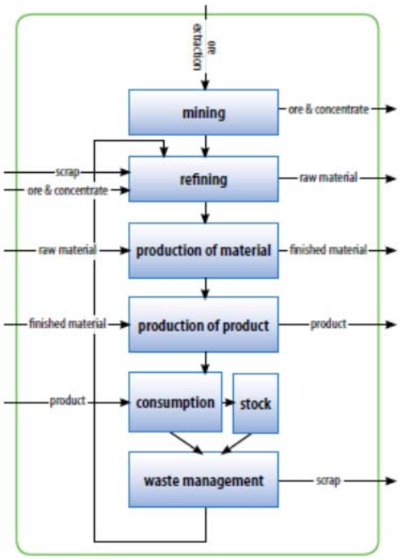


Figure 4-2: The life cycle of materials (UNEP 2010a)

According to (UNEP 2010a), energy requirements for mining and extraction today are large -roughly 7% of the world's energy use goes into the metals sector - and will increase due to falling ore grades, potentially leading to a significant impact on total worldwide energy use (see also (MacLean et al. 2010), (Norgate 2010) or (Giurco et al. 2010).

Table 4-1: Priority list of elements based on environmental impacts from mining and refining according to (UNEP 2010a)

	Impact per kg primary metals	Impact global production primary metals
1	Palladium	Iron
2	Rhodium	Chromium
3	Platinum	Aluminium
4	Gold	Nickel
5	Mercury	Copper
6	Uranium	Palladium
7	Silver	Gold
8	Indium	Zinc
9	Gallium	Uranium
10	Nickel	Silicon

Table 4-1 shows a priority list of metals based on environmental impacts from mining and refining as published by (UNEP 2010a). A ranking based on impacts per kg of produced metal puts rare metals at the top of the list. However, when multiplied with the actual amounts of metals produced, the ranking changes: the metals produced in large quantities appear to end on top.

However, the UNEP Working Group on the Environmental Impacts of Products and (UNEP 2010a) does neither describe on what data and calculations the results of Figure 4-3 are based upon, nor does it make a reference. Results of existing LCA studies for primary production of selected metals will be compiled in a forthcoming UNEP report addressing environmental impacts of metals.

At least for the impacts per kg of produced metal, their results for the specific CO_2 emissions from primary metals production are more or less confirmed by own calculations based on ecoinvent 2.1 data with primarily economic allocation ((Wäger et al. 2010); see Figure 4-3and Annex 2 for data including long-term tailing emissions). It has to be considered, however, that these results may significantly change e.g. when using other allocation methods (see e.g.).

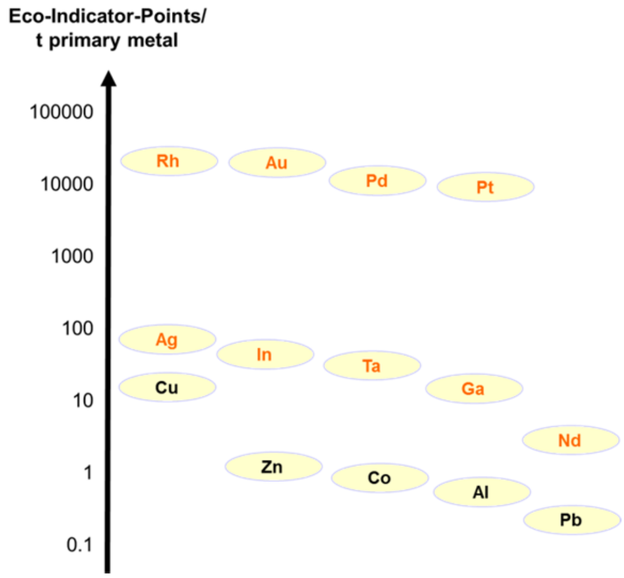


Figure 4-3: Aggregated environmental impacts (H/A) for the production of selected traditional industry metals (in black) and scarce technology metals (in red) based on ecoinvent 2.1 data and primarily economic allocation (ecoinvent Centre 2009) (Goedkoop and Spriensma 2001)

Significantly higher environmental loads for precious metals such as gold, platinum, palladium or silver than for conventional industry metals such as aluminium, lead or zinc also emerge when applying the Material Intensity per Service Unit (MIPS) method [11] (Schmidt-Bleek 1994, Ritthoff et al. 2002) (see Annex 3).

In the German project Material Efficiency and Resource Conservation (MaRess), a screening of about 70 metals was conducted to identify ten particularly environmentally relevant metals. To evaluate the environmental characteristics of the metals, the cumulated raw materials demand, the total materials requirement (TMR) and the cumulated energy demand were chosen as indicators. With regard to TMR, some metals showed high specific values but turned out to be absolutely less relevant due to a very low production volume (e.g., rhodium);other metals showed only medium specific relevance but were highly relevant from an absolute perspective due to their high production volume (e.g., tin, zinc) (see Figure 4-4)

[11]) The MIPS method calculates the material input along the life cycle, considering five resource input categories: abiotic resources, biotic resources, earth movements in agriculture and silviculture, water and air (Ritthoff et al. 2002).

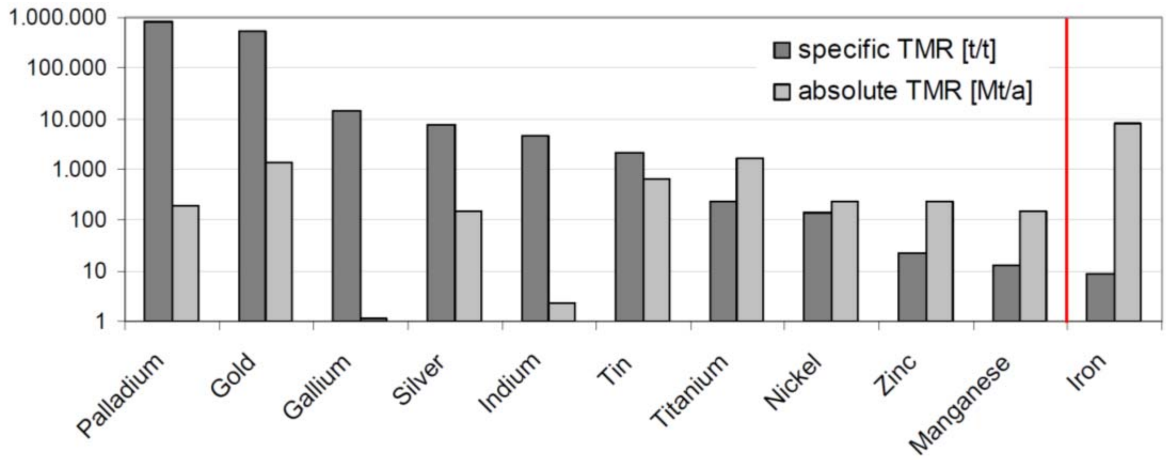


Figure 4-4: Specific and absolute Total Material Requirement (TMR) of selected metals compared to iron according to (Koch and Kohlmeyer 2009)

According to (Hagelüken and Meskers 2008), the CO_2-emissions for the recovery of metals from recyclables and smelter by-products are almost five times lower than the CO_2-emissions from primary production of metals (Hagelüken and Meskers 2008). However, (Hagelüken and Meskers 2008) did not further specify the assumptions (e.g. the allocation rules) underlying their calculations, which were made with ecoinvent v2.0 data and based on 1100 t of Ag, 32 t of Au, 32 t of Pt/Pd/Rh/Ru/Ir, 70000 t of Cu/Pb/Ni and 4100 t of Sn/Se/Te/In/Sb/Bi/As from a mixture of low-grade smelter by products and high-grade materials like EEE or catalysts.

Significantly lower environmental impacts of secondary production of precious metals such as gold and palladium are confirmed by a life cycle assessment of the Swiss WEEE Collection and Recycling systems (Wäger et al. 2011a). How far this is true for the secondary production of other scarce metals is not yet established and will depend on the specific collection, pre-pocessing and recovery processes, which either do not yet exist or are under development.

Various environmental impact assessment methods have been developed to assess resource depletion. These are based on stock ratios, static depletion time, exergy consumption and additional energy requirements, or costs for future production due to reduced ore grade (Steen 2006, Folkeson et al. 2010, UNEP 2010a). None of these methods take into account the essentiality of the metals (i.e. the degree to which a metal is essential, i.e. cannot be substituted for in important uses), the ease of recycling with current or future uses, product designs or recycling technologies, or the entire ore concentration distribution (UNEP 2010a).

In a study on the life cycle impact of the global economy, (Goedkoop et al. 2008) and (Wegener Sleeswijk et al. 2008) assessed the depletion of fossil fuels and minerals separately in a two-step approach with the ReCiPe method. The additional cost of future extraction due to marginally lower ore grade with the extraction of a unit of the metal in question is the basis for weighting resource extraction rates. For the metals, the depletion of platinum, gold and rhodium were evaluated to contribute to almost all the depletion (see Figure 4-5).

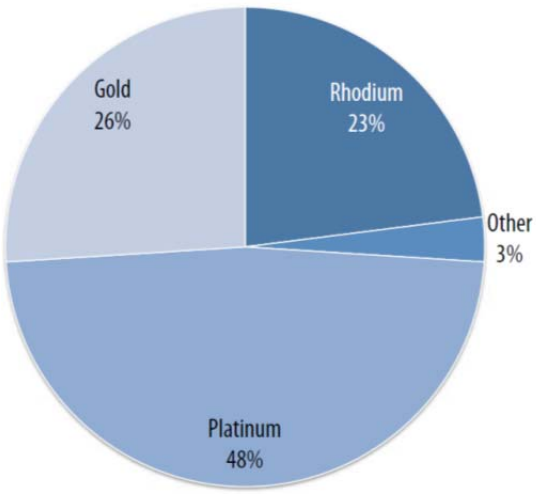


Figure 4-5: Relative contribution on the impact of resource depletion for the world in 2000 by resource category at the midpoint level (UNEP 2010a)

4.2 Dissipative emissions of scarce metals

According to (UNEP 2010a), environmental impacts which may arise in the use phase through dissipative emissions (related to e.g. corrosion of copper roofs, lead sheets in buildings or zinc fences or as 'contaminants' of fossil fuels, phosphate rocks or other metals) are becoming increasingly important. Although the flows of such contaminants are minor compared to functional metal flows, their environmental impact is dominant: once in the environment, they cannot be recovered and tend to accumulate in soils and biomass (Van der Voet et al. 2009). In this context, the emission of scarce technology metals such as silver might become more relevant in the future due to nanotechnology.

4.3 The effect of decreasing ore grades

(Norgate et al. 2007), who assess metals that are currently or potentially extracted in Australia regarding their cradle-to-gate environmental impacts, emphasize that current efforts for dematerialisation will be more than compensated by the growing demand in developing countries. They conclude that 'as higher grade reserves of metallic ores are progressively depleted, mined ore grades will gradually decrease.' As a consequence, in the future more material will have to be handled and disposed of, which will increase the environmental impacts of metal production. According to (Norgate et al. 2007) it is therefore necessary to develop new technologies for both existing and alternative metal production processes in order to counterbalance these effects. (Norgate and Haque 2010) state that 'many of the newly discovered ore deposits are complex and finer-grained, requiring grinding to finer sizes to liberate the valuable or waste minerals in order to achieve separation and concentration. This will also increase the energy consumption of the mineral processing stage [...].' In Figure 4-6, the effects of lower ore grade and finer grind size, as they were derived from theoretical calculations, are shown for the energy input for copper production. Again, (Norgate and Haque 2010) highlight that with implementation of new technologies and further developments this effect might be reduced. (Norgate 2010) identify similar impacts of lower ore grades on water consumption, due to the additional amount of material that has to be treated.

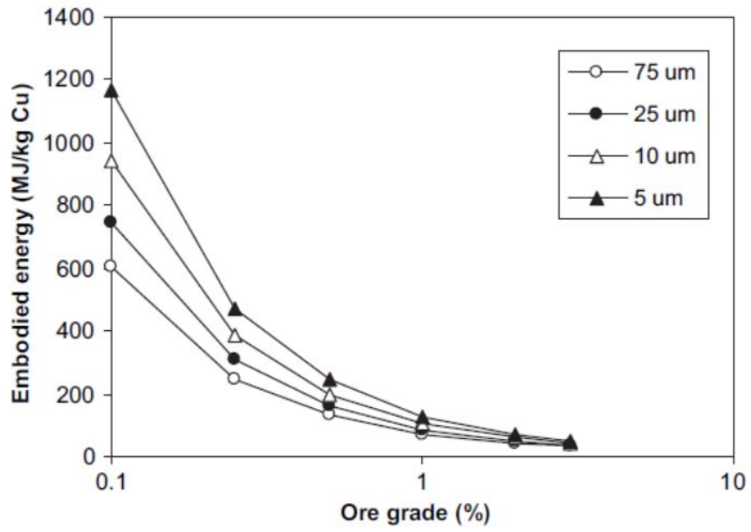


Figure 4-6: Combined effect of ore grade and grind size on embodied energy for pyrometallurgical copper production (Norgate et al. 2007).

In a series of publications, the Australian researcher Gavin Mudd analyses the sustainability of mining in Australia. Amongst others, (Mudd 2007a) gives an overview of historic trends in base metals mining in Australia. For copper he exemplarily argues that lower ore grades will keep 'upward the pressure on environmental aspects such as solid wastes, energy, water and pollutant emissions per t of Cu produced (e.g., t CO_2/t Cu)' According to (Mudd 2007a, b) this also holds to be true for Pb–Zn–Ag ore resources, Ni laterites and gold production. In a summarizing paper on 'key mega-trends and looming constraints' of environmental sustainability of mining in Australia, (Mudd 2010) concludes that while it seems to be inevitable that future deposits will have lower ore grades, it remains open if further developments in technologies can prevent resource intensity to rise.

Considering these and other publications of Mudd and Norgate, (Giurco et al. 2010) highlight the relation of declining ore grades and rising environmental impact is in their 'Peak Minerals' study. The peak concept is better known in the context of oil and is introduced by the authors to explore the future threats to, and benefits from the Australian minerals industry. The authors dampen the expectations on technological breakthroughs to mitigate expected increasing environmental impacts due to lower ore grades, since they would generally only 'delay increases in impact rather than reversing them.' In Giurco et al. (2010) summarizing graphs of some of the studies by Mudd are presented, which illustrate global trends of declining ore grades and the relation of ore grade and carbon intensity of production (see Figure 4-7).

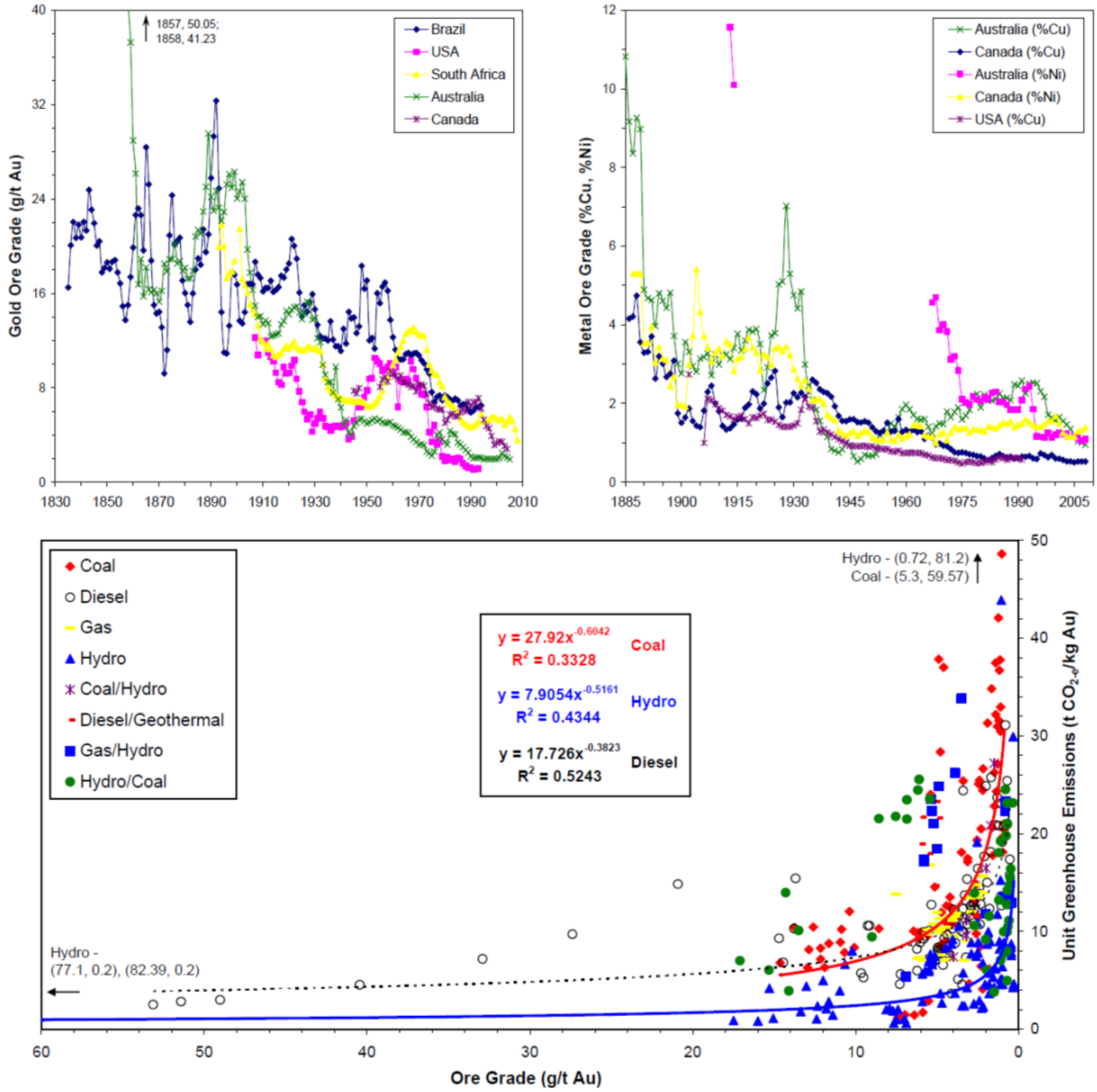
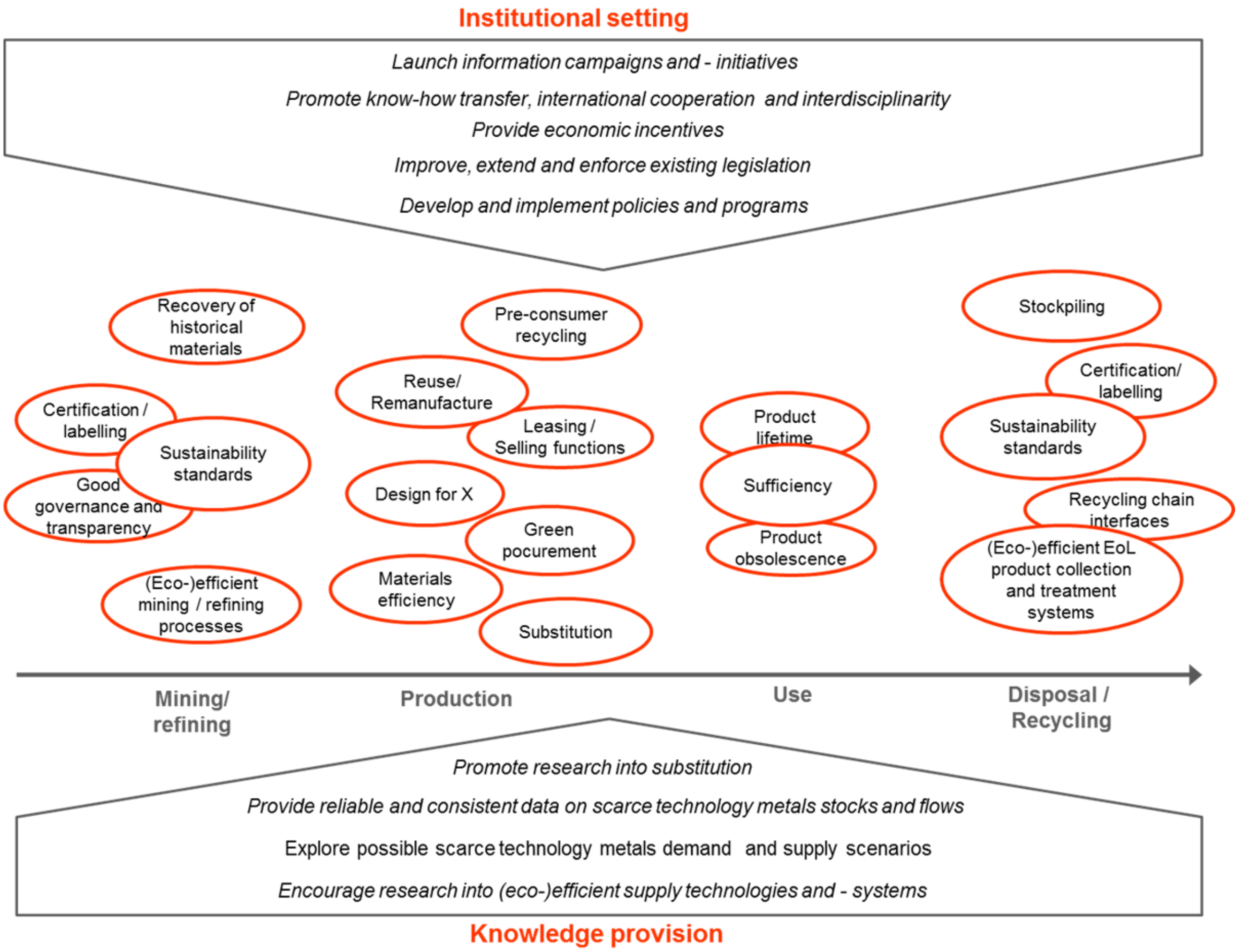


Figure 4-7: Declines in ore grades for gold (a: top left) and copper (b: top right), and (c: bottom) carbon intensity of gold production versus ore grade (Giurco et al. 2010).

5 Intervention options for a more sustainable scarce metals governance

A top-down approach to systematically identifying interventions towards sustainable governance of scarce metals would consist of applying a systemic perspective that considers all the relevant factors affecting the further development of the socio-technical processes involved (see e.g. (Lang et al. 2007)) under consideration of the entire life cycle of a technology metal (see e.g. (UNEP 2010a). (Wäger et al. forthcoming) have used a bottom-up approach, where they identify interventions proposed in recent publications that have addressed the issue (see e.g. (Achzet et al. 2010) (Bleischwitz and Bringezu 2007) (Bleischwitz and Pfeil 2009) (Buchert et al. 2009) (European Commission 2010) (Hagelüken and Meskers 2010) (National Research Council 2008, MacLean et al. 2010, Wäger et al. 2010)) (Böni and Widmer 2011)) and allocate them to the following three intervention levels:

1. Knowledge provision;
2. Possible interventions along the scarce metals life cycle;
3. Institutional setting.



4.

Figure 5-1: Intervention options for a sustainable governance of scarce metals addressed in recent studies according to (Wäger et al. forthcoming)

Figure 5-1 summarises the results of this process and shows some prominent intervention options addressed in recent studies. Based on (Wäger et al. forthcoming), these intervention options will be commented in the following three sections.

5.1 Knowledge provision

Providing and integrating relevant knowledge is a fundamental prerequisite for informed decision making. As pointed out by e.g. (UNEP 2010b); (MacLean et al. 2010)), there still are major knowledge gaps to be addressed in the field of scarce metals supply, including, in particular the

- promotion of research on substitution.
- provision of reliable and consistent data on scarce metals stocks and flows;
- exploration of possible scarce metals demand and supply configurations;
- encouragement of research on (eco-)efficient supply technologies and –systems;

a) Promote research on critical metals substitution

The ad hoc working group of the EC recommends that substitution should be encouraged, notably by promoting research on substitutes for critical raw materials in different applications and by increasing the opportunities under the EU RTD Framework Programmes (European Commission 2010). Similarly, one of the pillars of the strategy to increase the flexibility of the supply chain for the development of clean technologies proposed by the DOE is the development of substitutes covering both material and technology substitutes (U.S. DOE 2010b). Today, substitution is in many cases expected to reduce the performance of a technology and/or to shift the problem onto other critical raw materials (e.g. by substituting antimony tin oxide (ATO) for indium tin oxide (ITO), niobium or multi-layer ceramic capacitors for tantalum in micro-capacitors or samarium-cobalt magnets for dysprosium magnets ((Angerer et al. 2009), (USGS 2010)).

b) Provide reliable and consistent data on scarce metals stocks and flows

Consistent and reliable information on scarce metals still appears to be missing both for primary and secondary supply. Regarding primary production, annually updated data are provided for a large number of critical metals by e.g. the United States Geological Survey (USGS) (USGS 2010) and the Austrian Ministry of Economy, Family and Youth (Weber et al. 2010); however, there still are inconsistencies and data gaps due to *inter alia* differences in the calculation methods or limitations in data accessibility (proprietary data) ((Gordon et al. 2007), (Tilton and Lagos 2007)).

Regarding secondary production, a review of 54 metal stocks in society performed recently has shown that information on the in-use stocks is reasonably detailed only for five base metals (aluminium, copper, iron, lead and zinc), whereas it is sparse for nineteen other metals such as antimony, gold, palladium, platinum, rhodium and silver, and almost inexistent for "specialty metals" such as indium or lanthanides. In particular, there seems to be essentially no information on stocks in "hibernation", in tailings repositories, in industrial stockpiles, or in landfills, nor on in-use lifetimes for almost the entire periodic table of the elements (UNEP 2010b). However, secondary production is expected to become increasingly important, because for many scarce metals their extraction from geological resources has significantly increased in recent decades and induced a continuous shift to metals stocks in the anthroposphere (see Figure 3); (Du and Graedel 2011). For example, estimated in-use stocks of REE amounted to 440 Gg in 2007, with most of the stock in the "big four" REE cerium, lanthanum neodymium, praseodymium, which corresponded to some four times the annual REE production in the same year. At least for some scarce metals (e.g. gold, palladium, platinum, silver or tin), post disassembly concentrations in components of products such as Electrical and Electronic Equipment and automobiles are typically higher than minimum profitable ore grades (see e.g. (Johnson 2007)).

The need to improve the availability of reliable, consistent stock and flow data, along with their dissemination, have been highlighted in several studies as prerequisites for sound policy- and decision making (see e.g. (European Commission 2010); (U.S. DOE 2010b); (UNEP 2011)). The ad hoc working group of the EC specifically proposes to prepare a European Raw Materials Yearbook with the involvement of national geological surveys and mining/processing industries (European Commission 2010). According to UNEP, critical issues such as the communication of uncertainties and the validation of results should be addressed, the availability of dynamic stock information improved, and measures of recycling performance for informed policy making are needed ((UNEP 2010b), (UNEP 2011)).

c) Explore possible future scarce metals demand and supply configurations

Modelling and simulation are considered to be increasingly important with regard to the representation, evaluation and mitigation of the social, environmental and economic implications of possible future scarce metals demand and supply configurations (see e.g. (Hagelüken and Meskers 2010); (MacLean et al. 2010); (UNEP 2010b)). According to UNEP (UNEP 2010b), the development and application of dynamic material flow models would be helpful to generate scenarios for future demand and supply for primary and secondary materials with a level of sophistication similar to that of energy scenarios. As shown by McLean et al. (MacLean et al. 2010), first dynamic models have been set up for the analysis of growth patterns of stocks in use, the assessment of the impacts of stock dynamics on future resource availability or the forecast of resource demand by linking material stocks with services. In global dynamic technology based material flow analysis (MFA) models, elements and products have been interconnected and linked to mining and metallurgy as well as to environmental impacts (see e.g. (Reuter et al. 2006)). An approach integrating an agent-based behavior model, where demand emerges from individual agent decisions and interaction, into a dynamic material flow model, representing the materials' stocks and flows across their lifetime, has been proposed by Knöri et al. ((Knoeri et al. 2011)).

The ad hoc working group of the EC proposes to support research on life-cycle assessments (LCAs) for raw materials and their products on a "cradle-to-grave" basis (European Commission 2010). First steps in this direction on a cradle to gate basis have been done e.g. for lithium in the context of electric mobility, under consideration of different system levels (raw material, product component, final product) ((Notter et al. 2010), (Stamp et al. 2011a).

d) Encourage research on (eco-)efficient systems and technologies

Another issue addressed with regard to improving the knowledge base is research on (eco-) efficient systems and technologies. In this regard, the ad hoc working group of the EC advocates, in particular, the promotion of research on mineral processing, mineral extraction from deep deposits, system optimisation and recycling of technically challenging products and substances, notably under EU RTD Framework Programs (European Commission 2010). Similarly, the NRC recommends the enhancement of research for extraction and processing technologies as well as remanufacturing and recycling technologies (National Research Council 2008). According to Bucher et al. (Buchert et al. 2009), basic research on metals with serious technical recycling problems such as tantalum in dissipative applications should be enhanced, and recycling technologies corresponding to specific fields of application (e.g. solar panels or LCD-monitors) should be developed and implemented. (Schüler et al. 2011) propose developing pilot recycling plants to learn more about complex recycling processes. (Faulstich et al. 2010) address, *inter alia,* the development of recycling technologies allowing one to recover homogeneous valuable materials from highly complex material composites, such as integrated circuit boards, and the improvement of shredding and sorting processes in view of avoiding technology metals dissipation, as recently reported by e.g. (Chancerel and Rotter 2009), and increasing their recovery rates.

5.2 Intervention options along the scarce metals life cycle

A sustainable governance of scarce metals requires specific interventions along the scarce metals life cycle. Below, some intervention options typically addressed in recent studies (see Figure 2) are briefly commented. Taking into account that every scarce metal has its own demand and supply 'history' (European Commission 2010, Wäger et al. 2010), and that different policy levels (inter alia consumer, company, business sector, state, international community) with their particular possibilities and limitations are addressed, this generic framework for possible interventions will have to be prioritized for every scarce metal or scarce metals family.

a) Mining and refining

Several recent studies address the necessity to increase the efficiency of extraction and refining processes (see e.g. ((MacLean et al. 2010), (European Commission 2010); (National Research Council 2008)). (MacLean et al. 2010) for instance propose improving mining practices in order to reduce the amount of waste to be handled and treated, performing more ore breakage in the blasting stage prior to crushing and grinding, utilizing more energy-efficient grinding technologies, using alternative processing routes such as *in situ* leaching, the wider use of renewable energy technologies, and treatment and reuse of *inter alia* water and dry processing.

In recent years, the issues of *good governance and transparency* have been brought to the fore by the extractive industry transparency initiative (EITI) and the Publish What You Pay-Initiative (PWYP) (see e.g. (Schieritz 2009)), in particular. Likewise, the ad hoc working group of the EC (European Commission 2010) recommends specific policy actions aimed at promoting good governance, capacity-building and transparency in relation to the extractive industries in developing countries (notably in the area of critical raw materials).

In parallel, first steps in the direction of a more sustainable exploration and extraction have been undertaken within the Mining, Minerals, and Sustainable Development project of the Institute for Environment and Development ((International Institute for Environment and Development 2002)) or the Sustainable Development Framework by the International Council on Mining and Metals (ICMM) (Sethi 2005, International Council on Mining & Metals 2011). An increase in sustainable exploration and extraction inside and outside the European Union is advocated by the ad hoc working group of the EC (European Commission 2010).

Certification of raw materials and their supply chain, which allows material purchasers to selectively buy te raw materials under more sustainable conditions than others (Searchinger 2009) has recently become an issue for conflict minerals such as the tin, tantalum and tungsten (the 3T's). Pilot projects for certified trading chains for the 3T's have been initiated by the German Federal Institute for Geosciences and Natural Resources (BGR) in cooperation with authorities in Rwanda and the Democratic Republic of Congo (Bundesanstalt für Geowissenschaften und Rohstoffe 2010b). In particular, a method for identifying the fingerprint of tantalum ores has been developed by the BGR (Bundesanstalt für Geowissenschaften und Rohstoffe 2010b).

Another intervention proposed is the recovery of historical stocks in unmined parts of ore bodies, tailings, slags or landfills (Faulstich et al. 2010, Hagelüken and Meskers 2010).

b) Production

Substitution and materials efficiency are intervention options prominently addressed in various studies (see e.g.(European Commission 2010, Faulstich et al. 2010, U.S. DOE 2010a). Besides a material substitution of critical metals by less critical ones, which is considered rather difficult for many scarce metals without significant drawbacks on the functionality (see e.g. the substitution of indium tin oxide (ITO) or neodymium in permanent magnets), the substitution of a product or technology by another which fulfils the same function, i.e. functional substitution ((Ziemann and Schebek 2010)), could play an important role in the future. Amongst others, the question will have to be addressed, how much performance is really needed for the different application contexts. Regarding an increase in materials efficiency, the trade-off between less material use per product unit and e.g. rebound effects in the use phase (through an increase in product demand) or lower recovery rates through lower concentrations in EoL products and their products (see e.g. (Johnson 2007).

Alongside the substitution and efficiency issue, improving product design in view of a better recyclability becomes increasingly important in view of closing the end of life (EoL) product cycles (see e.g. (MacLean et al. 2010) and chapter 6.2). This includes, in particular, promoting the ease of disassembly, where possible avoiding the application of elements or combinations thereof, which are difficult to recover, and integrating features that support product take-back. It will be important to know the technological possibilities and limitations in the recycling chain (see e.g. (Reuter et al. 2005)) and to consider the trade-offs associated with recovery of technology metals from complex "mixtures" with different pre-treatment and recycling processes.

Another intervention option addressed is pre-consumer recycling (see e.g. (UNEP 2011); (U.S. DOE 2010b). Compared to recycling of EoL products, the efficiencies of pre-consumer recycling are usually better due to a high awareness of the involved stakeholders, economic recycling incentives, transparent and professional handling throughout the product life cycle, and a rather limited change of ownership and location of use (UNEP 2011).

c) Use

Consumption of technologies and products based on scarce metals determines the demand for these non-renewable resources. A limitation of consumption per capita could be achieved by increased srive lifetimes through changes in consumer behaviour or a ban of planned product obsolescence. However, considering amongst others that (i) the possession of new products and technologies is an essential element of our present lifestyles in developed countries, (ii) emerging countries such as China or India are increasingly adopting the 'western' lifestyle, (iii) establishing an awareness for life cycle impacts of resource consumption is not easily achievable, and (iv) increased product lifetimes could be counterproductive with regard to energy efficiency (because of higher energy consumption by older, energy-inefficient devices in the use phase), the effectiveness of such interventions might be limited.

d) Recycling

As shown by UNEP (UNEP 2011), with the exception of some precious metals in particular, for many scarce metals the recovery rates from EoL products are typically very low: for e.g. gallium, germanium, indium, osmium, REE, tantalum or tellurium they were estimated to amount to less than 1%. As a consequence, the need for the implementation of (eco-)efficient collection and recovery systems for increasingly complex EoL products, which will allow for a gradual transition from open to closed loops, is prominently addressed in several studies ((Hagelüken and Meskers 2010),(European Commission 2010),(National Research Council 2008),(Böni and Widmer 2011),(MacLean et al. 2010)). Schüler et al. (Schüler et al. 2011), for instance, recommend building up a collection and pre-treatment scheme for wastes containing REE, under consideration of already existing schemes such as the directives on Waste Electrical and Electronic Equipment (WEEE), end of life vehicles (ELV) or batteries.

The implementation of (eco-)efficient recovery systems includes, in particular, measures to avoid dissipation of these elements through incorporation into material streams as impurity or "tramp" elements (Chancerel and Rotter 2009); (UNEP 2011) . Still, it will not be possible to completely avoid trade-offs in the recovery of scarce metals, which is why the right priorities should be set under consideration of, inter alia, the variety of scarce metals in EoL products and their components (i.e. their 'complexity'), their concentrations and distribution and the dependency of EoL products and components recycling from metals with a high economic incentive such as e.g. copper, gold, palladium or silver for printed wiring boards (Hagelüken and Meskers 2010).

Another intervention option to be considered in this context is the optimisation of the interfaces along the recycling chain to avoid significant losses in overall recovery efficiency (Hagelüken and Meskers 2010). The focus on interfaces and the application of a comprehensive, global life cycle perspective on scarce metals recovery with mining and recycling as coevolving systems to improve the overall organisation, logistics and efficiency of recycling chains is also supported ad hoc working group of the EC (European Commission 2010).

According to (Buchert et al. 2009) a focus should lie, in particular, on the increasing stocks of used products in developing countries (e.g. old cars containing automotive catalytic converters and electronic devices, used consumer electronics, batteries etc.). The ad hoc working group of the EC recommends *mobilising EoL products* with critical raw materials for proper collection instead of stockpiling them in households or discarding them into landfills or incinerators (European Commission 2010). Still, a controlled stockpiling of EoL products and - components should be considered an interesting option as long as recycling solutions are not available or economically not feasible (see e.g.(Böni and Widmer 2011)). This includes keeping the critical elements in the stock of operating infrastructure through reuse and remanufacturing (e.g. EV batteries at <80% capacity re-used as electrical grid buffers), which might be the simplest and most cost effective temporary solution as long as efficient material recovery technologies are not available.

For (MacLean et al. 2010), an appropriate life cycle structure should be provided, including active cooperation of citizens supported by legislation and marketing efforts to help gradually restructure open systems into closed ones, keeping the product traceable throughout its life cycle, recycling deposits or more fundamental approaches such as changes in business models (e.g. leasing of products or selling functions instead of products), a global recycling infrastructure for products exhibiting great global mobility, an international division of labour benefiting from specialization and economies of scale (MacLean et al. 2010). Still according to (MacLean et al. 2010), technological innovation across the entire mineral life cycle should be promoted and various types of entrepreneurship implemented.

5.3 Establishing an appropriate institutional setting

In order to be successful over the medium and long terms, the implementation of interventions specified on the previous two intervention levels requires an appropriate institutional setting. Under consideration of the studies reviewed, establishing such a framework would, in particular, include

- the development and implementation policies and programs;
- the improvement and extension of existing legislation;
- the promotion of know-how transfer, international cooperation and interdisciplinarity;
- the launch of information campaigns and initiatives.

a) Develop and implement policies and programs

Bleischwitz((Bleischwitz and Bringezu 2007), (Bleischwitz and Pfeil 2009), (Bleischwitz et al. 2009)) proposes the implementation of a global resource governance system, which consists of the following three cornerstones.

- An International Panel for Sustainable Resource Management, which has been established at the initiative of the European Commission in the framework of the United Nations Environment Programme (UNEP). The expert committee is inter-governmentally legitimated and issues recommendations comprising a view of the state of knowledge that is as objective as possible regarding sustainable resource management on a worldwide level.
- An international agreement to be drafted with the goal of managing resources sustainably and peacefully. The agreement should establish the following two legal principles: Firstly, it entails the principle of a common heritage of humankind, according to which resources are left to the states and actors for use, but are ultimately to be considered as a heritage, and therefore to be handed on to future generations at least in their most important functions. Secondly, it entails the principle of materials stewardship, according to which an optimal and appropriate extraction, production and use of raw materials

for the good of society and under consideration of environmental issues should be promoted. A recent study has developed elements of such an international covenant on scarce metals (Wilts et al. 2010).

- An international agency for sustainable resource management, which would provide data and would guarantee the implementation of internationally agreed tasks – e.g. roadmaps and projects for a sustainable resource management in developing countries. Alternatively, such an institution could be established under the roof of an existing organization.

Whereas the International Panel for Sustainable Resource Management has been active since 2007, agencies for sustainable resource management have thus far been implemented only on a national level (Bundesanstalt für Geowissenschaften und Rohstoffe 2010a).

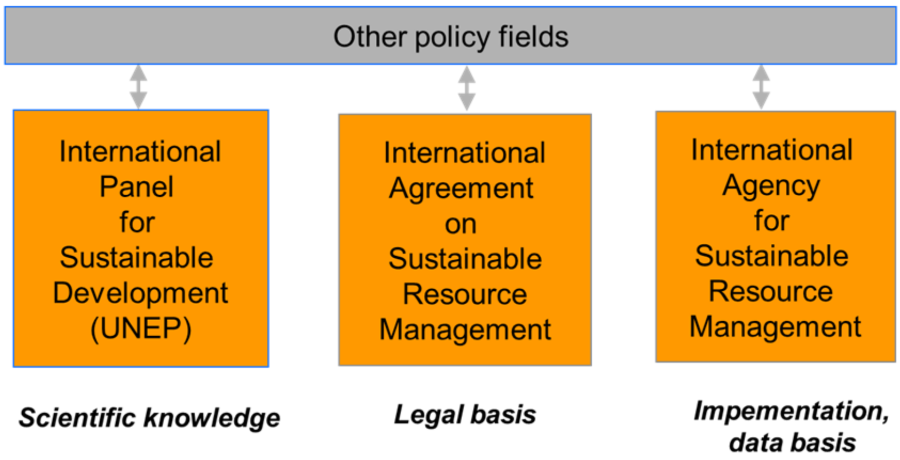


Figure 5-2: Cornerstones of a global resource management system according to (Bleischwitz and Bringezu 2007) and (Bleischwitz and Pfeil 2009)

The ad hoc working group of the EC recommends continuing to improve the coherence of EU policy with respect to raw materials supply, for example, in the assessment of injurious dumping and subsidies, and establishing indicators of competition to land substitution (European Commission 2010). Buchert et al. (Buchert et al. 2009) propose a European Union critical metals recycling program, which could include the encouragement of research and development activities, the installation of first demonstration plants and special investment programs including low interest credits to support the design and implementation of large scale recycling plants for critical metals.

Bleischwitz et al. have developed a strategic approach that encourages industry to innovate and to steer markets towards long-term sustainability (Bleischwitz et al. 2009). Taking advantage of the "low hanging fruits" or untapped opportunities that exist in many firms and private households, a *first pillar* may consist of incentives for better information and dissemination. A *second pillar* may address more risky innovation into new products and services as well as an industrial transformation for resource-intensive sectors. A *third pillar* may have to address framework policies for more radical pathways and a transition where economic incentives and long-term R&D programmes may play a role. Interesting to note, all areas of research into such policies require not only an interdisciplinary approach to economic, legal and political expertise, but also engineering capacities and an international perspective with stakeholder involvement. The idea of an international covenant for the recovery and re-use of scarce technology metals put forward by Wilts et al. (Wilts et al. 2010), for instance, requires knowledge about technical processes, international trade statistics, international law and economics, and specific expertise on key target countries.

b) Improve, extend and enforce existing legislation

According to (Hagelüken and Meskers 2010), recycling targets need to emphasize the collection, treatment, and recovery of all EoL products. In particular, a high recycling rate as defined in the existing European directives does not mean anything, as long as the collection rate is insufficient e.g. because scrap escapes recycling by dubious export practices, and critical metals are lost because the recycling rates are mass based. Besides monitoring and the enforcement of an appropriate legislation, an extended producer responsibility (EPR) concept aiming at a division of labour, a specialization in pre-treatment and metals recovery, and the application of economies of scale to recycling should be considered to improve the situation. However, legislative measures may be counterproductive whenever system boundaries are crossed: for example, when prioritising reuse above recycling in European legislation for EoL products with open loop structures means that reuse will take place in other parts of the world, where the final EoL product will most likely be discarded (Hagelüken and Meskers 2010).

According to the recent study done by (Schüler et al. 2011) with focus on REE, a proper recycling scheme for waste containing REE requires an appropriate design with regard to logistical and technological issues, as well as the existence of an appropriate legal framework. A first step towards such a legal framework would consist of screening existing regulations, including a verification of whether the European Ecodesign Directive and related regulations should be adapted in order to support the dismantling and recycling of REE components from energy-using products.

Regarding primary supply, on July 21, 2010, the US Financial Stability Act was signed, which includes measures to restrict the market for “conflict metals” and requires United States companies to submit an annual report to the United States Securities and Exchange Commission, disclosing whether their products include tantalum, tungsten, tin and gold sourced from the Democratic Republic of Congo or adjoining countries (Lipschutz 2010, RAM 2010).

c) Provide incentives

Economic incentives such as extraction taxes with revenues going into a raw material fund are considered to be an option also for other primary raw materials and countries, where they have been successfully implemented (e.g. Norway and Chile; see (Bleischwitz and Bringezu 2008)). The DoE recommends considering financial assistance for domestic production and processing, for example, the issuing of loan guarantees for improved technologies reducing greenhouse gases. Direct support to the production capacity for critical materials would require significant further investigations with regard to its appropriateness (US DOE 2010).

Regarding secondary materials from EoL recovery, (UNEP 2011) proposes to encourage high old scrap ratios as an incentive to increase the EoL recycling rate and to make fabrication processes more efficient.

d) Promote know-how transfer, international cooperation and interdisciplinarity

According to e.g. (Buchert et al. 2009), technological issues regarding the recycling of critical metals should be comprehensively adopted in existing courses of study (special programs and professorships), and know-how/technology transfer; likewise, international cooperation should be accelerated by holding international recycling conferences, funding technological implementation programs in emerging economies and developing countries, and through specific scientific exchange programs. The NRC specifically mentions coordination and data exchange among (U.S.) agencies collecting mineral information (National Research Council 2008). It also suggests identifying and applying training measures to counteract the existing and growing shortage of resource professionals in industry, government and educational institutions. This becomes, for instance, especially important when considering the recent discussions on restoring REE mining and processing in the United States and other Western countries in order to lower their dependency on China, which has severely restricted its REE exports lately (see e.g. (Kim 2010); (Service 2010)). (Bleischwitz and Bringezu 2008) propose an international agency for sustainable resource management that could take on such tasks (see above). (MacLean et al. 2010) emphasize that the "challenge of sustainability" most importantly requires a generation of practitioners and analysts with a "multidisciplinary" understanding of a broad set of issues related to *inter alia* economics, engineering, geology, ecology and mathematical modelling.

In a recent report focusing on REE, (Schüler et al. 2011) propose installing a European Competence Center for Rare Earth Elements, which would convene an assembly of recycling companies, producers, authorities and representatives from politics and science.

e) Launch information campaigns and initiatives

(MacLean et al. 2010) see the necessity of better informing stakeholders and citizen initiatives. (Buchert et al. 2009) propose the launch of information campaigns and initiatives by the EU and the member states to draw the attention of the public to the importance and value of critical metals. *Inter alia*, they recommend addressing the issue of used consumer goods which are "bunkered" in households (e.g. mobile phones in drawers) and hence are not available for a critical metals recovery for many years.

6 Recycling- and product design opportunities

6.1 Recycling

In the primary production of metals, there are complex interdependencies between 'carrier metal' (or major metal) - and' co-element' (or minor metals) production (see Figure 6-1 and Figure 6-2). Well-known examples for these interdependencies are indium, which typically is obtained as a by-product in zinc production, or PGMs, which are typically produced as coupled products ((Reuter et al. 2005)).

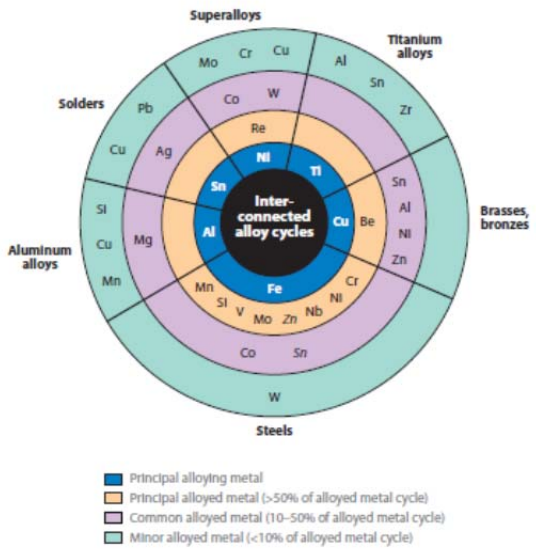


Figure 6-1: The wheel of metal linkages in modern alloys. Metals coated rather than plated are shown in italics. (Reuter et al. 2005, International Council on Mining & Metals 2011, Stamp et al. 2011b)

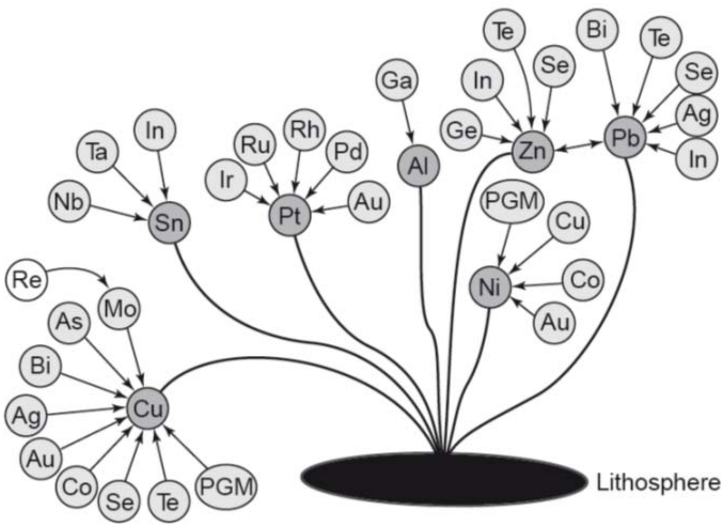


Figure 6-2: Coupling of major and minor metal production (Hagelüken and Meskers 2010)

The interdependencies found in primary production, also exist for the secondary production of metals from complex post-consumer waste, e.g. Waste Electrical and Electronic Equipment (WEEE) (Wäger et al. 2010). When recycling WEEE, elements such as gold, palladium and silver typically are the main drivers for recycling due to their high economic value. With modern metallurgic processes, associated elements such as indium, selenium or tin may also be recovered. As a consequence, metals which play the role of 'carrier elements' in primary production may become co-elements in secondary production, and vice versa (Wäger et al. 2010).

Recycling is an option to provide these metals with fewer environmental impacts, at the same time alleviating potential supply restrictions from limited geologic availability or geopolitical constraints. However, the recovery of potentially critical scarce metals differs from conventional (base) metals, in that in EoL equipment they typically occur at very small concentrations in complex mixtures. Amongst others, this requires particularly well designed life cycle structure, allowing to avoid losses of these metals through dissipation, i.e. their dispersion into fractions or environmental compartments, from where they will not be recovered economically (Hagelüken and Meskers 2010). As shown by (Chancerel et al. 2009), in a typical WEEE pre-processing facility, only about a quarter of the gold and palladium and a tenth of the silver in the input material is sent to output fractions from which precious metals will be directly recovered. Most of the precious metals are transferred to the most relevant fractions with regard to their mass (plastics and ferrous metals), where they are found at relatively low concentrations of (24 g/t of gold and 8 g/t of palladium in the plastics, and 24 g/t of old and 5 g/t of palladium in the ferrous metals), however, the considerable mass of the outputs makes the flows of precious metals very relevant.

Typically, recycling of pre-consumer waste will have first priority, as in this type of waste scarce metals tend to occur at higher concentrations and in rather pure form. Whereas the recovery efficiency of scarce metals from pre consumer waste is estimated to be rather high for e.g. PGM (and hence the additional recovery potential from pre-consumer waste is considered to be low), it is not known for REE due to the wide variety of application, mostly with a very fine dispersion (Buchert et al. 2009).

6.1.1 Possibilities and limitations of scarce technology metals recycling

The possibilities and limitations of a recycling of selected scarce technology metals for emerging sustainable technologies have been comprehensively assessed by (Buchert et al. 2009). According to their evaluation, particularly serious recycling restrictions are to be expected for lithium, REE and tantalum (see Table 6-1).

Table 6-1: Criteria for the evaluation of recycling restrictions and scarce technology metals fulfilling these criteria (Buchert et al. 2009)

Criteria	Metals fulfilling the criteria
High scale of dissipative applications	- gallium, germanium, indium, tantalum, tellurium
Physical/chemical limitations for recycling	- lithium, tantalum and REE
Lack of suitable recycling technologies and/or recy-	- lithium, REE, tantalum

cling infrastructure	
Lack of price incentives for recycling	- lithium

In annex 3, an overview of the pre- and post-consumer recycling potentials identified by (Buchert et al. 2009) is given. According to this overview, in the pre-consumer domain there are future recycling potentials e.g. for cobalt (increasing recycling process efficiency), germanium (increasing production), indium (increasing production), ruthenium (high prices and large new scrap volumes) and tellurium (electronics, solar cell production). In the post-consumer domain, the recycling potentials are estimated to be especially high for germanium (fiber-optic cables), lithium (lithium batteries), palladium (automotive catalysts, dental material, WEEE), platinum (automotive catalysts and WEEE) and ruthenium (automotive catalysts and WEEE). A major prerequisite for an increased recycling of elements such gallium, PGMs or tellurium, are efficient WEEE collection systems, in particular also in developing countries. For REEE, further analyses in the pre-consumer domain would be necessary to identify the recycling potential in the pre-consumer domain; the recycling potential in the post-consumer domain is estimated to be low due to to the widespread use at low concentrations, frequent application in alloys and a tendency to being transferred into slags (as oxides) in smelter plants.

6.1.2 Recovery of critical technology metals from EoL equipment

In a Swiss study, material flows linked to electrical and electronic equipment (EEE) in Switzerland were investigated for the year 2006 ((Müller and Widmer 2008), see also section 2.1. The results of this material flow analysis show that the material recovery rate is higher than 90% for bulk metals as well as for most of precious- and heavy metals and glass. On the other hand, over 80% of plastics were thermally disposed of in 2006 leading to an irreversible loss of included elements such as e.g. antimony ((Mathys R. et al. 2007); see also Figure 6-3). Indium, which is mainly contained in flat displays such as LCDs, is so far not recycled in Switzerland but also mostly incinerated and therefore lost. Mercury, which is still used in lighting equipment, is mostly recovered in specialized facilities and sold to the still existing mercury market.

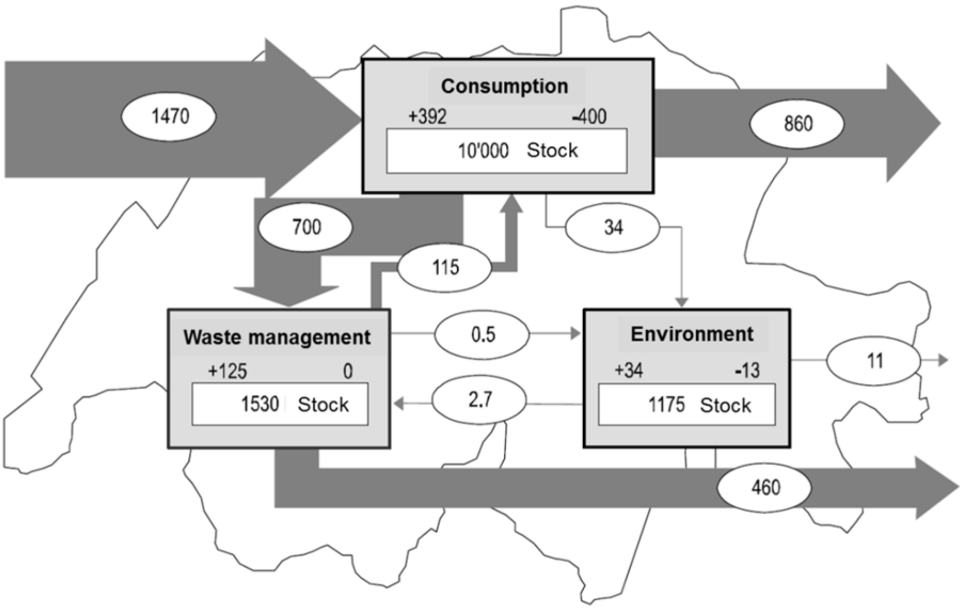


Figure 6-3: Antimony flows through Switzerland (Mathys R. et al. 2007) Overall antimony consumption stock in Switzerland amounts to around 10'000 tons. Most of the stock is allocated to plastics in Flame retardants (FR) products (73 %).

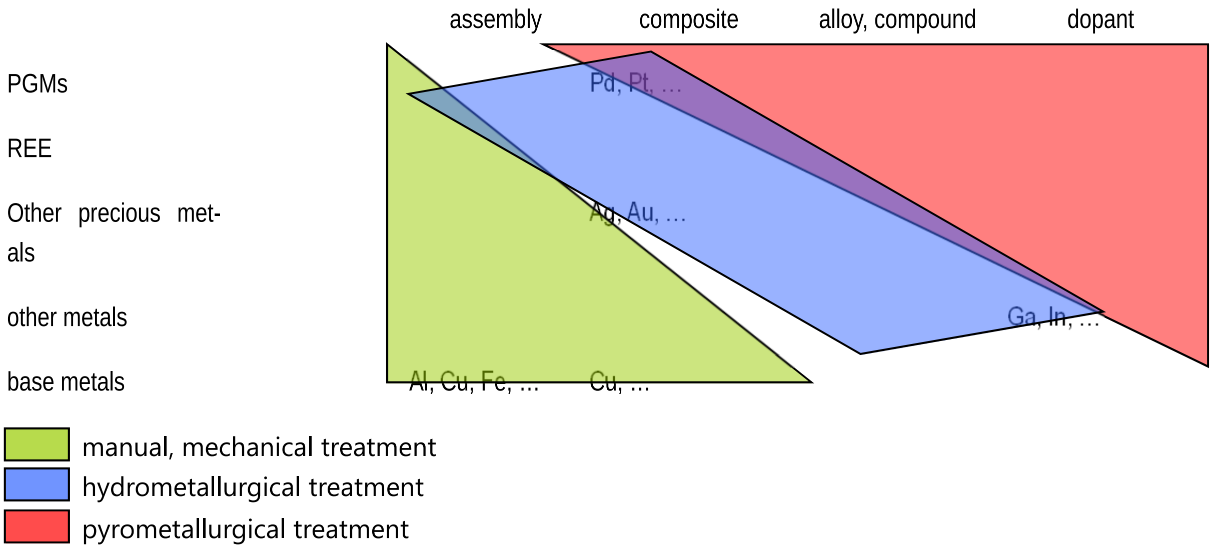
In view of identifying the recovery potentials of scarce technology metals from WEEE, a Japanese research group recently quantified the scarce metals content of different WEEE product types and performed a cluster analysis under consideration of the identified metal contents and the annual amounts of the corresponding WEEE product types. The results will be published in 2011 (Oguchi 2010).

As shown in chapter 2, critical scarce metals are used in many applications and in a multitude of different application forms. Hence, there cannot be a simple recipe for their recovery; rather, recovery might be as complex and resource demanding as the assembly phase in the equipment's / infrastructure's life cycle. This most probably exceeds the current intrinsic value (the value of the contained scrap material) of the EoL equipment. Not (yet) having mechanisms in place which could finance such complex recovery operations, it might be required to define / adopt strategies to achieve the optimal performance under current circumstances. Possibly, similar or analogous strategies as those applied to maintain the global genetic diversity could be applied.

The important dimensions and cost drivers in the recovery processes for potentially critical technology metals are (1) the concentration levels and (2) its integration with other materials in the EoL appliance - and of course the targeted recovery efficiency. Table 6-2 is an attempt to combine these issues and give it a scale. Feeding this table with data for real world cases such as printed wiring boards might help to develop an overview of current losses and lead to recommendations for optimized but pragmatic recovery strategies.

Table 6-2: Tentative application of segregation , concentration and recovery technologies to populated printed wiring boards

assembled PWB	1	0.001 - 0.999	$1x10^{-9}$ – $1x10^{-3}$



Following, the terms and classifications exemplarily applied in Table 6-2 are briefly described.

a) Assembly

An assembly is a set of parts or components assembled to a completed product, such as a machine or a an electronic circuit.

Potentially critical metal concentrations in assembly composites are assumed to lie in the range of 0.001 to 0.999, requiring a pyrometallurgical recovery process with manual and/or mechanical pre-treatment.

b) Composites

Composite materials are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct at the macroscopic or microscopic scale within the finished structure. An example is printed wiring boards (PWB), which are populated with electronic components to form for instance computer mother boards.

Potentially critical metal concentrations in composites are assumed to lie in the range of 0.001 to 0.999, requiring a pyro- or hydrometallurgical recovery process with manual and/or mechanical pre-treatment.

Alloys

An alloy is a partial or complete solid solution of one or more elements in a metallic matrix (see also List of alloys). An example is solder, a fusible metal alloy with a melting point or melting range of 90 to 450 degree Celsius, used in a process called soldering where it is melted to join metallic surfaces. It is especially useful in electronics and plumbing. Lead-free solders in commercial use and mandatory in Europe may contain tin, copper, silver, bismuth, indium, zinc, antimony, and traces of other metals.

Potentially critical metal concentrations in alloys are assumed to lie in the range of 0.001 to 0.999, requiring a pyro- or hydrometallurgical recovery process.

Compounds

A chemical compound is a pure chemical substance consisting of two or more different chemical elements that can be separated into simpler substances by chemical reactions. Chemical compounds have a unique and defined chemical structure; they consist of a fixed ratio of atoms that are held together in a defined spatial arrangement by chemical bonds. Chemical compounds can be molecular compounds held together by covalent bonds, salts held together by ionic bonds, intermetallic compounds held together by metallic bonds, or complexes held together by coordinate covalent bonds.

Potentially critical metal concentrations in compounds are assumed to lie in the range of 0.001 to 0.999, requiring a pyro- or hydrometallurgical recovery process.

Dopants

A dopant, also called a *doping agent*, is a trace impurity element that is inserted into a substance (at very low concentrations) in order to alter the electrical properties or the optical properties of the substance. In solid-state electronics, using the proper types and amounts of dopants in semiconductors[12] is what produces the p-type semiconductors and n-type semiconductors that are essential for making e.g. transistors and diodes. Pure or intrinsic semiconductors that have been altered by the presence of dopants are known as extrinsic semiconductors. Dopants are introduced into semiconductors in a variety of techniques, known as doping: solid sources, gases, spin on liquid, and ion implanting.

It is useful to note that even high levels of doping imply low concentrations of impurities with respect to the base semiconductor. In crystalline intrinsic silicon, there are approximately 5×10^{22} atoms/cm^3. Doping concentration for silicon semiconductors may range anywhere from 10^{13} cm^{-3} to 10^{18} cm^{-3} thus on the order of parts per billion to parts per thousand. Boron, arsenic, phosphorus, antimony, among many other substances, are commonly used dopants.

Dopants for silicon and germanium, group IV semiconductors are:

- group V atoms (donors): antimony, phosphorus, arsenic
- group III atoms (acceptors): boron, aluminium, gallium

Dopants for gallium arsenide, a group III-V semiconductor are:

- group VI and group IV atoms (donors): sulphur, selenium, tellurium, silicon
- group II and group IV atoms (acceptors): magnesium, zinc, cadmium, silicon

[12] A semiconductor is a material with electrical conductivity due to electron flow (as opposed to ionic conductivity) intermediate in magnitude between that of a conductor and an insulator. This means a conductivity roughly in the range of 10^3 to 10^{-8} siemens per centimeter. Semiconductor materials are the foundation of modern electronics, including radio, computers, telephones, and many other devices. Silicon is used to create most semiconductors commercially - dozens of other materials are used, including germanium, gallium arsenide, and silicon carbide.

Dopants for lasing media[13] are chromium (Cr), neodymium (Nd), erbium (Er), thulium (Tm), ytterbium (Yb), europium (Eu) holmium (Ho) and others. Potentially critical metal concentrations in dopants are assumed to lie in the range of $1x10^{-9}$ to $1x10^{-3}$, requiring a pyrometallurgical recovery process.

6.2 The role of product design

Current recycling strategies (see WEEE Directives and WEEE Directive review) on the one hand prefer market mechanisms to recover economically viable fractions such as base and precious metals (Fe, Cu, Al, etc.). On the other hand these strategies tend to remove potentially toxic substances already in the design stage (see ROHS Directive) and/or enforce their early removal in the recycling process and forbid their dilution in general (see VREG). Many critical scarce metals do not fall into either of these two categories. This is mainly due to the fact that these metals are often used to obtain a very specific technological performance, usually at very small amounts (e.g. in alloys, thin layers or as dopants). As a result, most of the non-precious scarce metals are lost as tramp elements in base metals, slags or ashes leaving the recycling process.

Because critical scarce metals are often irreplaceably linked to the required functions, the quest to 'design them out' becomes a rather formidable task and is expected to require many years of R&D (e.g. alternative transparent conductors to ITO) or totally different technologies (e.g. the replacement of current electrochemical systems such as rechargeable batteries used for mobile energy storage). In the end, this might even simply lead to the substitution of a critical scarce metal by another critical scarce metal, or negatively affect e.g. the environmental performance of a product or function when considering the whole life cycle (i.e. also the extraction and refining, use and recovery phase).

Nevertheless, increased efforts should be undertaken to avoid the use of critical scarce metals, or, if this is not possible, to design products in such a way that scarce metals are accessible and can be efficiently recovered. In particular, this means easy disassembly of parts containing scarce metals. If scarce metals are part of very compact blends (e.g. composites, alloys or compounds) and/or extremely thinned out (e.g. dopants) product designers could concentrate these functionalities in easily removable building blocks.

However, this requires a very good knowledge of existing and probable future recycling chains, which in turn demands for a better information exchange between the production and the recycling sectors.

[13] A lasing medium is a transparent crystal, ceramics or glass and is used to produce the active medium for solid-state lasers.

7 Conclusions

7.1 Critical technology metals applications

As shown in chapter in chapter 0, Switzerland is neither producing primary nor secondary scarce metals. Rather, these metals enter the country in the form of raw materials or semi-finished and finished products which provide the services in demand. Today, Because of their very specific properties, scarce metals are generally difficult to substitute - unless society would be ready to accept less 'sophisticated' services. According to different scenario analyses, emerging technologies are expected to significantly increase the demand for these metals in the near future. As a consequence, a demand competition between technologies might arise (energy- (e.g. PV) vs. ICT applications), which would increase the pressure on scarce metals supply, but also could drive the development towards a minimisation of scarce metal requirements or substitution.

7.2 The 'criticality' of technology metals

According to recent studies addressed in chapter 3, the following scarce metals appear to have a high supply risk or to be 'critical': antimony, beryllium, cobalt, gallium, germanium, indium, niobium, PGM, REE, tantalum and tungsten. However, this result has to be interpreted with care, since the scopes and methodologies of the studies addressed differ from each other and the criticality of a metal is subject to high temporal dynamics, i.e. that it may rapidly change due to e.g. altering geopolitical conditions.

A separate evaluation of scarce metals criticality for Switzerland makes sense insofar as raw material supply restrictions might have other impacts on the economy than those identified in the above mentioned studies for the European Union and the United States. In particular, as it is expected that the major share of potentially critical metals enters Switzerland (indirectly) through (semi-finished) products, the impacts of scarce technology metals supply restrictions on their availability should be further investigated.

7.3 The environmental dimension of 'criticality'

As demonstrated in chapter 0,particularly high environmental impacts are generated during the primary production of scarce technology metals such as gold and PGMs. However, because many scarce technology metals either occur as by-products or coupled products, which requires the application of arbitrary allocation rules, the extent of these environmental impacts is debatable.

In the future, the environmental impacts associated with primary production of scarce technology metals are expected to increase either due to a shift to other resource types (as it is the case e.g. for lithium), decreasing ore grades (as it is the case for e.g. gold) or mining at greater depths. Australian studies, in particular, argue for higher impacts, since they are rather pessimistic that technological developments in mining will counterbalance higher material throughput with lower ore grades.

For the secondary production of scarce metals from EoL products, significantly lower environmental impacts compared to the primary production have been reported for precious metals such as gold and palladium in a recent life cycle assessment of the Swiss WEEE collection and recycling systems (Wäger et al. 2011a). How far this also will be true for the secondary production of other scarce metals from EoL products will depend on the specific collection, pre-processing and recovery processes. Provided that data on such processes are available, this will have to be investigated in future LCA research projects.

In view of reducing the environmental impacts of scarce metals supply, important decisions will lie in the hands of the producers, in particular regarding product design and the procurement of raw materials or semi-finished products for which scarce metals are required. In any case, a reduction of environmental impacts related to scarce metals supply to the minimum will require the application of a life cycle perspective to identify the "hot-spots" and to allow for appropriate interventions. This should include the consideration of possible rebound effects induced by the consumption of a great number of environmentally optimised products.

7.4 Intervention options for a more sustainable scarce metals governance

As shown in chapter 5, in existing studies and reports addressing scarce metals supply risks and criticalities, different interventions towards a more sustainable governance of scarce metals have been implicitly or explicitly proposed. (Wäger et al. forthcoming) integrated the typical intervention domains addressed into a generic framework towards a sustainable governance of scarce metals, which transcends the strategic issue of supply independency. In view of its application, the generic framework will require two specifications at least. Taking into account that every scarce metal has its own demand and supply 'history' (European Commission 2010, Wäger et al. 2010), and that different societal levels (inter alia consumer, company, business sector, state, international community), with their particular possibilities and limitations are addressed, this generic framework of possible interventions domains will have to be prioritized for every scarce metal or scarce metals family. First steps in this direction have been undertaken on the occasion of an expert workshop (Wäger et al. 2011b)

Establishing a simple hierarchy of most effective interventions for a specific scarce metal or scarce metals family however appears to be difficult, not least because the scarce metals life cycle typically transgresses the boundaries of traditional political entities and involves many actors with limited information. A main issue to be considered when establishing intervention priorities will therefore consist in identifying possibilities to motivate and integrate actors along the life cycle, not least in the recycling chain.

For any political entity the possibilities for interventions will depend on its specific natural, societal and techno-economic conditions. For an economically well-developed political entity without any significant primary mineral resources and limited emerging technology production capacities like Switzerland, the most obvious direct interventions along the life cycle phase will be related to the production, use, recycling and disposal life cycle phases, accompanied by measures related to knowledge provision (e.g. supply chain certification, identification of substitution options, providing data on anthropogenic scarce metals stocks and flows, developing (eco-)efficient pre-processing and recovery processes) and the institutional setting. Although the impact of these interventions on a global scale may be limited, contributing to supply security, avoiding dissipation of scarce metals and generating less specific environmental impacts than primary production are considered to be sufficient reasons to support their consequent implementation.

7.5 Recycling – and product design opportunities

While for some scarce metals recycling technologies are available and EoL recycling rates are comparatively high, for many precious metals such as gallium, germanium, indium, osmium REE, tantalum or tellurium EoL recycling rates are below 1% (UNEP 2011). Increasing the EoL recycling rates requires a good accessibility of the scarce metals, a good EoL collection rate, and efficient pre-processing - and recovery processes. While in Switzerland the collection rates of e.g. WEEE are high, pre-processing and recovery of most scarce metals except some precious metals are very low. Indeed, for several critical scarce metals such as lithium, REE or tantalum are not yet available or will never be economic for thermodynamic reasons.

Compared to base metals, scarce metals are mostly used at very low concentrations. Product design could greatly improve EoL recycling rates by designing products in which scarce metals can be easily localized and accessed. In particular, this means easy disassembly of parts containing scarce metals and, if scarce metals are part of very compact blends (e.g. composites, alloys or compounds) and/or extremely thinned out (e.g. dopants), a concentration of these functionalities in easily removable building components. The use of easily removable components could be promoted by specific recovery targets for certain elements, as well as the installation of a proper pre-treatment infrastructure allowing to feed them into optimized recovery operations (electro, hydro- and/or pyrometallurgical processes).

An increase of EoL recycling rates for scarce metals allows, in particular, to avoid a dissipation of scarce metals into other materials (as tramp elements e.g. in base metals) or into the environment (e.g. via landfilling of slags), which will mostly be thermodynamically irreversible, and to take advantage of the most often lower environmental impacts of recycling compared to primary production (for example, the primary production of REE is associated with the emission of radioactive isotopes, which would not be the case for their recovery from e.g. WEEE; see e.g. (Schüler et al. 2011)).

For some EoL products and components, reuse or remanufacturing may be the preferred option over recycling. In particular, reuse is an option for components where the recovery of the elementary metal and its reintegration into the same alloy is energy intense (such as NdFeB magnets). Moreover, keeping the critical elements in the stock of operating infrastructure (e.g. EV batteries at <80% capacity re-used as electrical grid buffers) might be the simplest and most cost effective temporary solution as long as efficient material recovery technologies are not available.

Besides EoL product recycling and reuse, the recycling of production scrap should be given a high priority, as it is to be expected that it generally has a higher recycling potential (scarce metals concentrations, homogeneity, amounts) than EoL scrap.

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Annexes

Annex 1

Annex 1: Overview of recent studies addressing factors determining the criticality of metals (in their order of appearance)

	Goals and scope	Elements considered	Heuristics/ methodology	Most critical elements according to evaluation
Behrendt et al., 2007	Evaluate the 'rarity' of metals applied in Information and Communication Technologies (ICT) using selected criteria;	Au, Ba, Be, Bi, Cd, Co, Cr, Cs, Ga, Ge, Hf, Hg, In, Ir, Mg, Mn, Mo, Nb, Ni, Os, Pb, Pd, Pt, Re, REE (incl. Sc and Y), Rb, Rh, Ru, Ta, Sb, Se, Sn, V, W, Zn, Zr	- Analysis of arguments for the 'rarity' of elements using selected criteria;	- In (5 criteria fulfilled) - Sb (4 criteria fulfilled) - Au, Co, Ir, Pd, Pt, Re, Rh, Ru, Sn, Zn (3 criteria fulfilled)
Buchert et al., 2009	Analyse the global availability and expectations for the development of the 'critical metals' demand, supply and prices in-depth; Comprehensively analyse their recycling potential and identify gaps; Explore favourable framework conditions, proposed course of actions, policies, incentives, funds, instruments, models etc. to predict and monitor the availability of critical metals and recycling systems	Co, Ga, Ge, Li, In, Pt, Pd, REE, Ru, Ta	- Classification of minor metals according to demand growth, supply risks and recycling restrictions, with sub-criteria for each of these topics.	- Ga, In, Te (short-term) - Li, Pd, Pt, REE, Ru, Ta (mid-term) - Co, Ge (long-term)

	Goals and scope	Elements considered	Heuristics/ methodology	Most critical elements according to evaluation
Eisler et al., 2009	- Evaluate technology metals with expected significantly increased future demand with regard toindustry sectors they are applied, where they are extracted, which are the known stocks and how the supply situation could change until the year 2030.	- Ga,Ge,In,Nd, Sc,Ta	- Database and literature review	- Ge,Nd
National Research Council, 2010	Address nonfuel mineral issues in advance of a national crisis (it is potentially prudent and cost-effective to determine policy and appropriate action before any such crisis occurs).	Cu, Ga, In, Li, Mg, Nb, PGM (Pd, Pt, Rh), REE, Ta, Ti, Va	Development and application of a 'criticality matrix' considering supply restrictions (horizontal axis) and their impacts (vertical axis)	Ti (very high supply risk and impact) In, Mn, Nb, Pd, Pt, REE (high supply risk and impact) Ga (high supply risk, moderate impact)
European Commission, 2010	Develop a methodology to assess criticality and apply this methodology to a selection of raw materials	Ag, Al, Barytes, Bauxite, Be, Bentonite, Clays (and kaolin), Co, Cr, Cu, Diatomite, Feldspar, Fluorspar, Ga, Ge, Graphite, Gypsum, In, Iron Ore, Li, Limestone (high grade), Magnesite, Mg, Mn, Mo, Nb, Ni, Perlite, PGMs, REE, Re, Sb, Silica sand, Talc, Ta, Te, Ti, V, W, Zn	Development and application of a 'criticality matrix' considering supply restrictions (horizontal axis) and their impacts (vertical axis)	Be, Co, Ga, Ge, In, Mg, Nb, REE, Pd, Pt, Sb,Ta

Annex 2

Annex 2: Global warming potential and aggregated environmental impacts for the production of selected traditional industry metals and scarce technology metals

	Global warming (GWP 100) kg CO_2-Eq / kg [1)]	Environmental impacts in EcoIndicator'99-Pointse / kg [1)]
Traditional industry metals		
Aluminium (at plant)	12.4	0.82
Copper (at refinery)	3.2	18.6
Lead (at regional storage)	1.1	0.39
Reinforcing steel (at plant)	1.5	0.10
Zinc (at regional storage)	3.4	1.2
Scarce technology metals		
Gallium (semiconductor quality, at regional storage)	210	11.3
Gold (at regional storage)	13'200	17'300
Indium (at regional storage)	154	46.4
Neodymium (as neodymium oxide, at regional storage)	38.6	3.5
Palladium (at regional storage)	9'730	10800
Platinum (at regional storage)	14'800	9540
Rhodium (at regional storage)	29'000	19'300
Silver (at regional storage)	100	82.8
Tantalum (capacitor quality, at regional storage)	260	30.1

Annex 3

Annex 3: Material intensities per service unit (MIPS) for the production of selected traditional industry metals and scarce technology metals (http://www.wupperinst.org/uploads/tx_wibeitrag/MIT_v2.pdf)

	MIPS in tons / kg
Traditional industry metals	
Aluminium	1.096
Lead	0.016
Copper	0.717
Steel (blast furnace)	0.064
Zinc (electrolytic)	0.368
Scarce technology metals	
Gold	540
Palladium	527
Platinum	320
Silver	7.5

Annex 4

Annex 4a: Pre- and post-consumer recycling potential for selected scarce technology metals according to (Buchert et al. 2009)

	Pre-consumer recycling	Post-consumer recycling
Cobalt	Potentials are seen in an increasing efficiency of the recycling process.	Enhanced recycling flows are possible. The recycling quotas of the EU Battery Directive will lead to an increasing number of collected batteries.
Gallium	Pre-consumer recycling rate already very high.	Potentials might be realized when gallium input in recycling plants will rise and gallium prices will deliver economic incentives The most promising recycling technology is recovery of gallium in WEEE smelting plant
Germanium	Increasing potential due to increasing production figures.	A large potential would lie in the access to fiber optics cables. A higher germanium availability is expected through the introduction of the new WEEE Directive The lack of data on global reserves could boost the necessity for enhanced recycling technologies.
Indium	The amount of accrued new scrap will rise due to higher production figures.	Further potentials could be opened up depending on the extension of suitable recycling facilities. From a technical perspective the post-consumer recycling of indium is less difficult as compared to e.g. tantalum.
Lithium	Depends on the production developments of lithium batteries and the price developments.	A large downstream material flow from batteries is expected. Collection rates for batteries will rise due to e.g. the EU Battery Directive. However, the economic incentive for lithium post-consumer recycling is lower than for other metals.
Palladium	No further potentials expected.	Remarkable further potentials from consumer applications, in particular dental material as well as automotive catalysts and WEEE in industrial and developing countries.
Platinum	No further potentials expected.	Remarkable further potentials from consumer applications, the key for success being an enhanced collection of automotive catalysts and WEEE in industrial and developing countries, and a progress in international co-operations regarding recycling chains.
Ruthenium	Further potential expectable due to high ruthenium prices and large new scrap volumes (hard disks and sputter target production scrap for hard disk manufacturing).	Because different refining plants are equipped to separate ruthenium from copper, an increased post-consumer recycling potential can be expected for the future. Due to the dissipative applications of ruthenium and a drain of WEEE into developing countries the global take-back infrastructures will be the crucial challenges. .

Annex 4b: Pre- and post-consumer recycling potential for selected scarce technology metals according to (Buchert et al. 2009) (cont'd)

REE	REE applications comprise a wide variety, mostly with a very fine dispersion. Potentials can only be identified on the basis of a detailed analysis for each element and its applications.	Probably low potential due to the widespread use at low concentrations, frequent application in alloys and a tendency to being transferred into slags (as oxides) in smelter plants.
Tantalum	No further potentials besides efficiency enhancements.	The dissipation of tantalum in post-consumer waste and its chemical properties are a crucial challenge for further research and development. Technical improvements (in pyrometallurgical processes, tantalum oxidises and is transferred into the slag phase) would open new potentials.
Tellurium	Probably high potential in electronics and solar cell production.	Almost no potential for tellurium recovery from dissipative applications (e.g. alloys) However there is a potential from electronic scrap if the scrap is processed in appropriate smelting plants already having the ability to recover tellurium. Precondition for this recycling route is an efficient electronic scrap collection.