ERA-MIN Research Agenda

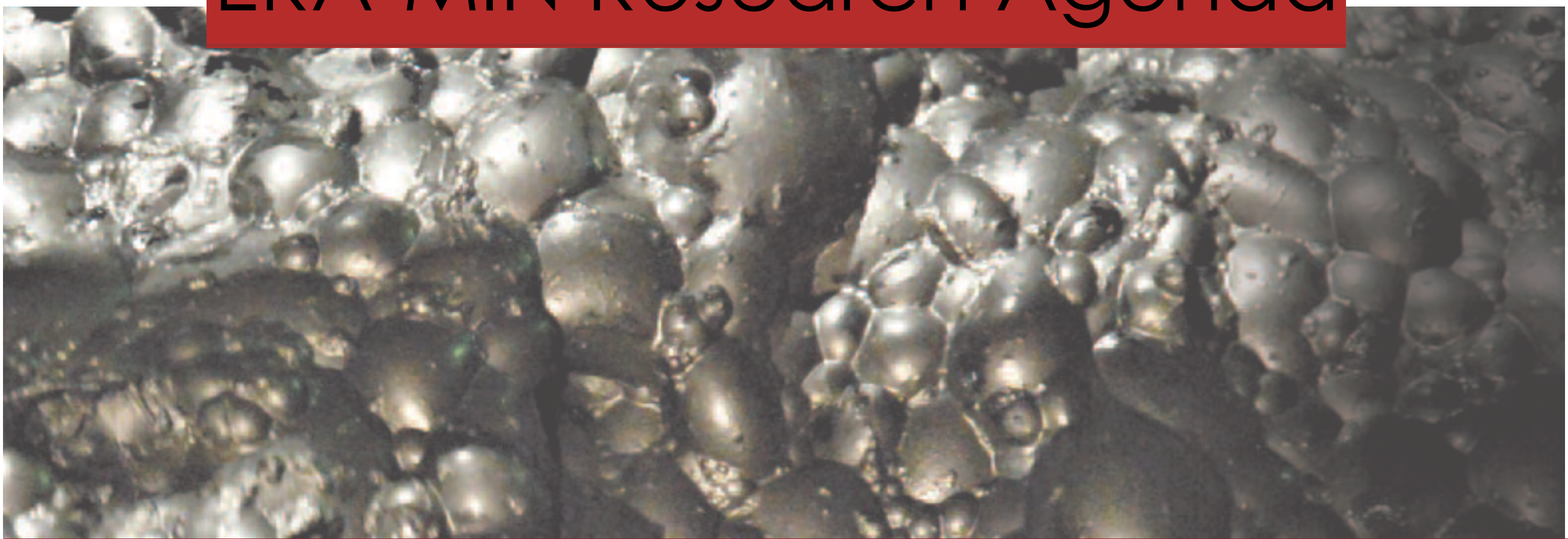
Olivier Vidal, Pär Weihed, Christian Hagelüken, Derk Bol, Patrice Christmann, Nicholas Arndt

ERA·MIN

NETWORK ON THE INDUSTRIAL HANDLING
OF RAW MATERIALS FOR EUROPEAN INDUSTRIES

SEVENTH FRAMEWORK PROGRAMME

ERA-MIN Research Agenda



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NETWORK ON THE INDUSTRIAL HANDLING
OF RAW MATERIALS FOR EUROPEAN INDUSTRIES

Forword

ERA-MIN (http://www.era-min-eu.org/) is an ERA-NET on the Industrial Handling of Raw Materials for European industries that was launched in November 2011 . It is supported by the FP7 and is aimed at setting up networks and mechanisms to foster coordinated research in the field of industrial production and supply of non-energy, non agricultural raw materials, in line with the "EU Raw Materials Initiative". To achieve this objective, ERA-MIN is conducting three main tasks: 1) Mapping and networking of the European non-energy mineral raw materials research community, 2) Defining research priorities, and 3) Implementing the research actions and European research programs financed by the fifteen national and public funding agencies involved in ERA-MIN.

The Research Agenda presented in the following pages lists the most important topics of research and innovation identified and discussed by 150 experts from the academic and industrial sectors during the year 2012. It addresses issues covering the whole value chain of non-energy, non-agricultural raw materials, and it tries to maintain a comprehensive vision including both the industrial and academic points of view. The nature of proposed research themes and their timeframe are discussed, in order to help the national and regional funding agencies identifying the topics they can support financially. The ERA-MIN Research Agenda has been written by the leaders of the five working groups that were set up by ERA-MIN during its kick-off meeting in February 2012 : Pär Weihed (Primary resources, Christian Hagelüken (Secondary resources), Derk Bol (substitution), Patrice Christmann (Public policy support and mineral intelligence), Nicholas Arndt (Education and international cooperation), and Olivier Vidal (other sections and general editing). These authors express their warm acknowledgements to all the experts who have actively contributed to the working groups discussions.

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Executive summary

Non-energy and non-agricultural raw materials underpin the global economy and our quality of life. They are vital for the EU's economy and for the development of environmentally friendly technologies essential to European industries. However, the EU is highly dependent on imports, and securing supplies has therefore become crucial.

A sustainable supply of mineral products and metals for European industry requires a more efficient and rational consumption, enhanced substitution and improved recycling. Recycling from scrap to raw materials has been rapidly gaining in quantity and efficiency over the last years. However, continuous re-use cannot provide alone the necessary quantities of mineral raw materials, due to i) recycling losses, ii) the worldwide growing demand in raw materials, and iii) the need of «new» elements for the industry. To fully meet future needs, metals and mineral products from primary sources will still be needed in the future. Most of them will continue to be imported from sources outside Europe; but others can, and should, be produced domestically.

Advanced research and innovation are required to improve the capacity of existing technologies to discover new deposits, to improve the efficiency of the entire geomaterials life cycle from mineral extraction to the use as secondary resource of products at the end of their industrial life, and to reduce the environmental footprint of raw materials extraction and use.
Research and innovation must be made to acquire knowledge as well, and to improve our basic understanding of all engineering and natural processes involved in the raw materials life cycle, as well as the coupling of these processes. Finally, research has to go beyond the present-day economic and technological constraints, and it should be closely associated with training and education in order to maintain existing skills and to share the most recent developments with the industrial sector. A long-term vision of research is necessary in order to have the capacity of evaluating the environmental and societal impacts of present and developing industrial activities and to imagine tomorrow's breakthrough concepts and technologies that will create new industrial opportunities. These objectives require the input of contrasted scientific and technical skills and competences (earth science, material science and technology, chemistry, physics, engineer, biology, engineering, environmental science, economy, social and human sciences, etc). An important challenge is to gather all these domains of expertise towards the same objective.

The ERA-MIN Research Agenda aims at listing the most important topics of research and innovation that will contribute to i) secure the sustainable supply and management of non-energy and non-agricultural raw materials, and ii) offer opportunities of investment and employment opportunities in the EU. The ERA-MIN Research Agenda

- addresses issues covering the whole value chain, which have been distributed and discussed within five groups gathering about 150 experts during 2012: WG1-primary resources, WG2-secondary resources, WG3-substitution, and two groups focused on cross-cutting issues: WG4-Public and private policy support and mineral intelligence, and WG5: Education and international cooperation.

- maintains a comprehensive vision including both the industrial and academic points of view. The nature of proposed research themes (fundamental vs technological/applied) and their timeframe (short term goals; medium term goals; long term goals) are discussed, in order to help the national and regional funding agencies to identify the topics they can support financially.

Main challenges and issues related to the raw material life cycle

Main challenges

The following main challenges of research and innovation were identified by the working groups:

- Improve techniques for finding and mining the new resources that are necessary to satisfy the growing worldwide demand. As large, rich deposits located in countries that offer access to their mineral resources are getting rare, research is vital to explore deeper-seated deposits in Europe, deposits in higher risk countries and to develop knowledge on unconventional resources.
- Improve the efficiency of material production and use throughout the whole supply chain to turn this chain into a materials circle where waste becomes the resource needed by another process, and where dissipation is avoided as much as possible. To achieve this, innovative recycling technologies for technology metals from complex products are as important as non technical innovations to obtain better access to secondary resources and ensure their resource efficient processing throughout the recycling chain.
- Overcome metallurgical and especially extractive metallurgy challenges to enable a resource (whether primary or secondary) to give raise to the metals used by the downstream industry. This will contribute to reducing Europe metal import dependency and create jobs and business opportunities.
- Reduce or avoid the use of scarce materials. A significant reduction can be achieved by substituting scarce elements by more abundant ones with the same functionalities, or by substituting the functionality itself. This requires specific research in the field of elements and material properties.
- Ensure, in harmony with the economic stakeholders and the society, the flow of minerals and metals needed by the economy and to ensure that this happens in line with the sustainable development framework. This requires reliable data and information on the global mineral resources industries, on capitalistic controls, trade and non-trade barriers, market drivers, recycling and related facilities, trade flows, life-cycle and material flow data, etc, and the development of modelling integrating economic, environmental and social factors as well as objective functions controlling them. Such information and modelling is needed to develop and implement an EU non-energy mineral raw materials policies.
- Fill up the research vacuum that developed over the last three decades after the closure of research centres in major companies combined with decreased activity in both universities and government agencies.

- Ensure the training of young generations that will have to cope with the multi-faceted raw material issues. Training of professionals is also necessary to disseminate the latest knowledge and good practices in the fast evolving field of research on non-energy and non-agricultural raw materials.

Specific issues along the raw material value chain

Primary resources supply

In a context of growing demand, new resources have to be found on shore and off shore. However, mining activities will be possible only if eco-efficient, environmentally sound technologies are developed and by social dialogue. It is also necessary to develop technologies adjusted to the properties of the processed raw materials to increase extraction efficiency maximising metal recoveries of the production processes and minimising pollutant emissions at competitive production costs. EU sustainable supply of primary resources needs:

- New geological, geophysical and geochemical data, which are lacking for most of Europe, as exploration in the EU lags far behind that of most developed countries.
- To address the social and ecological aspects of sustainable development. Environmental goals like waste reduction, reduced mass movement and land use should become inherent objectives of the ecological part of every future mining/quarrying related development activities.
- New methods and technologies and the assessment of potentially associated risks in deep mines with high rock pressure, high temperatures and dusty and remote single working place
- New methods and technologies for mineral processing at an industrial scale, from comminution to concentration and extraction. These technologies will need to be energy- and resource-efficient, whilst at the same time have a minimal environmental footprint, and they will be adapted to the treatment of primary mineral resources of increasing complexity and decreasing grade. Innovation in metallurgy is one of the key factors to unlock the development of a growing number of mineral deposits that otherwise cannot be technical and economically exploited.

The ERA-MIN roadmap lists the most important research and innovation topics in four key areas related to the above-mentioned challenges: exploration, mining/ quarrying, mineral processing, metallurgy, and mine closure and rehabilitation.

Secondary resources supply

Recycling is mandatory to secure the access to raw materials and to improve resource management, energy efficiency and environmental impacts. Metals in principle are infinitely recyclable without a degradation of quality. However, recycling becomes much more difficult with increasing product complexity. Substantially boosting metal recycling requires innovation throughout the entire life cycle, and technical solutions that offer the flexibility to cope with future and new product types. Technical innovation is however not sufficient, and recycling needs to be embedded in a broader context of non-technical, economic and social/behavioural issues.

The ERA-MIN Research Agenda focuses on the following specific challenges that need to be addressed by research and innovation along the main steps of the product / material life cycle:

- Recycling of mining and smelting residues (including historical dumps and tailings)
- Product manufacturing
- Product distribution & use
- End-of-life collection and logistics
- End-of-life pre-processing
- Metallurgical extraction
- Closing the loop from an integrated approach

For all these steps, innovation is needed in the following areas:

- Information / availability of data
- Technology and process
- Economics
- Others (organisation, behaviour/social, environment)

The overarching objective is to integrate these challenges into a systemic view of the whole chain with all research activities coherently feeding into this while considering interdependencies.

Substitution of critical materials

One way of reducing the dependency of European industry and society on critical materials is by eliminating or reducing the use of these materials in products and infrastructure; and replacing them with other, more abundant materials. This is a challenging issue, because the materials we are using are the result of many years of research and development, and they are often optimised for their purpose and the required properties. Moreover, to develop a new material from first research to production usually takes 10 years or more. Will the critical materials to be replaced still be critical and expensive 10 years from now? And will the R&D route taken for substitution not become obsolete by a whole new material or a whole new products ? These questions should be answered before investment in specific substitution efforts, which requires the thorough analysis and involvement of all stakeholders.

The ERA-MIN Research Agenda focuses on the following types of substitution:

- Substitution of critical elements in existing materials by more abundant ones and material saving.
- Replacement of existing materials by new materials containing less or no critical materials.

The following key areas of material applications were investigated:

- 1. Materials for green energy technologies (enable the building up of a green energy infrastructure of solar cells, wind turbines, grids, batteries, electro motors, electric cars, etc.)

- 2. Materials under extreme conditions (enable the production of special tooling, high temperature materials for gas turbines, super lightweight alloys, high quality coatings, etc. which depends less on critical materials)
- 3. Critical materials in bulk applications (reduce the use of critical materials in base metal alloys and other high volume applications like building infrastructure)
- 4. Materials for electronic devices and medical applications (reduce use of critical materials to ensure availability/ affordability of electronics and medical devices for European and export markets)

These key areas have been chosen either because critical materials are used or will be used in large quantities (1. and 3.), or because critical materials are used in small quantities but play a key role in achieving certain material properties (2. and 4.), or both (1.) The definition of key areas also anticipates two grand societal challenges: the transition toward the use of sustainable energy sources and the ageing of our society. In addition to above listed four key areas on material applications, a last key area has been defined:

- 5. Enabling technologies & research infrastructure (generic research, technologies, models, databases and analysis tools to support substitution research). This key area does not focus on one specific area of material application, but is of a generic nature and is needed to provide a basis for substitution R&D to be carried for the other four key areas.

Overlapping and transversal issues

Several research and innovation topics of the general themes listed above possess interdependent and common features with high cross fertilization potential: Energy and environmental issues, Mineral and element separation, Material science, and setting up Databases. These topics require a strongly coordinated research involving technical, scientific and social disciplines, as well as public and private sectors. This is also the case of the following themes that were addressed by the two remaining working groups:

Public policy support and mineral intelligence

The achievement of sustainable, secure and affordable access to mineral raw materials and the efficient, environmentally responsible use of mineral resources not only depends on scientific and technical progresses. It also depends on i) clear, enabling public policies; ii) capable and responsible partners in the primary and secondary minerals and metals industries; iii) effective, well-trained and suitably resourced administration iv) collaboration of public and private sectors in a spirit of partnership.

The ERA-MIN Research Agenda addresses the research and innovation needs related to public policy and minerals intelligence in the following areas:

- Information / availability of data
- Material flow and life-cycle analyses as public goods
- Long-term mineral raw materials criticality assessments

- Addressing public acceptance in the EU
- Fostering eco-efficiency

Education and international cooperation

Europe currently imports between 60 and 100% of all metals. The production of high-technology materials and consumer goods, on the other hand, is spread throughout Europe. It is therefore necessary to foster ***international cooperation*** in research and education between European countries and between these countries and the producers and consumers of raw materials throughout the world.

In the past 5 years, renewed interest in the minerals sector has led to a renewal of mining, particularly around the fringe of Europe. In parallel, activity in mineral processing and particularly in recycling has increased and issues related to the security of supply of raw materials is gradually leading to an increased interest in materials science and engineering. This recent evolution is accompanied by a strong need of teachers and administrators with accurate and complete information about all parts of the materials life cycle. However, in many sectors, there is a scarcity of trained specialists and a lack of infrastructure and teachers. Revitalised ***research*** in the materials life cycle must also be coupled with improved and expanded ***teaching and training***, particularly in the latest clean technologies. Promoting education and training is necessary in order to: a) contribute to Europe's overall expertise in the field; b) increase the public awareness of the importance of raw materials as part of the foundation of modern society's material quality of life, and c) maintain the supply of professionals (geologists, materials scientists, engineers, designers, teachers) needed to support both traditional and high-technology industries in Europe.

The ERA-MIN research agenda focuses on the need to

- Establish databases of present European education in all disciplines related to the raw materials life cycle, identify current skills shortages and adapt training programs to meet emerging needs; Identify the specific needs of industry in the domains of research and education, support specialised, high level short courses for graduates and professionals, develop capacity-building courses co-sponsored by funds from the public and private sector, define existing and future possibilities for internships for students and 'sabbaticals' for researchers and teachers in all sectors of the minerals industry; promote collaborative work and exchange with non-European countries; support existing and proposed research and teaching pan-European networks. It might be suitable to establish a European Centre of research and training in sustainable use of materials complemented by an infrastructure research network.

- Develop direct links with the companies and other agencies that produce metals, support EU companies willing to engage in exploration in EU partner countries, develop links with countries surrounding the EU that either have an active mining industry or a high geological potential.
  Improve cooperation with developing countries, with special emphasis on the Africa Union and ACP.

Introduction

Rationale

Non-energy and non-agricultural raw materials, which encompass the metals, construction minerals and minerals used by industry (e.g. ceramics, abrasives), underpin the global economy and our quality of life. They are vital for the EU's economy and for the development of environmentally friendly technologies essential to European industries – automotive, aviation, wind power, photovoltaic and lighting – as well as the high-tech sector as a whole, which uses tons of metals each day for their products. However, since domestic production of metals and mineral products in the EU is limited to 3% of global production, while consumption is about 20% of the total, the EU is highly dependent on imports. The EU currently imports between 60 and 100% of all metals used by its industry, with attendant penalties for the continents balance of payments and security of supply.

In the present context of i) growing demand, not only for base metals but also for "new" commodities and materials used in the high-tech sector, including green technologies; ii) anticipated decrease in the use of fossil energy driven by environmental concerns if not by supply problems; and iii) increase of world population and anthropogenic environmental footprint, the EU faces a range of critical issues that can threaten the security of supply of the highly diversified mineral resources needed by its economy. Securing supplies has therefore become crucial. This requires advanced research and innovation to improve the capacity of existing technologies to discover new deposits, and to improve the efficiency of the entire geomaterials life cycle, from mineral extraction and processing to product design, use, reuse and the exploitation as secondary resource of products at the end of their industrial life. Closing the loop, the development of a circular economy incorporating a maximum level of recycling, substitution and optimised use of resources must become a top priority if the challenges faced by humanity in the coming decades are to be addressed.

Fig. 1 shows that the lifecycle of raw materials starts with the discovery and mining of ore deposits, which brings materials from the "geosphere" into the "technosphere". Extracted raw materials must then be used as efficiently and economically as possible during manufacturing and throughout their entire life cycle and their dissipation during their use can be minimised. Hence, a sustainable management of raw materials requires:

- Reduction of the loss of elements within residues and waste products during the entire life cycle;
- Reduction of the amount of energy, water and aggressive compounds used during mining, refining and processing;
- Intelligent product design as well as smart and aligned processes over the entire value chain, with the double goal of reducing the need for rare metals and fostering end-of-life recycling of such metals;
- Enhanced substitution at the product design and manufacturing stages, with

the goal of replacing critical elements by more abundant and cheaper elements with the same properties and functionality.

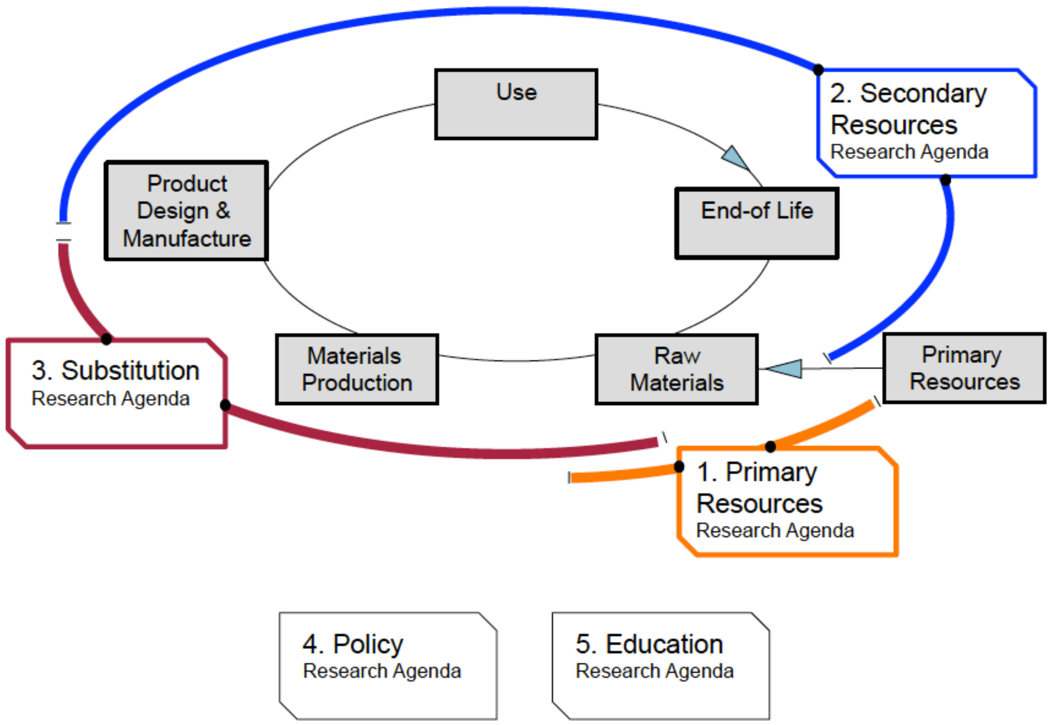

Figure 1: Life cycle of raw materials (grey colour) and corresponding working groups that were set up to formulate the ERA-MIN research agenda (open boxes).

Research efforts must be made to improve existing technologies and reduce the dissipation of raw materials, while reducing the input of water, energy and chemicals and the output of all kind of emissions to air (including greenhouse gases) and water, any harmful solid waste and any negative impact on biodiversity during mineral exploration, extraction and processing.

Research and innovation are also necessary to acquire knowledge and improve our basic understanding of engineering processes involved in the geomaterials life cycle, the fundamental properties and behaviour of elements in various environments and under various conditions, and our basic understanding of natural processes responsible for the transportation, concentration and deposition of elements to form viable resources. In that sense, research has to go beyond the present-day economic and technological constraints. It should not be restricted to the supply of present-day critical materials, and it should be closely associated with training and education in order to maintain existing skills and to share the most recent developments with the industrial sector. Finally, research should foster a long-term vision in order to have the capacity of evaluating the environmental and societal impacts of present and developing industrial activities and to imagine tomorrow's breakthrough concepts and technologies that will create new industrial opportunities. Research on the supply of raw material is complex and requires the input of contrasted scientific and technical skills and competences (earth science, material science and technology, chemistry, physics, engineer, biology, environmental science, economy, social and human sciences, etc). An important challenge is to gather all these domains of expertise towards the same objective.

To achieve this and foster coordinated research in the field of non-energy and non-agricultural raw materials, ERA-MIN[1] has prepared a Research Agenda addressing most of the above-mentioned issues, and listing the most important technological and scientific challenges to be addressed by future research with a two to ten years' time horizon.

Objective of the research agenda

The ERA-MIN Research Agenda aims at listing the most important topics for research that will help to secure the sustainable supply and management of non-energy and non-agricultural raw materials. The Research Agenda is expected to be complementary to other scientific vision documents and research agendas issued by parallel European initiatives, in particular the Strategic Research Agenda from ETP-SMR[2].

The particularity of ERA-MIN is that 1) it addresses issues covering the whole value chain, which have been distributed into the five groups shown in Fig. 1 (primary resources, secondary resources, substitution, and two groups focused on cross-cutting issues), and 2) it focuses on national, regional and EU public funding to feed the future ERA-MIN research programs on raw materials. The national funding agencies having different visions concerning the kind of research they are willing to support (short vs long term research, applied vs basic research, primary vs secondary sources of raw materials, etc), ERA-MIN tried to maintain a comprehensive vision including both the industrial and academic points of view. For the five research areas shown in Fig. 1, both the nature of research (fundamental vs technological/applied) and its timeframe (short term goals - 2 years; medium term goals -5 years; Long term goals (2020 and beyond) are discussed.

Methodology

Five working groups (see Fig. 1) have been set up during the ERA-MIN kick-off

1 ERA-MIN is an ERA-NET program on the Industrial Handling of Raw Materials for European industries and is supported by the European Commission's 7th Framework Programme. It is aimed at setting up networks and mechanisms to foster coordinated research in the field of industrial production and supply of raw materials, in line with the "EU Raw Materials Initiative". To achieve these objectives, ERA-MIN is conducting three main tasks: 1) Mapping and networking the European non-energy mineral raw materials research community, 2) Identification of research priorities, and 3) Implementing research actions and European research programs financed by several European countries. http://www.era-min-eu.org/

2 European Technology Platform on Sustainable Mineral Resources, http://www.etpsmr.org/

meeting in February 2012:

1: Primary resources supply;

2: Secondary resources supply;

3: Substitution of critical materials;

4: Public policy support and mineral intelligence;

5: Education and international cooperation

The working groups involved about 100 experts[3] coming from industry, academia, research centres, and funding agencies. During the ERA-MIN kick-off meeting, the working groups leaders were designated as well, and discussions have been directed towards the topics to cover, the agenda and the main expected outcomes of each WG. Representatives of the ETP-SMR were invited to actively participate to the ERA-MIN reflexion and roadmapping procedure (WG1, 2 and 4, see Fig. 1, were led by representatives of the ETP-SMR). The WGs have been completed between February and June 2012, under the responsibility of the WG leaders. The groups worked in parallel during six months, and all groups had at least one plenary meeting to organise their work and homogenise the sub-groups contributions. The work has been a transparent process where each expert who has indicated an interest in the reflexion has had the opportunity to contribute to the process. In December 2012, the WG leaders drafted a document synthesising the main outcomes of this collaborative work. A meeting of all WG leaders and the ERA-MIN coordinator has been organised in January 2013 to homogenise the contributions, discuss the possible overlaps, and identify transversal issues not yet addressed by the WGs. The drafted version of the Research Agenda has been sent in February to independent stakeholders and experts of the raw materials issues (most of them had not been involved in the roadmaping process). These have been invited to the ERA-MIN Lisbon meeting in March 2013, where the research agenda has been presented and discussed in parallel and plenary sessions during two days. After the meeting, the present and consolidated version of the roadmap has been prepared.

Identified topics of research and innovation

Main challenges

The following main challenges of research and innovation were identified by the working groups:

- Improve techniques for finding and mining the new resources that must be found to satisfy growing worldwide demand. As large, rich deposits located in countries that offer access to their mineral resources are getting rare, research is vital to explore deeper-seated deposits in Europe, deposits in higher risk countries and to develop knowledge on unconventional resources.

[3] See Appendix

- Improve the efficiency of material production and use throughout the whole supply chain to turn this chain into a closed circuit within which waste systemically becomes the resource needed for a succeeding process, and where dissipation is avoided as much as possible. To achieve this, innovative recycling technologies for technology metals from complex products are as important as non technical innovations to obtain better access to secondary resources and ensure their resource efficient processing throughout the recycling chain.
- Overcome metallurgical and especially extractive metallurgy challenges to enable a resource (whether primary or secondary) to give raise to the metals used by the downstream industry. This will contribute to reducing Europe metal import dependency and create jobs and business opportunities.
- Reduce or avoid the use of scarce materials. A significant reduction can be achieved by substituting scarce elements by more abundant ones with the same functionalities, or by substituting the functionality itself. This requires specific research in the field of elements and material properties.
- Ensure, in harmony with the economic stakeholders and the society, the flow of minerals and metals needed by the economy and to ensure that this happens in line with the sustainable development framework. This requires reliable data and information on the global mineral resources industries, on capitalistic controls, trade and non-trade barriers, market drivers, recycling and related facilities, trade flows, life-cycle and material flow data, etc, and the development of modelling integrating economic, environmental and social factors as well as objective functions controlling them. Such information and modelling will help to propose EU non-energy mineral raw materials policies and the legal basis to develop it.
- Fill up the research vacuum that developed over the last three decades after the closure of research centres in major companies combined with decreased activity in both universities and government agencies.
- Ensure the training of young generations to meet coming shortages of manpower and expertise in all parts of the geomaterials cycle. Training of future professionals, who will have to cope with the multi-faceted raw material issues, is necessary to disseminate the latest knowledge and good practices in the fast evolving field of research on non-energy and non-agricultural raw materials.

Overlapping and transversal issues

It clearly emerged that the research themes identified by the five working groups are often interdependent and possess common features. Moreover, the distribution of topics related to raw materials into different working groups that worked in parallel on the preparation of the Research Agenda should not hide the necessity of integrated research, as well as research that goes beyond the specific topics addressed by the working groups. These issues generally require research efforts involving contrasted scientific communities and have often a potential to emerge as breakthrough discoveries. This is particularly true for the following research themes, which are developed in the last section of the document:

- Energy and environmental issues
- Mineral and element separation, Material science

- Need for Databases
- Information for decision-makers, the citizens, and the industry
- Education, training and formation
- Integrated research and cross fertilization potential

Boundary conditions and structure of the research agenda

Almost all the elements of the periodic table are used in many different ways in engineered materials and components, and these are integrated into a myriad of products. The present version of the roadmap focuses on metallic minerals and metals, but construction minerals and minerals for the industry were considered in the first chapter dedicated to primary resources. Our analysis was not restricted to critical elements as defined by the EU[4], because today's list of critical materials may not cover all materials that will become critical in the future, and because each country has a somehow different set of critical materials. In addition, the definition of criticality may need an in-depth revision as the current approaches all focus on the assessment of current issues, while there is a crucial need to develop long-term criticality scenarios looking well into the future (10 to 20 years ahead from now). A fair and regularly updated estimate of the level of criticality for all the elements and minerals used by the industry must be made. This point is addressed in this Research Agenda. However, no prioritisation of research actions was made regarding the present level of element criticality.

The major outcomes of the five WG are summarised in five successive chapters. The structure of each WG contribution is similar, with a brief rationale, the addressed general challenges, some details about the motivation that lead to select specific research topics, and the adopted procedure of work. Then, the different challenges, innovative needs and research goals are listed in different subchapters. Several overlapping and transversal issues are presented in the last chapter.

The keys of success

The objective of the researches proposed in the following Research Agenda is to provide new concepts, approaches and technologies that will improve the sustainable and environmentally friendly management, production and recovery of raw materials, and thus the reduction of the EU dependency to their importation. To reach this objective,

- The efforts of research must be put on all levels of the Technology Readiness

4 Critical raw materials for the EU, Report of the Ad-hoc Working Group on defining critical raw materials, June 2010. In 2013 an update of this list will become available

Level (TRL) scale, from Basic Technology Research to System Test, Launch and Operation. Basic and non-technology research is important as well and is the condition of emergence of breakthrough concepts beside incremental improvements. This is true for the new challenges related to substitution, but also in more classical fields such as primary resources. Defining Key Performance Indicators is possible when the first level of the TRL scale is reached (and this is done in the ERA-MIN roadmap), but much more difficult for basic and non-technological research, which must remain risky and of long term.

- The human and financial support and capacities necessary to conduct the proposed researches must be available. ERA-MIN will organise the implementation of European joint calls fed by public funding provided by the national agencies involved in the network. However, The ERA-MIN Research Agenda is ambitious and a contribution from the private sector is another condition of success. Research at the TRL 1 to 3 should be coupled to existing or new industrial enterprises which will produce and apply the new materials and/or technnologies after proof of principle and prototyping. These enterprises should be involved from the start with an increasing financial contribution during upscaling the TRL. SME, which have not the critical mass to individually contribute to the discussions at the European level and to the efforts of research should remain active stakeholders of ERA-MIN through their national federations.
- Very contrasted fields of expertise will have to be involved on the same objective. As already mentioned and illustrated in the following pages, collaboration of public and private sectors is necessary, as well as collaboration between natural, social and financial sciences, lawyers and engineers working on different parts of the raw materials value chain.
- ERA-MIN actions should be linked and when possible team up with other European and national initiatives.

WG 1: Primary resources supply

Introduction

General challenges

One of Europe's challenges is to secure sustainable supply of raw materials, increasingly from European sources. Rapid increase in exploration investments is needed to find new resources to fulfil this goal. EU and Member States should improve the exploration infrastructure (research, knowledge base, data) to attract more investments in exploration within Europe. On going exploration has found recent highly economic deposits in Europe (e.g., Sakatti and Las Cruces) confirming that the chances of finding new important deposits in Europe are high. As land-based deposits become increasingly scarce, seafloor exploration opens possibilities to find new resources.

In line with the Europe 2020 mining and quarrying aim to achieve smart, sustainable and inclusive growth. Following the observed demographic trends global populations will increase to 9 billion by 2050, resource demands may start to outstrip the capacity to supply some of them in economic, environmental and social sound conditions. Securing mineral raw material supply and access to domestic mineral resources are crucial for the European society. Although further increases in recycling are expected to contribute in meeting the expected growth in demand, a further increase in global production of primary raw materials will be necessary.

Mineral raw materials must be mined 'where they are'. Therefore, we need to support policy development in land-use planning in order to secure as much as possible access to minerals deposits, even if they are located in harsh environments like the sea floor. We can support this by developing eco-efficient, environmentally sound technologies for minerals exploitation and by social dialogue activities to improve the image of mining/quarrying.

Metallurgy is the necessary step to transform a resource into the raw materials the downstream industry needs. Increase in mining activities in Europe is not dissociable to innovation needs in metallurgy, since a resource requires its task specific process to become the product the downstream industry needs. As mineral and geological trends show that resources are becoming lower grade and more interlocked, metallurgy requires (1) a further integration of Research and Industry and (2) access to up-scaling facilities in Europe (including pre-processing, pyrometallurgy and hydrometallurgy). This would contribute to giving an industrial reality to a resource. Emphasis in metallurgy should be on increasing extraction efficiency at competitive production costs, generating high quality products, maximising metal recoveries of the production processes, as well minimising pollutant consumption and emissions (including greenhouse gas), and the environmental impact (including biodiversity).

Mitigating the environmental impact while assuring the economical viability of the process is the major challenge in metallurgy. In this sense, efforts should be shared between minimizing environmental impact of existing metallurgical processes, on the one hand, and developing new ones, on the other hand. Development of new processes will take into account the whole spectrum of environmental assessments to which Europe and the world is now aware of. It is at process design that the implementation of the latest findings from Europe Research in the field (whether is it is minimizing environmental footprint or maximizing metal recovery) can be done. Implementing new metallurgical processes will support Europe's ambition to take a first mover advantage in the challenging field of metallurgy which has a great potential now for giving raise to significant innovations.

Rationale

Deposits with surface expressions are still to be found but the majority of new deposits, especially in known mine camps, will be at depth (>> 200 m). New geological, geophysical and geochemical data are lacking for most of Europe. Compared with regions such as Australia or Canada, the scope and sophistication of exploration lags far behind. European universities and research institutes in the Geosciences have experienced more than a decade of decreasing interest in exploration geology, and geophysics and there is an urgent need to reverse this trend.

Sustainability is one of the envisaged higher objectives in mining/quarrying. It comprises health and safety and environmental aspects, thus addressing the social and ecological aspects of sustainable development.

Especially, but not limited to, in deep mines with high rock pressure, high temperatures and dusty and remote single working places in combination with new methods and technologies and potentially associated risks health and safety is an important aspect. Environmental goals like waste reduction reduced mass movement and land use should become inherent objectives of the ecological part of every future mining/quarrying related development activities.

Mineral processing at an industrial scale includes a series of technological steps, from comminution to concentration and extraction. It is commonly the most capital- and energy-intensive step in the value chain of metalliferous resources. Given the fact that primary mineral resources available for future use especially in Europe are of increasing complexity and decreasing grade, innovative technologies for minerals processing are urgently needed. These technologies will need to be energy- and resource-efficient; whilst at the same time have a minimal environmental footprint. Factors of particular concern include water usage, dust generation, chemicals used, as well as volume and stability of tailings produced.

In recent times there has been a growing interest in studying the whole process chain to improve the efficiency of minerals and metals extraction (geometallurgy). There is a need to extend the studies to include all the relevant minor elements in increasingly complex raw materials. A mine-to-metal concept would be the most appropriate approach at this respect.

It would also desirable to evaluate new metallurgical approaches for designing processes including combinations of the advantages of the novel processes with the traditional hydrometallurgical and pyrometallurgical processes. This view is especially useful for benefiting complex and polymetallic raw materials, ores, and concentrates. Innovation in metallurgy is one of the key factors to unlock the development of a growing number of mineral deposits that otherwise cannot be technical and economically exploited.

There has been a tremendous development of reducing the environmental footprint of mining the last several decades, but mining operations may still have detrimental effects on soil, water and biota. Mining operations generally require large areas of land, and associated conflicts arise that are primarily related to competing land uses. The mining industry is also a major energy consumer and carbon dioxide producer. Leakage of the nutrient nitrogen from undetonated explosives and from cyanide leaching for gold extraction is common. Dust and noise problems are common at mine sites. However, these effects occur only as long as a mine is active. The major potential long-term environmental effect of mining is formation of acid rock drainage (ARD) in sulphide-bearing mine waste, which can last for hundreds or even thousands of years in different deposits.

It is particularly important with methods that ensure safe disposal over very long periods of time. Neutralizing ARD by liming is common, but is a short-term solution that results in increased amounts of waste, although of another type. Also other types of treatments of drainage waters from waste piles must be considered as short-term solutions although sometimes necessary.

Structure of sections

Developing new innovative technologies and solutions for sustainable primary resources supply concerns research, development and innovation aspects of the primary resources value chain defined as: exploration-mining/quarrying-mineral processing-metallurgy-environment. The work to develop an RDI roadmap for WG1 of ERA-Min has therefore been subdivided into the five subareas as defined above. In the following pages we have tried to set the stage answering the questions why is this important and what societal challenges are we addressing? We then try to break each sub area down in to short medium and long term RDI needs and finally proposes some key areas where we see a need to develop joint research agendas.

The work has been a transparent process where all experts that have indicated an interest in WG1 issues (around 40 experts) have had the opportunity to help the subgroup leaders to develop the roadmap. After compiling a first version of the roadmap for each subarea, a meeting in Frankfurt in October 2012 was held to further refine and harmonise the different subareas. The current roadmap is the updated roadmap for WG1 based on the decisions made at the Frankfurt meeting.

Exploration

Challenges

The most important issue is to integrate ore related research to understand how small and large-scale mineralizing systems operate and how this information can be used in exploration targeting. The major goal is to understand the metallogeny and evolution of the lithosphere. Origin, distribution and exploration fingerprints of deep-sea raw materials are also key issues. Both metals and non-metallic resources should be considered. We should understand the cause for geophysical anomalies and how ore and pathfinder elements are spread out and recorded in different substances. Another important issue is to study how different satellite data can be better utilized in exploration and integrated with ground and deep bedrock data.

New techniques and concepts for the search of deep ore deposits should be developed from the methodologies used in the oil industry. Downhole, ground and airborne geophysics as well as satellite techniques should improve their depth penetration. Drilling techniques combined with in situ chemical, mineralogical and geophysical measurement techniques, as well as high performance tools in the search of miniaturized microscopic, spectroscopic, chemical, gas content and fluid inclusion observations during logging should be developed. Advanced, laboratory and in situ, geochemical methods for different media (rock, soil, water, gas) to detect anomalies, caused by mineralizing fluids, in covered areas with no outcrops and in samples from deep drill holes away from fluid flow centres are needed. New innovative software and concepts for 3D modelling, especially in polyphase deformed crystalline bedrock, is needed to create easily upgraded models. Data management and mining of huge amounts of heterogeneous data also require new concepts, knowhow and software development. An integrated approach is called for where geological and geophysical, as well as new technology is utilized. In this respect the growing field of geometallurgy is seen as a road forward.

This work package could also provide input data for legislation and standardisation and reporting within EU. WP1 could also provide very important data for decisions related to land use and CSR issues

Key performance indicators

- By 2020 50% of Europe should be covered by 3D geological models in exploration scale focused on mineral deposits
- By 2020 a pan-European pilot action on integrated drilling and analytical technologies for deep exploration. Reduce drilling costs per meter by 30%, increase cost efficiency by 30%
- 30% increase in domestic resource base by 2020
- 10% increase in European SMEs involved in exploration and exploration consulting by 2020

Innovation needs

We have to develop sustainable exploration concepts leading to social license to operate in the whole of Europe (with WG4). Successful exploration along with its appropriate metallurgical process, helps Europe to produce a larger share of its consumption than today, attracts new investments and creates new SME activity in exploration. Europe has to have its own top-level exploration industry from manufactory (drilling and measurement equipment) to services (software, concepts) to govern the whole value chain from exploration via mines and processing to high-value added products.

Research goals

Short term goals (2 years)

Create and modernize the knowledge- base and collaboration networks (in research, education, technology and most importantly innovation) within Europe (in co-operation with WG4/5) to enhance the capacity to perform highly productive exploration. Start orientation projects following concepts used in Australia (Minerals downunder) or Canada (TGI series) for creating Europe's own concepts for mineral systems mapping and 3/4D exploration.

Medium-term goals (5 years)

New ore deposit models, and concepts, methodologies and technologies for onshore mineral systems mapping (2D/3D/4D) and deep-sea exploration are developed. Distributed system of homogeneous databases of ore deposits drill core and other relevant data in Europe, and metallogenic map of Europe are ready. New 3D geological, geophysical and geochemical data from key metallogenic belts in Europe are produced. New exploration technologies and exploration methods for known and new, un-conventional raw materials will be developed.

Long term goals (2020 and beyond)

Exploration activity is spread out throughout Europe and new discoveries help Europe to produce a much larger share of its resource consumption than today. We understand the 3D (spatial), 4D (+time) and 5D (+ chemistry/ heat) evolution of the lithosphere, and new genetic concepts on European metallogenic systems and new ore types have been defined. New concepts, technologies and methodologies in onshore and offshore exploration are continuously developed and Europe is a leading continent in sustainable exploration.

RDI topics

- Minerals system mapping; 2/3/4D modelling, ore deposit models, spatial data mining
- In-situ chemical, petrophysical and mineralogical analysis in drill holes
- Development of techniques integrated drilling, geological and geophysical techniques for assessment of hidden mineral resources, deep, sea floor
- Assessment of far-field geochemical characteristics of mineral deposits
- All actions needs an integrated approach for S&T

Mining/Quarrying

Challenges

The Mining and quarrying area needs to work with sustainability issues and general image issues of the sector. The public perception of mining is in many parts of Europe negative while the sector in other parts of Europe works with cutting edge technology and minimal environmental impact. They will become even more imminent when sea floor resources will be extracted in the future. Basic investigations into rock mechanics and strata control for deep deposits and improved mining methods for deep mining need to be established in Europe. Investigations into new functional materials for use in mining equipment and continuous improvement of existing and development of new intelligent IT systems and sensor technologies are key actions needed. It is anticipated that many future mines will be smaller and therefore technologies for mining of small deposits should be developed together with improved extraction rates and more energy efficient mining. This could be done by further improving mechanical extraction systems, develop methods for selective mining, methods for automation of equipment and autonomous machinery and develop energy efficient transportation in the mines and quarries.

Improved waste/tailings handling (regarding land use, efficient utilisation of deposits), reduced water consumption, sustainable management of water and recovery and use of geothermal energy from deep mines are all actions that would lead to more sustainable mining and quarrying. Making mines and quarries attractive workplaces with improving health and safety conditions are also major challenges for future mining and quarrying.

The future need of metals and minerals will also mean that Europe needs to improve its knowledge of the potential of offshore/sea floor mining. Also develop technologies related to sustainable extraction on the sea floor need to be developed.

An integrated approach is important also within mining and quarrying and as for exploration integration of unit operations is key for competitiveness. This includes the geometallurgical concept, resource characterisation, IT and positioning systems.

Key performance indicators

- 20 new sustainable, automated mines in Europe by 2030 running an integrated approach, reducing import dependence by 10%
- European CSR green mining label by 2020, incl. energy and resource efficiency targets,
- Increase global share of deep mining supply by 5% 2020
- 10% increase in European SMEs involved in mining and mining technology by 2020

Innovation needs

Challenges from the new technologies will additionally affect the demand for mineral raw materials. New technologies in almost any field of the daily life will require increasing input of crucial raw materials. There are several methods for mining minerals depending on the type of mineral and the deposit. In general, mining operations must become more eco-efficient by reducing energy and water consumption, waste production and the impact on biodiversity associated to open-pit mining. This may be achieved by developing fully automated and autonomous machinery fully integrated in the overall mining processes. This machinery should aim at selective mining with boundary layer and material detection. Local navigation systems at the face together with collision avoidance and machine guidance systems will contribute to autonomy of the machines and to eco-efficiency. Improved predictive maintenance by means of advanced on-board condition monitoring should become integral part of machinery development.

In a rapidly changing global economic landscape, mining in the deep sea, specifically at hydrothermal vents and the vast areas covered by polymetallic nodules, has gone from a distant possibility to a likely reality within just a decade. As our knowledge of the deep seafloor increases, new possibilities for deep-sea resources continue to appear, such as the extremely large amounts of REY (rare earth elements and yttrium) in sediments of the floor of the Pacific Ocean. For the moment, European Industry is well positioned to develop engineering and knowledge-based solutions to resource exploitation in these challenging and sensitive environments. However, against an international backdrop of state-sponsored research and development in sea floor resource discovery, assessment and extraction technologies, European operators are at an increasing disadvantage. Hence, there is a growing imperative for a better-defined European policy in this area and a clear need to initiate pilot studies to develop breakthrough methodologies for the exploration, assessment and extraction of deep-sea minerals (e.g. volcanogenic massive sulphide (VMS) deposits).

The development of a new mine will become a real challenge especially in deep mining when operations need to access mineral raw materials in increasingly greater depths. The tools and methods for mine development need to be adapted to the conditions in greater depths, e.g. ability of cutting very hard rock or coping with challenging conditions as to rock stability. A lot of work will be necessary in this field.

The (underground) mine of tomorrow will need a transition from static control model control to the dynamic control one to be able to process large amount of varying kind of data. The solution resides in novel mass flow and logistics system reference model based on centralised plant design, economic control parameters principles and an intelligent technological logistics system design. Further to that, the mass flow management and logistics has to be renewed.

New eco-efficient technologies will be applied in order to make the entire mining process more efficient and environmentally sound supporting a socio-economic community. The mine of tomorrow will run an integrated concept, meaning that all operations necessary for the eco-efficient provision of the minerals will be carried out within the boundaries of the mining operation and mainly the final product will be shipped to the customer. The emissions and waste streams shall be managed in a way that the environmental (including biodiversity) impact is minimised with the vision of zero impact. This means for underground mines minimising the installations required above ground and hence the environmental impact. The necessary level of automation in mining operations regarding also health and safety and logistics issues can only be achieved by reaching a higher level of integration in all parts of a mine. Fully integrated underground technologies and processes for diagnosis, maintenance and extraction as well as communication, health and safety issues are the key for the success. Also, improved near-to-face (pre-) concentration and processing methods including backfill procedures need to be developed. We need to improve the mining process-chain of mineral extraction at all stages ranging from the face production, transport, hoisting and processing to the final product (mine-to-mill integration). Such future improvements will have to come from fully integrated underground technologies and processes which should be developed with the vision of the next step i.e. eco-efficient and effective mine-mill-smelter integration.

No matter what kind of final solutions will be adapted in the chain of integrated processes, there will be a need for running an innovative and eco-efficient waste management (EEWM). The prerequisite of the new management concept is accepting only such solutions which lead to "zero waste" target and keep waste close to places where they are generated. It means avoiding as much as possible waste generation and recovering the fundamental part of waste volume. So, EEWM requires application of a specially refined process, which is able to fulfil such requirements. For example, in the case of underground mine, the process should selectively mines the minerals and therefore reduces waste production closer to the mineralisation. Also, another prerequisite is organising an integrated production process to treat wastes as valuable useful mineral or mixture of minerals or product, not as a waste and still looking for new possibilities of their usage. Integrated mining processes strictly connected to the processing and EEWM need solutions as e.g. backfilling but there are also other eco-efficient possibilities which should be selected, validated and tested, depending on specific limitations and waste characteristics.

To recruit employees in the future the mining industry must treat the interfaces between man-technology-organisation, and specifically study how to create sustainable attractive work places that engage and motivates even youngsters that are not particularly interested to work within the mining industry. A challenge for the future is to attract more women to the mining sector.

Research goals

Short term goals (2 years)

- Development of concepts for future mining/quarrying activities
- Attractive education and state-of-the-art training methods

Medium-term goals (5 years)

- Eco-efficient technology for mine development
- Logistics concepts adapted to upcoming new mining environments (e.g. going deeper)
- Integrated processes
- Safe and attractive workplaces, Working conditions in deep mines

Long-term goals (2020 and beyond)

- Innovative waste management (e.g. near-to-face (pre-) concentration / processing including backfill)
- Sustainable mineral raw material supply

RDI topics

- Eco-efficient onshore and offshore mining technologies
- Eco-efficient technology for mine development
- Logistics concepts adapted to upcoming new mining environments (e.g. going deeper)
- Integrated processes, system approach
- Innovative waste management
- Safe and attractive workplaces

Mineral Processing

Challenges

Development of new and further improvement of existing technologies used to reject gangue material at coarse particle sizes, thus reducing energy consumption by rejecting unwanted material before crushing and grinding will be important. Preconcentration technologies developed to allow early concentration and separation of ore particles at the coarsest possible particle size will also be a key issue. Near-to-face comminution and pre-concentration technology solutions and comminution and pre-concentration near the place of extraction will reduce transport (energy) costs. Development of alternative comminution techniques and flow sheet solutions, including the use of HPGR (high pressure grinding rolls), electrostatic pulse and microwave-based comminution technology are called for. In general terms processing of fines should be improved.

Considerable improvements in separation technology, in particular when dealing with coarse and very fine particle sizes should be developed. Especially needed are improvements in flotation of particle sizes of < 10 µm. New technologies are needed for the effective separation of complex mixtures, including the separation of phosphates and silicates (e.g. REE minerals). This will, in particular, require the development of environmentally benign and more efficient chemicals for flotation (i.e. collectors, modifiers, activators and frothers). Production of complex concentrates with higher added value and lower environmental impact should be part of this. A quantitative understanding of processes taking place in flotation cells is also need. Development of suitable numerical models and visualization tools are important.

Optimizing the usage of water and minimizing water loss in industrial water circuits and advancing the efficiency of industrial water purification and re-circulation will increase in importance. Expanding the use of (desalinated) seawater in minerals processing and use of saline waters in the process will become important. Development of innovative dry mineral separation processes is a further challenge.

Bioleaching of polymetallic sulphide ores, including not only Cu, but also other base and high technology metals is seen as a challenge. Bioleaching of polymetallic Mn-Fe crusts and nodules recovered from the deep sea floor. Bioleaching of sulphide ores closely associated with organic carbon and carbonate carbon. The development of biosorption processes to effectively separate and remove metals from solutions. Increase the availability of bio-chemicals, e.g. bio-tensides for mineral processing applications.

Great improvement of the link between 3D geological knowledge and processing strategies for entire ore deposits is of importance. Effective utilization requires good knowledge of an ore body. Variability in compositions needs to be identified and production planning must accurately take the actual characteristics of the ore delivered to the processing plant into account. This geometallurgical model of the ore body will yield all characteristics tangible for minerals processing (see also “resource characterization” below). Development of suitable on-line sensors and off-line analytical methods, which will record characteristics such as grade, mineralogy, texture and metallurgical response (grinding energy required, plant throughput, expected recovery, product quality and tailings properties) should be developed. Enhanced data architecture and automation for entire processing plants.

Key Performance Indicators

- Energy efficiency increase by 20% by 2020
- Reduce losses by 30% by 2020, increase recovery of fines
- Define a target for reducing mining waste and methods for stockpiling residues for the future, with WG2
- Reducing fresh water consumption by 20% by 2020, recover metals from process water

Innovation needs

Once renewed exploration activities in Europe will discover new mineral resources, it will be necessary to obtain and retain the required social license to extract and process these resources on a densely populated continent. In addition, resources of the future will be of lower grade and higher complexity compared to those currently exploited. For this purpose, minerals processing technologies will need to be developed that are environmentally benign as well as more energy- and resource-efficient than technologies currently available. Another important aim is to turn current waste materials into products.

Research goals

Short term goals (2 years)

- Capacity and infrastructure need to be built in Europe on minerals processing. Efficient collaboration networks will be established that span from education and research into industry (in co-operation with WG4 and WG5). These networks will not be limited to Europe but be expanded globally particularly to leading resource countries.
- Pretreatment of complex ores, concentrates and semi-products for metallurgical processing by reverse flotation, preliminary leaching, roasting etc.

Medium-term goals (5 years)

Significant improvements need to be attained, which will address some of the major challenges in the field of industrial minerals processing. The following issues will be addressed:

- Comminution (i.e. the crushing and milling of mineral matter) is accountable for up to 80 % of the energy consumption of a mineral industry operation. Considering that the minerals and metals industry accounts for an estimated 4-8 % of the global energy consumption any increase in energy efficiency in minerals processing will make a significance contribution to reduce the CO2 footprint of the minerals industry. This will be achieved by the development and industrial implementation of new approaches to comminution techniques and flow sheet solutions.

- Minimize losses of fine particles containing the valuable metals, which requires overcoming (1) the surface to volume ratio challenges along with (2) the smaller throughputs (due to smaller particle sizes).
- Many large industrial processing plants routinely achieve recoveries of > 85 % for the major product whereas recoveries of by-products are typically much lower. This is further compounded by the fact that ore bodies of the future will be increasingly more complex, of finer grain size and lower grade. Minerals processing plants will thus have to place more emphasis on the recovery of a multitude of metals (and minerals) – rather than focusing exclusively on one major product.
- As volumes and complexity of ores to be processed will increase, water usage (in favor of saline water) will need to be strictly controlled and minimized in future minerals processing plants. At the same time, the impact of minerals processing on the quality of surrounding water reservoirs will be reduced. This aspect will be dealt with in the environmental segment of WP-1.
- Biotechnology is well known to provide a very energy- and resource-efficient alternative to conventional mineral separation and chemical processing routes. Particularly successful examples include bioleaching of Cu and refractory gold ores. However, there appears to be a wide scope to expand the application in the mining industry.
- Efforts have to be made to develop breakthrough approaches and concepts based on a better understanding of the natural processes responsible for the separation and accumulation of elements. Indeed, natural processes (e.g. temperature variations along a fluid circulation pathway) can lead to metal precipitation and concentration, and the formation of ore deposits. These natural processes are long lasting and require thermal energy. However, they use no aggressive or environmentally unfriendly compounds. Can such natural abiotic processes be reproduced experimentally to separate and pre-concentrate metals from various primary materials (mining waste, low grade ores, etc), and can their efficiency be increased to be economically viable? A positive answer to these questions would mean that elements might be successfully extracted from low-grade concentration rocks and ore deposits with environmentally friendly technics.

Long-term goals (2020 and beyond)

- In addition to the mid-term goals defined above, which will require an on-going research effort, there are some challenges that are of a more fundamental nature. This includes, in particular, the development and implementation of entirely novel technologies and flow sheet solutions, beyond the use of currently available concepts. A suitable example is the development of adaptive minerals processing plants, i.e. processing plants able to readily accommodate variations in ore composition.
- Every ore deposit is a unique geological body of very heterogeneous mineralogical, textural and chemical composition. In most mines ore types

with distinctly different compositional characteristics can be distinguished. It is current practice to blend these different types of ores to have a reasonably homogeneous feed to the processing plant. However, such blending exercises are only a crude compromise and ultimately result in energy and resource inefficiencies. It is thus an important goal to develop future minerals processing plants such that they will automatically recognize different feed compositions and be able to readily adapt to such variations.

RDI topics

- Energy efficiency in mineral processing
- Recovery of fine particles
- Resource efficiency in mineral processing
- Sustainable water usage in mineral processing
- Biotechnological processing
- Geometallurgy, should be a horizontal issue, should cover the value chain

Metallurgy

Challenges

Improving the medium and long-term raw material supply in Europe and increasing the competitiveness of the European mining and metal sector will require the implementation of new sustainable and economical extractive metallurgy processes adapted to the nature of the resource containing the valuable metals. Extractive metallurgy is a complex field for which up-scaling is the critical step prior to industrial implementation and job creation. Europe needs to strengthen its existing up-scaling facilities in pre-processing and pyrometallurgy as well as complete its offer with the missing hydrometallurgy pilot scale institute. This will allow for Europe to consolidate its network of competencies in the field and provide a fertile ground for innovative junior SMEs currently lacking in Europe. EU industrial policy and employment will significantly benefit from a stronger mining and metal sector resulting from the added-value to be generated from application of the above-mentioned new processes and innovation solutions to the existing unexploited mineral resources. Also new business opportunities will be developed for SMEs focusing on science-based and engineering services.

In base metals metallurgy it is becoming more and more difficult to distinguish between primary and secondary resources since at modern smelters today the amount of recycled materials is increasing and the different raw materials are entering the smelters at various stages in the metal production chain. On the other hand new installations for separate treatment of scrap materials are constructed. In addition the grades of primary ores are becoming lower with more complex mineralogy and elemental composition. The knowledge on how to economically treat complex and impurity rich mineralizations will strengthen the competitiveness of the European mining industry and at the same time the

European ore reserves will increase since large tonnages of currently known but unexploited complex mineralizations can be turned into valuable material. To reach those objectives technological improvements need to be implemented in all the steps of the value chain i.e. by Development of new processes (or modification of existing processes) to extract currently unused metals (e.g. In, Ge a.o.) from base-metal deposits.

Fundamental research and applied research need to be intimately linked thanks to a strong Research and Industry European network, and oriented towards understanding thermodynamic and kinetic processes associated to metal separation. At the same time, metallurgical processes need to be up-scaled to assure that the developed process can be implemented in the real industrial conditions and to measure and thus minimize environmental impact (water recirculation loops, residues and dust production for downstream tests). This will allow for new processes to be developed for a sustainable use of natural and secondary resources

Many of the by-products produced in one metal production line become raw material for the production of another metal. An efficient use of by-products, such as, for example, slags, dusts (EAF), Waelz oxides, leaching residues, etc., both from the metallurgical sector itself as well as from other industrial sectors will provide for a sustainable use of mineral and metal resources by reducing the amount of waste produced and increasing the metal reserve.

To have a sustainable use of natural resources new processes have to be developed where minor and strategic elements like antimony, beryllium, gallium, germanium, indium, cobalt, magnesium, REE, niobium, PGMs, tantalum and tungsten and deficit elements like Sn, Mn, Mo, Ni, Li, Re, Te are recovered. Further development of *solvent extraction and the use of ionic liquids* to separate REE´s are important.

Optimal control of the products and processes during their entire lifecycle calls for more information on their usage and condition. For this, we need novel concepts to collect data and further to identify the relevant information (see chapter 4 «Public and private policy support and mineral intelligence».) This is achieved by embedding intelligence to systems and products. Data analysis tools are researched to bring information in easily understood forms to operators and for provision of services thus enabling outstanding human-system joint intelligence. Also the geometallurgical concept as an integrated approach should be introduced.

Key Performance Indicators

- Increased non ferrous metal production in Europe by 20% by 2020
- One new separation facility for HREE in Europe by 2020
- Increased process development capacities by 30% by 2020
- Energy efficiency increase by 20% by 2020
- Reduce environmental footprint, dust 30%, gas 30%....

Innovation needs

- Studies into metallurgical processes and reactions in the area of thermodynamics and kinetics of processes should be an overarching aim. Studies into new types of slags and molten salts together with new technological processes for treatment of polymetallic materials, ores, concentrates, by-products, dusts with recovery of metals are challenges that needs to be addressed.
- Promote and develop sustainable and economical extractive metallurgy. Successful implementation will transform a maximum of EU resources into ore reserves. Europe has the capacity to take now a first mover advantage in a new field: *sustainable metallurgy*, where the innovation potential is tremendous. Europe research can now give raise to the implementation of new processes that minimize environmental impact and optimize the use of a primary or secondary resource (metals recovery).
- Up-scaling metallurgical processes to assure that R&D ends-up on the market, ie. the creation of new metallurgical plants in Europe, as well as the implementation of incremental innovations for sustainable extractive metallurgy.

Research goals

Short term goals (2 years)

- Allow fundamental to applied research and pilot scale developments to work together toward overcoming the challenges in priority areas to be identified. Priorities shall be focused on sustainability, like recovering the energy for pyrometallurgy slags, dealing with iron in hydrometallurgy (iron precipitation, liquid/solid separation, physically and chemically stable solid residues…), elimination of metals in effluents, removing solvent from aqueous effluents.
- Treatment of non-ferrous secondary materials with application of new methods for reduction of impurities (Cl, F, K, Na, As and other toxic elements); e.g. supplementing of primary zinc materials with secondary oxide materials from recycling of EAF dusts, crude zinc oxides from Waelz processing of the dusts and residues from hydrometalllurgy and other materials.

Mid-term goals (5 years)

- Application of new pyro- and/or hydrometallurgical processes, including intensive leaching methods, solvent extraction, ion exchange and metal electromining for metal recovery from low grade, complex and polymetallic ores, low grade concentrates,
- Development of combined methods for recovery of critical (antimony, beryllium, gallium, germanium, indium, cobalt, magnesium, REE, niobium, PGMs, tantalum and tungsten) and deficit (Sn, Mn, Mo, Ni, Li, Re, Te) materials from ores and various secondary materials (dusts, slags, etc).
- Development of optimal metallurgical processes with respect to physicochemical properties of charge materials
- Studies into development and implementation of new extractants and ion-exchangers suited to the specific composition of solutions produced by biometallurgical methods,

- Development of ion-exchange and membrane techniques in non-ferrous metals hydrometallurgy, e.g. for recovery, enrichment and refining of rhenium, molybdenum, nickel, cobalt etc.
- Application of electrochemical methods for production of multicomponent cathodic deposits, especially nickel and/or cobalt alloys with refractory metals of high thermal and chemical resistance and production of composite materials with metallic and mineral non-metallic components for significant increase of hardness as well as chemical and mechanical resistance
- Development of ion-exchange and membrane techniques in non-ferrous metals hydrometallurgy, e.g. for recovery, enrichment and refining of rhenium, molybdenum, nickel, cobalt etc.
- Novel concepts and tools for planning production and processes
- Development of numerical modeling to predict metallurgical behavior and make metallurgical processes more adaptable to changing feed composition. Highly trained multi-skilled workforce (in metallurgy, mathematics, fluid mechanics) and the acquisition of databases are required.

Long term goals (2020 and beyond)

- Intensification of biometallurgical methods of recovery of metal value from non-ferrous industry waste of low content of metallic components; an alternative to pyrometallurgical processes and traditional hydrometallurgical and chemical processes
- New technologies for production of Cu, Pb, Zn with generation of slags of low metal content
- Treatment of polymetallic ocean concretion by application of modern technologies for separation of metallic components
- Creation of a European Institute of hydrometallurgy . It will complement the existing European innovation facilities for up-scaling processes (pre-processing in Finland and pyrometallurgy in Sweden) in order to provide Europe with a complete set of complementary tools and experts to tackle future challenges which include lower grade and polymetallic resources. It will help to trigger the crucial fundamental Research indispensable to the Industry and facilitate the development of innovative, industry oriented processes in Europe.

RDI topics

- Processing of low grade and complex materials in the most efficient and sustainable way
- Treatment of metallurgical by-products and waste with a maximum recovery of metal value
- New technologies for recovery of accompanying and critical metals for better utilisation of natural resources

- Design of large integrated multi-technology products and processes by flexible and concurrent design methodologies and tools as well as modelling and simulation
- Tackle the recurrent existing metallurgical challenges focusing on sustainable and technological overlaps in the field which include recovery energy from slags, neutralization of iron in hydrometallurgy, liquid solid separation, elimination of metals in effluents.

Mine closure and rehabilitation

Challenges

As within the mining and quarrying subarea, also the mine closure sub area needs to work with sustainability issues and general image issues of the sector. The public perception of mining is in many parts of Europe negative while the sector in other parts of Europe works with cutting edge technology and minimal environmental impact. In this respect environmentally safe mine closure and remediation are key factors for public acceptance of mining. The demand of metals and minerals in society will increase. Within the European Union much larger quantities of metals are used than what is mined. It is an important challenge to increase the mining in the Union in a sustainable way without negative impact on the environment. After mine closure, it should be possible to leave remediated waste deposits without continued maintenance. It should also be possible to make products of what is now considered as waste to a much higher degree than today.

Volcanogenic massive base metal deposits contain a few percent of the valuable metals, and thus more than 90% of the ore will be waste after processing. Porphyry copper ores often have an average copper concentration of less than 1%. Gold is mined in deposits with a grade as low as a few grams per tons. The major parts of ores thus will be waste. The global production of mine wastes is estimated at more than 15 000 - 20 000 million ton of solid waste each year.

The primary approach to the prevention and mitigation of ARD is to minimize the supply of the primary reactants for sulphide oxidation, and/or maximize the amount and availability of acid-neutralizing reactants. These methods involve minimizing oxygen supply through decreasing oxygen diffusion or advection/ convection, minimizing water infiltration and leaching (water acts as both a reactant and a transport mechanism), minimizing, removing, or isolating sulphide minerals and maximizing availability of acid neutralizing minerals and pore water alkalinity. Another prevention option is to remove the source, i.e., Fe sulphides, from the mining wastes with the aim to reduce the total amount of ARD-producing waste and remediation efforts needed. ARD may be formed in waste deposits containing Fe-sulphides such as pyrite and pyrrhotite when exposed for oxygen. This ARD is often rich in heavy metals and metalloids. Conventional mining generate two main types of wastes, which both may contain sulphide minerals. These waste types are waste rock (dominated by coarse material) that is removed to reach the ore, and finely ground tailings generated during the ore processing. Waste from Cu, Zn, Pb, and Au mining usually contain Fe-sulfides, in contrast to waste from Fe-oxide mining.

Mine closure should be an integral part already in the mine planning stage. An issue in Europe today is reopening of closed mines and therefore also re-design of old remediated areas. One challenge with reopening of old mines is the lack of documentation of un-mined parts of old mines (problematic for historic mines). This calls for recommendation for mining companies to provide detailed information after mine closure

More work on i.e. backfill of pastes and different types of water treating methods and optimization of use of chemicals are other challenges that need attention. In relation to health and safety issues dust, noise and vibrations reduction could be treated also under this heading, but are also horizontal issue for the entire ERA-MIN roadmap

Key Performance Indicators

- Identify all BAT for mine closure in Europe, WWB, establishing a comprehensive database for Europe by 2018
- Pilot plant on using tailings and/or ARD as a resource (WG2?)
- Cradle to cradle plan for new mines in Europe
- Pilot action on phytoremidiation?

Innovation needs

While decreased energy consumption and decreased waste production are important parts of the other areas of ERA-MIN, WG 1 Environment should focus on the prevention of formation of ARD in mine waste, the major problem. However, also immediate short-term problems such as metal recovery from drainage waters and dust prevention should be included. In general, the research will be of applied character. In some cases fundamental research will be needed to elucidate processes or properties of particular importance, e.g. surface reactions on Fe sulphides in different physiochemical environments.

Desulphidisation of mine tailings should be a new paradigm for waste management. Water flow management processes to reduce contact with ores (including draining systems, coating of exposed mineral surfaces, etc.) is a key sustainability indicator. Making products from mine waste and dust prevention are important issues where innovation is needed. Dry technologies development to avoid/reduce the water and energy related consumption and LCA/LCC studies to optimize the processes as much as possible are other environmental performance indicators that should be addressed.

Active biological processing of ARD and polluted soils needs further attention. Hybrid technologies for treatment of wastewater and eluates generated in industrial processes combined with metal recovery. New technologies for removal of toxic elements from material cycles in non-ferrous metals production are called for as well as new technologies for reduction of emission of sulphur and its compounds to the environment.

More innovative and efficient methods for remediation of mine waste, including increased use of waste from other industries (two problems solved at the same time) are needed. Post-closure added values for the society and the biosphere should be addressed. Methods for safe disposal of the waste formed when bioleaching is used are called for.

Research goals

Short term goals (2 years)

Research on new and innovative methods for mine waste management, drainage water treatment and remediation has been performed mainly in lab- and pilot-scale. The research has resulted in a good understanding of which methods are promising and worth scaling up to full-scale applications. Planning for research on these field applications has reached an advanced stage.

Mid-term goals (5 years)

The research has resulted in development of new and innovative methods for mine waste management, drainage water treatment and remediation after mine closure that has been tested also in field in full-scale applications offering good demonstration possibilities. Research results allow predictions of long-term performance of the different methods.

Long term goals (2020 and beyond)

Methods are developed so that the environmental footprint of mining is strongly reduced compared with the situation today. Mine waste including the Fe sulphides is to a large extent used as an asset that is turned into products. Methods for remediation of unavoidable waste deposits are efficient also on very long time perspectives. After mine closure, remediated waste deposits can be left without continued maintenance. Plans and possibilities for post closure added values such as increased biodiversity and increased possibilities for outdoor life and recreation are common at abandoned mine sites.

RDI topics

- Waste management
- Drainage and mine water treatment
- New technologies for rehabilitation of mines and tailings
- Long term monitoring systems

WG 2: Secondary resources supply (Recycling)

Rationale

Access to raw materials and resource efficiency are at the forefront of the EU political debate and recycling is part of the solution of many strategic objectives. It addresses resource scarcity and enhances securing of material supply, while contributing to higher energy efficiency and lower environmental impacts. Moreover, recycling offers significant investment, innovation and employment opportunities in the EU.

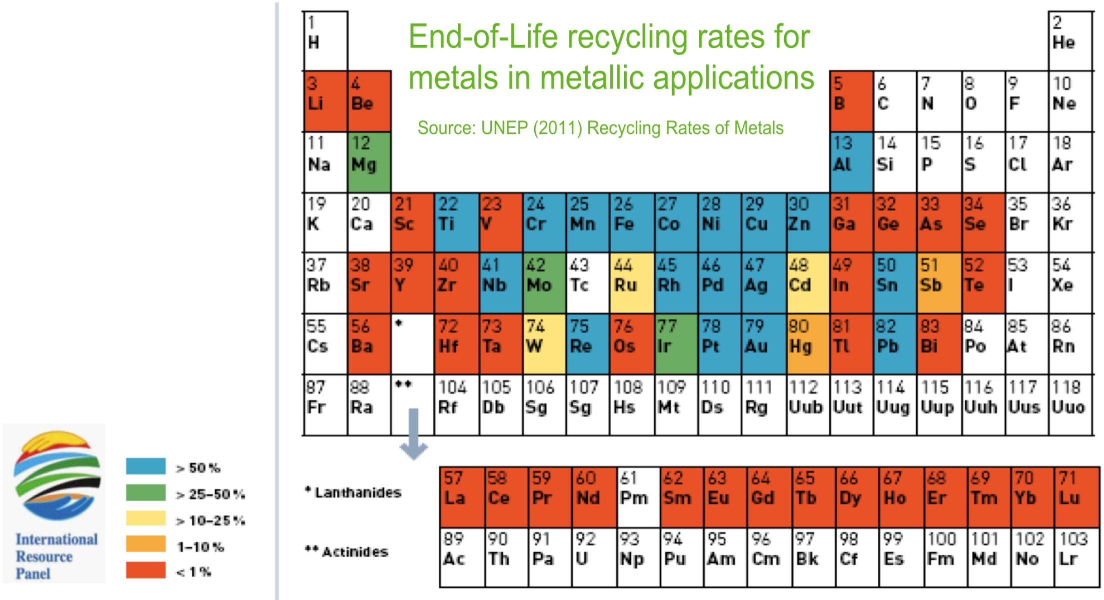

Figure 2: End-of-life recycling rates of metals [1]

Although increasing attention has been placed on recycling both from the political/ legislative side as from research, current recycling achievements are still far away from optimal and the vision of a "circular economy". This is particularly valid for many technology metals[5] and critical metals as shown in the 2011 UNEP report on Recycling Rates of Metals [1]. It shows that in most cases overall losses along the product and material life cycle are very high (Fig. 2) and results are worst for consumer products such as electronics or cars (even for precious metals which have high recycling rates in most industrial applications). As metals in principle are infinitely recyclable without a degradation of quality, innovation leading to increased recycling rates will bring access to a significant potential of additional supply of secondary raw materials.

Obtaining an optimised life cycle as elaborated in the introduction requires the minimisation of metal losses during all phases of the life cycle. This implicitly

5 Technology metals are crucial for the functionality of many high tech processes while – other than base metals - often are used in low concentrations only. They comprise the precious metals and most special metals, many of which are also regarded as "critical" by the EU [2].

means that scrap or residues generated during production as well as end-of-life products and residue streams are new sources of raw materials that need to be recycled with high efficiencies, i.e. enabling a wide range of substances being recovered with high yields at reasonable costs, energy consumption and environmental impacts (Fig. 3).

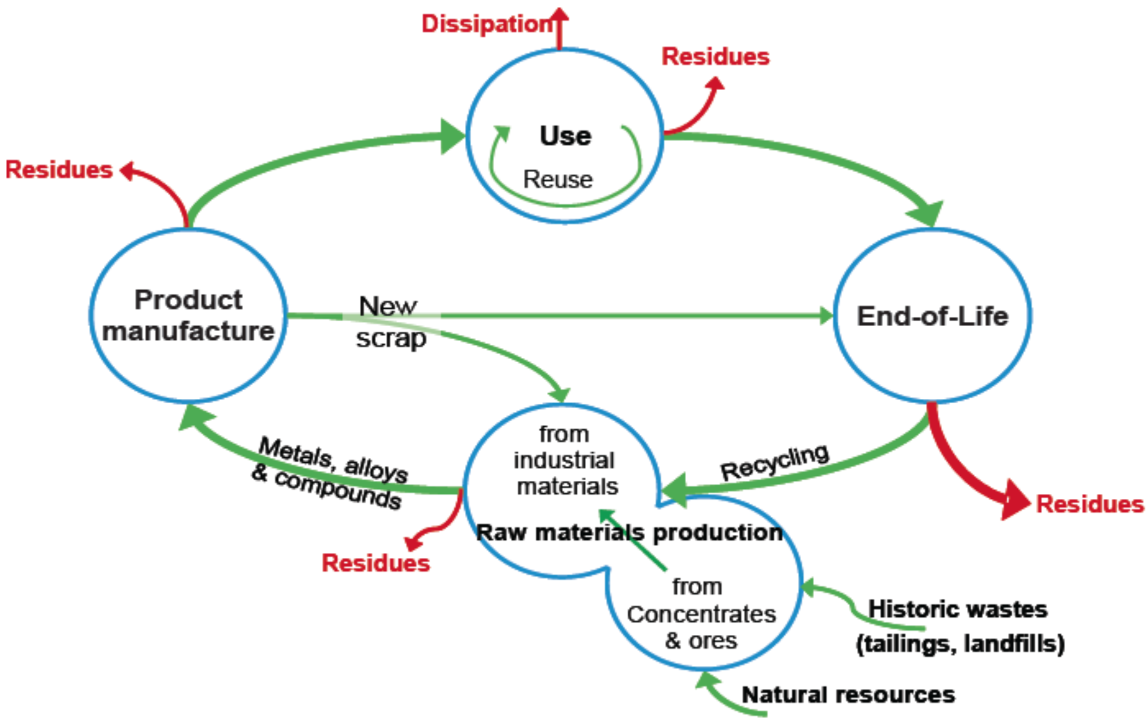

Figure 3: Efficient recycling along all steps of the life cycle can significantly enhance supply or raw materials [3]

It is technically relatively easy to recycle base metals from simple products, accordingly recycling rates for these are usually high (Fig. 3). With increasing product complexity recycling becomes much more difficult. Hence, the focus in innovation needs to be placed on the integral aspects of recycling of technology metals / critical raw materials and toxic constituents from complex (consumer) products respectively material streams (including redesign for recycling, collection and disassembly). Substantially boosting the recycling rates of these metals requires innovation to take place throughout the life cycle, and technical solutions that offer the flexibility to cope also with future (new) product types. The involvement of consumers as key stakeholders in a product lifecycle, and the continuous development of new products with new material compositions (often in combinations which do not occur in natural deposits) are an essential difference to primary metals supply, where ores can be also complex and numerous other technical challenges may exist but with a much higher stability and predictability.

Hence, in order to finally become successfully implemented, technical recycling innovation is not sufficient but needs to be embedded in a broader context of non-technical, societal innovation approaches and has to involve other stakeholders and disciplines along the life cycle of products and materials. Examples are end-of-life electronics or cars, where often advanced recycling technologies are already available but overall recycling rates suffer significantly from poor collection, high leakages of collected materials into non-suitable channels or inappropriate interface management between logistics, mechanical pre-processing and metallurgical metals recovery. As figure 4 illustrates, the overall recycling rate for a metal results from the product of the efficiencies of every step involved. Hence the weakest part in the chain – often lying in the non-technical area - needs to be addressed with highest priority.

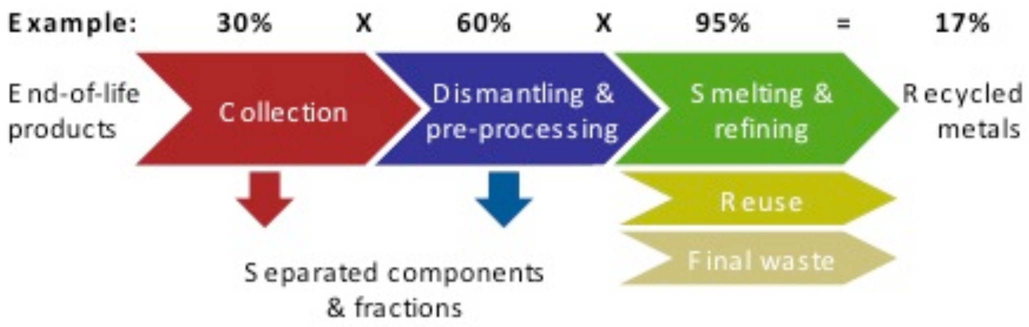

Figure 4: The recycling process chain for consumer products – the actual recovery rate is mainly determined by the weakest link (effective total recovery rate for e.g. gold from WEEE, fictitious numbers)

This non-technical part comprises economic as well as social/behavioural challenges. The former needs to be addressed bybusiness and regulatory innovation on how technically feasible processes can become profitable. It comprises, among others, business models, incentives and frame conditions for competition (creating a level playing field) to enable high quality recycling. The latter requires innovation to improve the knowledge base on stocks and flows of products and materials embedded therein, as well as innovation to stimulate recycling awareness and supportive activities of consumers, retailers, manufacturers and other stakeholders. Hence, the needed quantum leap in metal recycling rates can only be achieved by a holistic system approach and rigorous modelling of all its constituents, which takes the interdependencies of life cycle steps, impact factors and measures into account.

Manufacturing and product distribution / use can contribute to decrease the materials and energy intensity of products. For instance, products can be manufactured for service provision and new business model based on services (dematerialisation) should be developed. These new models could contribute to a more efficient use of resources and provide new job opportunities.

In WG 2 we have therefore addressed the specific challenges and innovation needs in subgroups along the main steps of the product / material life cycle:

- Recycling of mining and smelting residues (incl. historical dumps and tailings)
- Product manufacturing

- Product distribution & use
- End-of-life collection and logistics
- End-of-life pre-processing
- Metallurgical extraction

For all these steps we have looked into innovation needs in the following areas:

- Information / availability of data
- Technology and process
- Economics
- Others (organisation, behaviour/social, environment)

The overarching challenge is to integrate this into a systemic view of the whole chain as shown in Fig. 5 with all research activities coherently feeding into this while considering interdependencies.

As this integrated approach is of utmost importance for an effective and sustainable access to secondary raw materials this is reflected in an additional chapter with overarching challenges and innovation needs, covering all six main steps mentioned above.

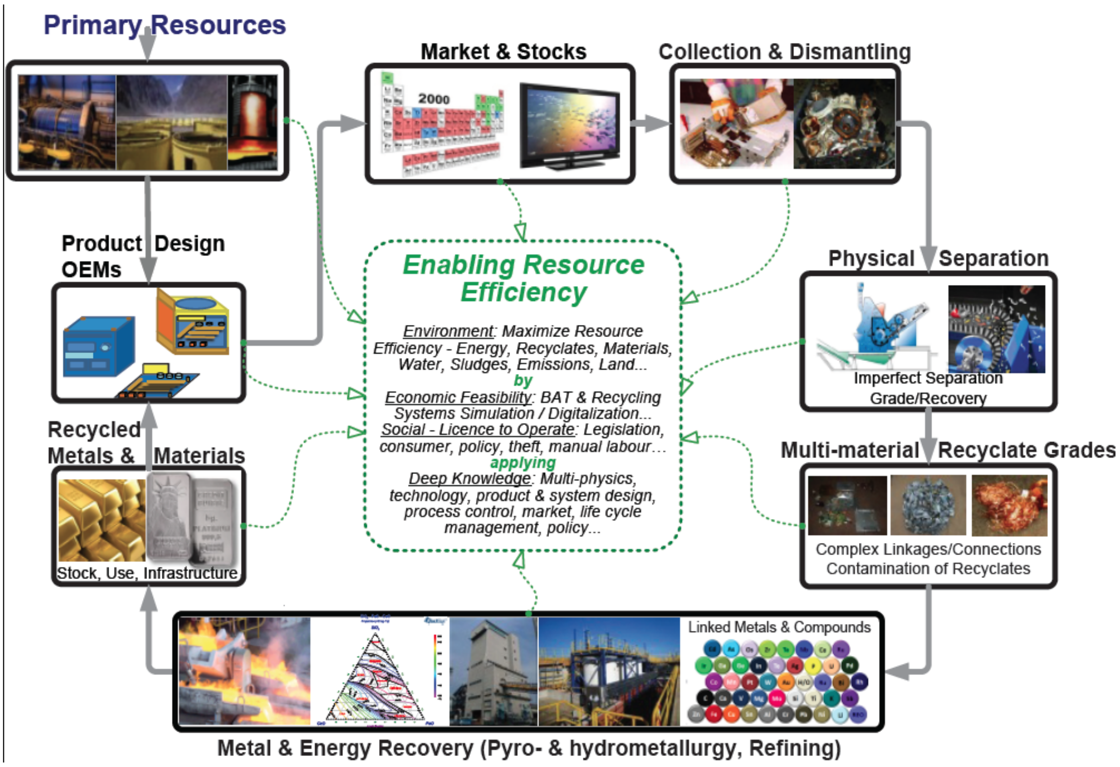

Figure 5: Sequence and interlinkages of process steps to be considered for achieving resource efficiency [4]

Recycling of mining & smelting residues

This section addresses current residue streams from mining, benefaction and metallurgical processing (tailings, slags, effluents, dusts etc.), as well as historic landfills/dumps from such operations. Such residues can be of particular interest for recovery of by-product metals such as Ge, In, Ga, Sb, Mo, Ta for which previously the technical and/or economical recovery feasibility was not existing. Innovation should specifically target the improved recovery of these metals. The section does not look into landfills from household waste.

Challenges

Insufficient information about composition/metals distribution in these residues and its physical properties (type of 'rock').

Insufficient information about evolution and overall availability of historic mining and smelting wastes (equivalence to geological ore data base).

Key performance indicators

- A comprehensive data base on current and historic residue streams from EU mining and smelting residues has been built up
- Residue management has become an integral part of mine and smelter planning/operation, new sampling and extraction technologies are tested and increasingly applied.

Innovation needs: applied research

- Characterisation of mine/smelter waste dumps: build a matrix data base identifying per application (= origin of residue) the metal composition, content and physical/chemical properties of the landfill. Understand the structural environment of metals contained in solid structures and their speciation in liquids. Include life cycle information into the data base.
- Make use of environmental remediation projects of such dumps to explore possibilities to combine with extraction of (technology) metals.
- Develop appropriate sampling technologies including non-destructive metal identification technologies for heterogeneous landfills.
- Develop new technology for metal recovery, e.g. biomediation and extraction or other innovative metallurgy to cope with the specific composition and properties in an economically viable way (fine grain, interlocked, low grade, presence of hazardous substances, etc.). Focus on system approach and interfaces between extraction, beneficiation and extractive metallurgy.
- Planning of waste management at an early stage of exploration and extraction of the deposit. This requires full documentation, including primary minerals and barren rock/overburden. Full holistic waste management would include as well a selective collection/deposition of waste streams that can be potentially used as input to other production, e.g. construction.
- Prioritisation is required, considering types of metals (critical - potentially economically viable special metals - most toxic/hazardous materials) as well as size and accessibility of residue streams/dumps. Also remaining volumes

and characteristics after recycling such streams need to be considered. Developing the appropriate criteria and evaluation tools for prioritisation in the overall system context will be an innovation need in itself and a basic step for focussed innovation approach in the other areas described in this document.

Research goals

Short-term goals

- Benchmark with geological surveys for primary resources (including sampling technologies). What is similar, what can be adapted, what needs new development?
- Collect existing data and develop European standard for data reporting and filing to address innovation needs above.
- Develop suitable prioritisation rules and decide on priority areas.

Mid- to long-term goals

- Compile existing data and systematically feed the data base.
- Conduct sampling campaigns in priority areas.
- Develop and test suitable metal recovery technologies (including bio-leaching).
- Include life cycle data in the data base

Product manufacturing

Challenges

- Create knowledge/education about design for reuse, long use, repair, and recycling requirements and integrate this into first-principles models. Develop design for resource efficiency tools by combination with requirements for functionality and service associated products used under new business models. Ensure sufficient depth to link via process simulation to metallurgical extraction technology.
- Improve recycling of the various types of production residues (incl. mixes of metals and organics/hydrocarbons, e.g. scalings).

Key performance indicators

- Design for resource efficiency has become a widely accepted approach for the development of resource relevant products. Reference handbooks, standards and labels have been developed in a cooperative approach between designers, manufacturers and recycling experts.

- Appropriate rigorous models have been developed and are regularly used by the relevant stakeholders in order to simulate recyclability and adapt design and recycling technology at an early stage if needed.

Innovation needs: fundamental research:

- Applied research on data acquisition and methodology to develop European standards and reference handbooks on environmental labelling of fast moving consumer goods.
- Predicting quality and quantity in a reliable manner. Rigorous Design for Resource Efficiency models (including all steps of a circular economy, i.e. design for repair, for maintenance, and for refurbishment), which supersede Design for Recycling Models will provide the basis to achieve this. These models are based on process simulation software integrating and including process metallurgical and recycling models (for background see [4]).
- Eco-design that permits quality prediction of end-of-life (EoL) streams from product dismantling and pre-processing output (recyclates) through to extractive metallurgy and deportation of elements into different streams. Also, possible processing routes should be predicted as well technology innovation should/could be an outcome. Create an Eco-Label as outcome of this rigorous basis to inform consumers.

The outcome is a first principle long use easy repair, easy refurbishment, Recyclability Index that is based on the theoretical considerations that are available in all 4 ERAMIN work packages.

Innovation in this area can only be successful in a truly cross-sectoral approach, which needs to involve all stakeholders along the value chain, from the product designers and developers to manufacturers together with material and recycling experts. Hence, a multidisciplinary build-up of projects is essential.

Research goals

Short-term goals

- Mapping and prioritisation of most relevant manufacturing areas (present and expected in future.
- Create joint education/exchange platforms for product designers and metallurgists/recyclers. Identify the main challenges. Introduce, discuss and adapt the existing models so that they are accepted as starting tool.
- Develop European standards and reference handbooks on environmental labelling.
- Identify and cluster production residues for improved recycling. Select most relevant residue streams and target metals.

Mid-term goals

- Develop comprehensive Design for Resource Efficiency models and tools that integrate all life cycle steps into a consistent framework.

- Develop Design for Recycling (DfR) rules that predict recyclability on fundamental basis i.e. using existing commercial flowsheeting tools.

Long-term goals (2020 and beyond)

- Broad implementation of models and tools, ensure that DfR starts getting the fundamental basis that it needs to ensure we start advancing Resource Efficiency on First Principles.
- In general, these improvements in manufacturing have to increase reuse and the recyclability of the products in an economical viable way throughout the recycling chain.

Product distribution and use

Challenges

- Insufficient knowledge about potential of the urban mine (although individual data on sales volumes, product composition, use model, lifetime of products, fate at end-of-life are often known, the combination of these and its implication is not developed).
- Current product distribution channels/business models are widely not adequate to get access to products at their end-of-life (closing the loop).
- Insufficient understanding of behaviour of consumers and other stakeholders: what are the psychological, economical and practical recycling triggers?

Key performance indicators

- A comprehensive inventory of the EU urban mine has been built up for the most relevant product groups. This enables to asses the potential availability of individual secondary raw materials by products and main regions over time and plan measures and capacities accordingly.
- New product distribution channels and business models are in place, facilitating a more efficient use of raw materials and the closure of the loop at products' end-of-life. Behavioural drivers of consumers and business are understood and considered therein.

Innovation needs: fundamental and applied research

Interdisciplinary research together with social sciences and economists in order to:

- Determine and predict current size and future development of the urban mine inventory.
- Understand and impact consumer and business behaviour (by involving all

stakeholders).

- Develop innovative business models to close the loop (focus consumer products).

Research goals

Short- to mid-term goals

- Identify data sources across Europe to feed the urban mine inventory. Develop model and standards for systematic collection and filing of data.
- Build-up a systematic product inventory, start with products and regions with highest relevance on (critical) resources. Create data sets in key areas where data are missing.
- Build business models and infrastructure to close the loop and increase the use phase. What approaches exist in other areas (e.g. deposit systems, leasing models) and how could they be adapted to address the needs for priority products? Benchmark existing systems in different countries.
- Start for pilot product groups/regions (e.g. mobile phones, PCs, cars).
- Develop suitable Resource Efficiency Indicators based on technology, recyclability, economics, environmental impact, distribution models etc. in order to provide (economic) incentives and to support more and better recycling. Build up on related existing work and extend to full system perspective. Use this as basis for stakeholder campaigns.

Mid- to long-term goal

- Extend the urban mine inventory data base to more products, materials and regions.
- Extend the business model approach to more products and regions. Incorporate "lessons learned" from start activities and fine-tune the business models where needed. Consider specific regional/cultural characteristics.
- Integrate the above with Design for Resource Efficiency system simulation models.

End-of-life collection and logistics

Challenges

- Insufficient collection (incl. hoarding at households) and high leakages of collected products/materials (prevent illegal/dubious exports; close the loop for legitimate exports of used goods).
- High losses of secondary raw materials before and within the recycling chain although existing recycling technology would permit their recovery; high burden on environment due to sub-standard treatment.
- Insufficient knowledge about current and future potential availabilities (arisings) of EoL products, about their flows through the recycling chain, and about final destinations and process efficiencies of resulting material streams.

Innovation needs: applied research

- Systematic compilation of information on potential waste arising (by products & composition; current and future prediction). This needs to be linked to the urban mine inventory (see above).
- Develop tools and technologies to create transparency about material flows along the entire EoL- / recycling chain. This comprises both rigorous simulation tools as well as in practice monitoring and documentation of real flows.
- Develop information and awareness raising tools to improve collection and recycling quality. Educate consumers and other stakeholders (incl. media) about the benefits of recycling to trigger active support and participation.

Key performance indicators

- Resource relevant end-of-life products (like WEEE and ELVs) are collected comprehensively throughout the EU, supported by appropriate infrastructure, consumer education and business models.
- These products are transparently channelled through a high quality recycling chain until the final treatment plant, supported by tracing and tracking technology, verifiable treatment standards, and a sound documentation.
- Illegal and dubious export streams are eliminated and systems have been built up in order to close the loop for legitimate exports of new and used products ("global recycling society").

Research goals

Short-term goals

- Develop criteria and prioritise products and materials for improved collection and logistics based on improved material characterisation and forecast of availabilities. What causes the gap between the current and the ideal situation?
- Develop optimised, cost efficient collection infrastructure for priority products. Can product distribution logistics be merged with take back systems? Benchmark with successful examples.
- Build up a model and data base structure to document EoL availabilities/ arisings and flows of identified target products/materials from collection throughout the entire recycling chain. Develop tools for plausibility checking and mass balancing.
- Develop criteria to evaluate process quality along the chain. How can these be translated into an auditing and certification system in order to stimulate high quality recycling processes throughout the chain and create a level playing field on an advanced level.
- Identify tagging, tracing and tracking technologies used in other areas (e.g. manufacturing and product distribution) and check what could be adapted

for EoL flows.

- Develop criteria for what to tag (in cooperation with manufacturers), what to group in categories etc. =>develop improved logistics and documentation of specific flows based on tagging, tracing& tracking. Study possibilities to integrate with other product tagging systems (e.g. product data information systems).

Mid-Term goals

- Develop and test as demonstrator case tagging, tracing & tracking of products/components for detection, sorting & following flows (building on experience from other segments, adapting these to suit needs of EoL flows).
- Identify a suitable pilot region and test in a coordinated multi-stakeholder approach the tools developed under short term goals.

Long-term goals (2020 and beyond)

- Broad implementation, data assessment and consequences for related fields. Incorporate "lessons learned" from start activities and fine-tune the approach where needed. Consider specific regional/cultural characteristics.

End-of-life pre-processing

Challenges

High losses of technology metals during pre-processing, impurities degrading product/residue quality, and inappropriate management of interfaces to pre-processing, both upstream (collection & logistics) and downstream (metallurgy).

Key performance indicators

- Resource relevant products have been systematically assessed and grouped according to collection and pre-processing requirements for minimisation of losses of technology metals.
- Appropriate pre-processing technologies have been developed and interfaces to collection and metallurgy as well as preprocessing residue streams (e.g. fluff) are actively managed and optimised.
- The approach has been successfully tested in a demonstrator project involving the entire end-of-life chain for a selected complex product group (e.g. ELVs or IT-electronics).

Innovation needs: applied and fundamental research

- Develop economic, energy efficient and environmentally sound pre-processing technologies for complex products to generate output fraction which optimally fit into subsequent metallurgical extraction and refining in order to recover maximum of critical/important/toxic metals (performance and downstream interface optimisation).

- Develop criteria for appropriate grouping of EoL-product types into collection categories in order to improve pre-processing performance while considering logistic efforts and costs (upstream interface optimisation).

Research goals

Short term goals

- Categorise products by technical pre-processing requirements. For example, which (sub-) components need to be removed before a shredder process in order to avoid losses of target metals and/or hazardous emissions? Which products are relevant for these components and how could they be grouped together to enable cost effective processing without sacrificing the process and separation quality? Select priority products/regions& prepare case study.
- Investigate pre-shredder technology and technologies for improved liberation. E.g. how to separate magnets, batteries, LCD screens, toxic/ hazardous components? Develop interface with design for disassembly.
- Investigate liberation and sorting technologies which avoid metals dissipation (with possible link to tagging). E.g., how can complex products be disintegrated in a way that relevant (sub-) components be removed and channelled into most appropriate metallurgical end-processes.
- Develop technologies that minimise the generation of unusable residues in the pre-processing stage.
- How to better treat pre-processing residues (fluff, effluents, ...) in order to recover residual valuable and hazardous substances/metals and find suitable outlets for remaining fractions (either as feed for downstream manufacturing or for energy recovery).

Mid-Term goals

- Conduct case studies, in depth interface optimisation with metallurgical processing (& other outlets).
- Process development for liberation& sorting for new requirements. Test with complex products such as cars or IT electronics.

Long term goals (2020 and beyond)

- Extend to more products and regions; integrate different metallurgical processing paths

Metallurgical Extraction

Challenge 1

Focus on current technical recovery limits: Coping with liberation constraints and thermodynamic limits hindering efficient recovery of (low concentrated) valuable, sometimes rare and/or toxic metals from new and complex substance combinations. This includes new metal/substance associations (not existing in geological deposits) deriving from products. Particular attention needs to be place on improved recovery of technology/critical metals. Context to consider is the complete product or sub-component "mineralogy" as well as the existing metallurgical production infrastructure[6].

Key performance indicators

- The product and material groups with the highest potential to recover the critical/technology metals widely lost today (e.g. indium, gallium, germanium, tantalum, rare earth elements, lithium) are identified and grouped according to metallurgical challenges.
- Metallurgical processes have been developed (in interplay with managing the pre-processing interfaces) to recover these metals when contained in complex material mixes.
- The approach has been successfully tested in a demonstrator project.

Innovation needs: fundamental and applied research

Pre-competitive research on extractive metallurgy considering interfaces to pre-processing technology, comprising:

- Define processes requirements and output qualities of pre-processing7 based on capabilities of advanced metallurgical processes. Develop such advanced pre-processing technologies to tailor their outputs for optimal metallurgical extraction while minimising metal losses during pre-processing itself (comminution under controlled atmosphere; sensor based sorting; advanced micro-size particle separation).
- Develop flexible, modular and robust integrated (beneficiation, pyro, hydro) extractive metallurgical processes meeting future resource challenges (polymetallic, lower grade, more interlocked). How to create "extraction hooks" for specific metals which are part of a thermodynamically incompatible mix? (E.g. pre-pyro or post-pyro extraction of Ta from a copper-precious metals dominated matrix such as circuit boards)[8].

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6 Ensure that R&D is limited to what is really needed rather than starting research on sub-topics that have already been solved. Some recent R&D projects have tried to reinvent what is already industrial practice.

7 In addition to the previous chapter pre-processing included here again to underline the importance of interface management with extractive metallurgy (Use metallurgical knowledge to develop appropriate pre-processing).

8 Check beforehand the theoretical success potential based on thermodynamic modelling and understand physics in well controlled experimentation e.g. in slag chemistry or hydrometallurgy.

Research goals

Short-term goals

- Material focus: Select most relevant material streams and target metals (see prioritisation under 2.1), identify the main metallurgical recycling constraints and classify into "challenge clusters".
- Process and system focus: Identify the most appropriate processing tools and pre-design potential principal flow sheets (incl. pre-processing) for the identified material clusters. Prioritise main pathways for research.

Mid- to long-term goals

- Fundamental research to understand the thermodynamic behaviour and separation of new metal/substance associations supported by the use of suitable simulation software.
- Fundamental and applied research on appropriate process developments. This involves iterative and interdependent steps and could be best addressed in a cluster of partly parallel research projects with good coordination and exchange.
- Applied research to support the critical metallurgical step which is up-scaling, which should be done in close cooperation with industry.
- Focus on innovation with potential to overcome current limits, providing access to a significant additional supply of secondary metals; incremental improvements are not in scope.

Challenge 2

Focus on process flexibility and sustainable system design: Develop sustainable metallurgical processes with a reasonable balance between not losing raw materials/metals and minimisation of energy consumption and environmental impact while remaining economical viable (under volatile metal prices and long investment time needs).

Key performance indicators

- Flexible metallurgical processes have been developed which are able to recover a wide range of (technology) metals from varying complex feeds with at least 20% improvement in energy and environmental performance
- Volumes of slags and other process residues from such processes with no or low end uses only have been reduced by at least 50% by identifying more suitable downstream uses and tailoring of residues according to their needs (implementation of industrial symbiosis)
- The approaches have been successfully tested in demonstrator projects, involving metallurgical process operators, downstream users and possibly other stakeholders.

Innovation needs: fundamental & applied research

- Holistic design and optimisation of an integrated metallurgical system (pyro, hydro, bio, electrochemistry) with respect to metal yields, energy consumption, environmental footprint and economic viability, considering upstream (pre-processing) and downstream (treatment/use of metallurgical wastes such as slags, dusts, effluents) interfaces. Develop flexibility in metallurgy with regard to changing feed materials. Go beyond incremental improvement to systemic breakthrough innovation, which needs to consider:
- Development of suitable system models based on process simulation and environmental software.
- Optimised internal recirculation of process wastes/intermediates.
- Measuring and minimising environmental process impact (water & energy consumption vs. yields, final waste and toxicity of waste). Use of thermal energy contained in slags, offgas or effluents (e.g. storage of excess thermal energy by dehydration – rehydration of minerals; use of slags to produce hydrogen).
- Improving energy and material efficiency by industrial symbiosis, aimed at utility sharing and cooperation among diverse sectors of the raw material industry (approach: process wastes or excess energy as feeds for other or downstream processes). Industrial symbiosis systems collectively optimise material and energy use at efficiencies beyond those achievable by any individual process alone.

Research goals

Short-term goals

- Investigate opportunities and organisational needs for improved internal and external recirculation of process wastes/intermediates and for improving overall energy efficiency.
- Characterise downstream user needs with respect to material composition and properties and identify priority areas for potential tailoring of process wastes (slags, dusts, effluents, excess thermal energy).

Mid-Term goals

- "Double sided optimisation" of process wastes. Are there ways to tailor such wastes in order to significantly improve their valorisation for downstream processes without negative implications on performance/yields of the metallurgical process?
- Metallurgical solutions to improve energy and environmental process performance
- (including fundamental research to better understand behaviour of toxic elements)
- Applied: set-up demo scale and experimental platform with potential to technical break-through.

Long term goals (2020 and beyond)

- Development of multi-scale models (from elementary phenomena to processing routes) using process simulation (flowsheeting) software tools.
- Development and implementation of models and management tools for a holistic technical-economical-environmental system optimisation.

Closing the loop from an integrated approach

The objective of this section is to focus on challenges and innovation needs for an overall view of the secondary raw materials value chain from a technical, environmental, social and economic perspective. In numerous cases we do not recycle something only for economic reasons but because it is reasonable for society in a broader sense. It is thus crucial to consider the complex interdependencies and advice stakeholders/decision-makers on overarching benefits and opportunities to close the loop. Some of these aspects are overlapping with those mentioned before but are included here to emphasise the system approach.

Challenges

- Demonstrate feasibility for closed loop models in different sectors.
- Achievement of an open communication and collaboration among different stakeholders belonging to different categories/steps involved in the value chain (producers, consumers, collectors, recyclers, policy makers, public bodies) in order to identify and implement feasible common beneficial solutions for the closure of the loop.
- Encourage the shift of stake-holders from "business as usual, according to linear economy principles" to a circular economy.

Key performance indicators

- A cross-disciplinary and multi stakeholder expert team has worked out in depth a comprehensive and realistic closed loop business model concept for beforehand identified key product groups in a selected territory/region.
- A case study has been carried out for this and the results obtained are analysed and communicated. The case study incorporated projects from the other innovation subgroups above (umbrella project approach).
- Based on the previous experience a larger demo case is executed which significantly improves raw material and energy efficiency, making use of a close stakeholder cooperation and industrial symbiosis.

Innovation needs

- Development of generic and specific methodologies for the closure of the loop, either designed for companies, industrial sectors, values chains, or territories (industrial symbiosis). Definition of the appropriate "circular economy" together with associated indicators.
- Adjustment of the LCA and LCC approach in raw materials sector for the overall loop evaluation. Combined use of LCA with other mass balance evaluation methodologies (i.e. material flow analysis – MFA, input-output matrices).
- Urban mine databases and raw materials traceability along the value chain.
- Development of novel business models benefiting all involved stakeholders and aimed at ensuring the technical, economic, ecologic and social feasibility of a circular economy.

Research goals

Short term goals

- Benchmarking already existing closed loop models in raw materials sectors emphasizing on both technical and business aspects.
- LCA and LCC guidelines for the evaluation of closed loop efficiency of raw materials.
- Elaboration of a harmonized approach and related guidelines for the evaluation of mass recovery eco-efficiency in each step of the loop.
- Evaluation of most promising sectors for closed loop approaches, based on a matrix-type study, focusing both on products categories and the metals/ minerals contained therein; selection of representative and EC significant case studies.
- Coordinated actions for putting together different actors in the loop (producers, consumers, collectors, recyclers) and creating proactive synergies among them.

Mid-term goals

- Case study implementation for closing the loop in at least three specific sectors, as identified above. The case studies shall be the basis for identification of obstacles as well as the implementation of effective communication and synergies among all stakeholders involved in the loop.
- Industrial symbiosis exploitation on territorial basis as successful methodology for closuring the loop for appropriate products/materials.

Long term goals (2020 and beyond)

- Extension of case studies to more products/territories and implementation so that main criticalities are covered at EU level.
- Creation of education/training opportunities and new "professions" that have broad competences along all steps of the loop and have an overall vision on

all the different aspects. Creation of a cluster of "closed loop" specialized experts that are able to act as closed loop models facilitators.

References

- [1] UNEP / Graedel et al. (2011), Recycling Rates of Metals - A Status Report, A report of the Working Group on the Global Metal Flows to the International Resource Panel
- [2] European Commission (2010), Critical Raw Materials for the EU
- [3] Based on: Meskers, C.E.M (2008), Coated magnesium, designed for sustainability? PhD thesis Delft University of Technology
- [4] International Resource Panel / Reuter, M. et al. (2013), Metal Recycling: Opportunities, Limits, Infrastructure. Nairobi: UNEP (in printing)

WG 3: Substitution of critical materials

Rationale

One way of reducing the dependency of European industry and society on critical materials is by eliminating or reducing the use of these materials in products and infrastructure; and replacing them with other, more abundant materials. This is not easy. The materials we use are the results of many years of research and development and are often optimized for their purpose and the required properties. However, new challenges will also evoke new ideas in the field of material science and product development.

Substitution can help, together with finding primary resources in Europe and winning back materials by recycling waste streams, to make Europe less dependent on raw materials from elsewhere. This is viable goal for the short and mid-term, and for this purpose, the ERA-MIN roadmap has been defined.

In the long term (beyond 2020) it is expected that raw materials will become less abundant by increasing demand from a growing and more prosperous world population and by a trend of decreasing ore grades. Substitution of scarce materials by more abundant and recyclable materials may become a key element for a transition to sustainable use of materials in the long term.

(Different terms for materials are used in this chapter. See the annex for a definition).

Scope

The Substitution Roadmap focuses on the following two types of substitution[9]:

- *Substitution of critical elements in existing materials by more abundant ones*. Substitution should also include reduction of the use of critical materials – not only strive for 100 % substitution
- *Novel materials with no or reduced use of critical elements.* Replace materials with other (new) materials which contain less or no critical materials.

Not included yet is substitution achieved by re-designing products in such a way that the need for parts containing critical elements are eliminated altogether. This way of 'functional' or 'system' substitution can form an important contribution to reduced dependency on critical materials. See also the section Future Work. Similarly, the possible applications of non technological basic research in the field of biomimicry was not considered, although it can be a valuable source of inspiration for substitution (see chapter 6 «interdependencies and transversal issues», section «Mineral separation, substitution and biomimicry»).

The critical materials as defined by the EU[3] are taking as the starting point for the Substitution Roadmap. Because the EU list is currently under revision, and it is likely that for each country and industry sector a somewhat different set of

9 For a more complete definition of substitution see the annex of this document.

critical materials may apply, a somewhat broader set of critical materials has been used. For instance Cr, Ag and Zn have been added. For more information, see on the critical materials considered; see the annex to this document.

The following boundary condition have been defined for setting up the Substitution Roadmap

- *Strive for breakthroughs (not incremental changes) in reduction of use of critical materials and improvement of material efficiency.*
  The roadmap should focus on big steps in substitution and improvement of material efficiency. This is also in line with the mission of EIP Raw Materials to 'find substitutes for at least three key applications for critical materials'.
- *Reducing or eliminating the use of critical materials - either by substitution or novel materials - should result in materials with similar or improved properties for the same or lower costs.*
  Substitution or new materials should not result in lower quality materials or higher costs.
- *Take into account substitution research environmental/ health risk related materials.*
  A lot of substitution related material research is being done on toxic materials, for instance in the context of the RoHS directive. Care should be taken not to copy these efforts, and where possible to make use of available results.
- *Strive for increased recyclability when substituting materials.*
  Substitution efforts to reduce the dependence on critical materials should take into account a good recyclability of materials by avoiding diffuse application and difficult disassembly (e.g. multi-materials).

Substitution challenges

Time and uncertainty are the key challenges for substitution. To develop a new material from first research to production usually takes 10 years or more. If new materials which depend less on critical materials are needed in 2025, research should start now. Uncertainty is another ingredient of all decisions with respect to substitution. Will the critical materials to be replaced still be critical and expensive 10 years from now? And will the R&D route taken for substitution not become obsolete by a whole new material or a whole new products? Investment in specific substitution efforts requires thorough analysis and involvement of all stakeholders. More generic efforts like material science education or material modelling which can serve broader substitution purposes may be easier to decide on.

Another challenge is broadness of the topic. Substitution spans up a very wide area of research. Starting with a large number of 35 critical materials[10], each of these materials can be applied in many different ways in engineered materials and components, which on their turn are integrated into a myriad of products. Finding substitution solutions for each and every product is not possible, and not always necessary.

10 The critical raw materials list of the EU defines 14 materials which include the REE group and PGM group. In total there are 35 materials.

There are several approaches for selecting topics for substitution[11]. For the Substitution Roadmap, a pragmatic approach has been chosen by defining the following key areas of material applications:

- 1. Materials for green energy technologies (enable the building up of a green energy infrastructure of solar cells, wind turbines, grids, batteries, electro motors, electric cars, etc.)
- 2. Materials under extreme conditions (enable the production of special tooling, high temperature materials for gas turbines, super lightweight alloys, high quality coatings, etc. which depends less on critical materials)
- 3. Critical materials in bulk applications (reduce the use of critical materials in base metal alloys and other high volume applications like building infrastructure)
- 4. Materials for electronic devices and medical applications (reduce use of critical materials to ensure availability/ affordability of electronics and medical devices for European and export markets)

These key areas have been chosen either because critical materials are used or will be used in large quantities (1. and 3.), or because critical materials are used in small quantities but play a key role in achieving certain material properties (2. and 4.), or both (1.) The definition of key areas also anticipates two grand societal challenges: the transition to use of sustainable energy sources and the ageing of our society.

In addition to these four key areas on material applications, one other type of key area has been defined. This key area does not focus on one specific area of material application, but is of a generic nature and is needed to provide a basis for substitution R&D to be carried for the other four key areas:

- 5. Enabling technologies & research infrastructure (generic research, technologies, models, databases and analysis tools to support substitution research in above challenges, e.g. micro structural models).

Structure of roadmap

Because of the novelty of the subject and the uncharted territory – except for the area of green energy technology, no examples of substitution agendas could be found – the working group has focused on getting a good picture of substitution targets in the different key areas and used the following table as template for the roadmap:

Key area (example: materials for green energy technologies)		
Application/ product	Reduction goal	Technology
Photovoltaic cells	*Reduction of critical materials (In, Ga, Ge)*	*Photon management to increase materials efficiency*

11 An discussion of several approaches is overview is given in the annex of this document. This document, Annex A Approaches for selecting substitution topics

The primary focus is on filling in the first two columns. Where possible an inventory of promising technologies (column 3) has been made, but this is not complete. A full inventory of technologies has to be made when specific substitution targets in terms of products/ applications and reduction goals are made. Or one could set out a call for proposals to receive good ideas for technologies.

Key areas for substitution

In this section for each of the five key areas a table with substitution targets has been filled in. A first prioritisation of substitution targets is given. The time element is not yet included in the roadmap. This requires know how of viable technologies for substitution and their level maturity. Once that is known a time path and definition of required research activities can be defined.

Materials for green energy technologies

The transition to sustainable production and use of energy will require large investments in new infrastructure in this decade and the next. The new infrastructure to harvest solar, wind and marine energy and other forms of sustainable energy sources will be by all means material intensive. The same applies to new forms of using sustainable energy for transportation (e.g. electric cars) and other purposes. Critical materials play an important role in many of these applications. The scale of this new infrastructure and the related demand for critical materials may outstrip the production of these critical materials.

Table 1 contains substitution targets for materials for green energy technologies.

Materials under extreme conditions

To endure extreme conditions, high performance materials with special properties are required. Special materials like alloys, ceramics and coatings have been developed and optimized in the last decades to achieve these special properties. Critical materials are essential ingredients for these materials.

Materials under extreme conditions can be found in aerospace engines and industrial gas turbines where materials are subject to high temperatures and heat fluxes; in fission and fusion reactors where strong particle fluxes exist; in high speed cutting tools which are subject to high wear and strong mechanical loading, and in many other applications.

Without materials for these extreme conditions our modern society cannot function. This makes finding solutions to make materials for extreme conditions with reduced dependence on critical materials a key area.

Table 2 contains substitution targets for materials under extreme conditions.

Critical materials in bulk applications

The properties of many familiar materials like high alloyed steel grades for automotive and tooling, and coating of bulk materials depend on critical materials as ingredients. Small fractions of critical materials in these bulk applications can still result in a large demand for these critical materials.

Considering the required volumes of critical materials for and the important role of the bulk applications for European industry and society, it is important to look here for substitution possibilities. Industry is already working on this, but coordinated research leading to breakthroughs will reduce the dependency on critical materials considerably and create a competitive advantage.

Table 3 contains substitution targets for critical materials in bulk applications.

Materials for electronic devices and medical applications

A large part of the periodic system can be found in present day electronic devices, like cell phones, LED lighting and LCD screens. The amount of critical materials per product is often modest, but essential for the performance and necessary to keep up with the on-going increase in functions and miniaturization of devices.

Although the materials costs are not always dominant in the overall costs of electronic devices, the heavy dependency on a large number of critical materials is considered a threat to the electronics manufacturing industry. Also the supply risk of electronic devices for industries that assemble them into their products is considered as a potential problem.

Medical applications form an entirely different category of products which depend on critical materials. Although the total number of medical applications or products for which critical materials are essential is limited, the relevance for our ageing society is high. A reduced dependency of medical industry on critical materials will benefit the European economy and at the same time help to keep medical applications affordable for European citizens.

Table 4 contains substitution targets for electronic devices and medical applications.

Enabling technologies and research infrastructure

Every substitution target defined for one of the first four key areas has its specific challenges in terms of materials science and product design. To fruitfully work on substitution challenges, it is essential that enabling technologies and research infrastructure are available. Enabling technologies, which are defined here as a generic basis for substitution related research in a wide area of applications, and a European research infrastructure which is equivalent to the Materials Genome Initiative as established by president Obama in 2011.

Table 5 contains targets for enabling technologies and research infrastructure.

Table 1 - Materials for Green Energy Technologies - Grey marked topics show a first prioritization.		
APPLICATION/ PRODUCT	**REDUCTION GOAL**	**TECHNOLOGIES**
Rotating electronics:		
Automotive traction and Wind energy	Reduce/replace **REE** (**Nd, Dy, Tb**) in permanent magnets used in in electric drive and propulsion applications in hybrid and electrical vehicles (electric motors)	Electric motors which do not rely on permanent magnets with REE.
		Increase magnetic strength of Nd-based magnets
		Motor design and cooling features to reduce operational temperature, thus lowering the grade of the magnet required
		Reduce grain size of Dy-magnet alloys
		Decrease particle size of iron nitride as substitute for REE-perm. Magnets
		Exchange spring magnets
		Use induction (electric) magnets in hybrid vehicles (currently only used in electrical vehicles)
		High-temperature-superconductors (HTS)-based magnets for direct drive generators (increase operational temperature to make them suitable for applications in (hybrid) electrical vehicles)
	Reduce **REE** (**Nd, Dy, Tb**) in permanent magnets for power generation in wind turbines (generators)	Substitute with Sm-Co-based magnet (used in the past; use has declined since the discovery of NdFeB magnet)
		Increase magnetic strength of Nd-based magnets
		Reduce size of wind turbines and increase density on wind-energy platforms (do not require large magnetic fields)
		Reduce grain size of Dy-magnet alloys
		Decrease particle size of iron nitride as substitute in REE perm. Magnets
Solar energy:		
Photovoltaics Crystalline Si (over 80% of the PV market); Thin film CIGS; Thin film CdTe; Thin film amorphous Si.	Reduce/replace the use of critical elements (**Ga, In, Ge, Se, Te, Ru**) in photovoltaics (PV):	Polymer casting technologies & roll-to-roll (better than vacuum thin film technologies)
		CZTSS (Copper-Zinc-Tin-Sulphide/Selenide) to substitute CIGS
		Fluorine or cadmium instead of Indium in transparent conductive oxides
		Transparent conductive polymers instead of ITO (Indium Tin Oxide)
		Inorganic (without polymers) transparent conductors
		Transparent conductive polymer composites with graphene or CNT
		Semiconductors based on Cu oxides, Fe and Zn sulphides
	Reduce/ replace critical materials in contacts: **Ag** in crystalline SiPV; **In** in anodes; **In**, **Ga** and **Se** in CIGS; **Ge**, **Ag** and In in contacts in Si-thin film PV.	To be defined

	Replace PV with solar thermal cells (system substitution)	Thermoelectric energy conversion
	Increase efficiency through manipulation of physical properties of materials (adsorption, band gap, photon splitting, efficiency)	Organic solar cells with an efficiency of 15%
		Increased material efficiency (by 25%) in thin film solar cells by photon management
		Nanocrystalline-Si materials applying hot carrier collection (creates high-energy electrons) to significantly boosting efficiency of nanoscale PV films
		36% efficiency through development if nano-wire arrays
Next generation solar powers	Reduce critical material content in high temperature alloys (700C)	Semiconductors based on abundant materials (Cu oxides, Fe and Cu sulphides)
	Replace **Ag** in contacts to sustain large scale applications	Resnick Institute Report (September 2011) – Case study 'Spotlight on Silver', pg. 25
Lighting:		
Fluorescent lamps; metal halide lamps; LEDs	Replace **Ga** and **In** in LEDs	To be defined
	Reduce use of **REE** in light convertors (**Tb** and **Eu** in CFL; **Y** in SSL)	To be defined
Energy storage:		
Super capacitors	Replace **REE** in super capacitors	Graphene-based supercapacitors
Batteries	Substitution of **Li, Co** in Li-ion batteries	R&D for less well studied battery storage chemistries involving more abundant elements (Na, S, Mg, Zn), with lower extraction costs
	Substitution of **REE** in NiMH batteries (where M = **La**; **Ce**; **Nd**; **Pr** up to 5%)	Idem
Catalyst devices and catalytic convertors:		
Catalyst devices and catalytic convertors	Reduce **PGM** (**Pt**, **Pd**, **Rh**) in catalysts and catalytic convertors	Use quantum-size effects
		Nano-sizing
		Core-shell materials
		Intermetallic compounds with close control of chemistry, size distribution and surface segregation
		Substitution of Pt or Pd-base wires by Pt or Pd clad wires with reduced PGM content
		Ni-Mo hybrid materials to substitute for Pt catalysts in cars a.o.
		Pt-free catalytic convertors (alkali-metal based catalysts)
		By means of bio-inspired catalysts
Energy conversion:		
Thermo-electric energy convertors	Substitution of critical materials in thermo-electric energy convertors (**Sb**, **Ge**, **Te**)	Electrically conducting steels
		Nanostructured magnesium silicates [1] M. Brigone, A.Zigotti, AIP Conf. Proc, 1449, 493 (2012)
		Organic semiconductors, Carbon Fullerenes, or Mg2Si or MnSi as alternatives (latter two with 50 % lower efficacy) Böttner et al. 2010 1st Int. Conf.on Materials for Energy, July 4-8, 2010, Karlsruhe. Book A pp.52

Table 2 - Materials under extreme conditions - Grey marked topics show a first prioritization		
APPLICATION/ PRODUCT	**REDUCTION GOAL**	**TECHNOLOGIES**
High temperature, heat flux (infrared, arc):		
Industrial furnaces (parts as heating coils, reflectors, structural material)	Substitute refractive metals (**W,Mo,Ta, Nb, Hf, Zr, Cr, V, Ti**) and others (**REE, Y, Re, Co, Ni**) in pure or alloy applications	Technologies: Bulk-coating combination; thermal barriers by ceramics; nano-particle coatings.
Glass melting equipment and similar applications (e.g. crucibles and boats)		
Bond coats in turbines		
High-temperature bonding and interconnect (e.g. for sensors on turbine blades)		
Electrodes and filaments (e.g. in lamps)		
Heat-dissipating parts e.g. X-ray tubes		
Catalysts in hydrogen fuel cells (Mo)		
Electrodes for welding (TIG)	Substitute refractive metals (W)	
Materials for friction stir welding (FSW) of light alloys in aerospace.	Reduce use of W and Re in tools (pins) used in friction welding. FSW is a promising lightweight alternative for traditional riveting methods. The technique is also being evaluated for joining in off-shore applications.	Design of alternative alloys or tools avoiding the use of REE.
High efficiency power plants (gas and steam turbines, super heater tubes) (also as alternative for closing nuclear power plants)	Substitute refractive metals (**W**,**Mo**,**Ta**, **Nb**, **Hf**, **Zr**, **Cr**, **V**, **Ti**) and other scarce metals (e.g. **REE**, **Re**, **Ir** in stainless steels and superalloys, and REE in thermal barrier coatings.	Alternative alloys and processing methods must be considered to achieve high creep strength, mechanical properties and corrosion resistance at high temperatures.
Aircraft turbines		Substitution high temp.alloys with ceramic (composites)
Spacecraft (rocket thrusters, nozzels)		
Materials for next generation of fusion applications	-	
Materials for next generation of fission applications	CFC, **Be** and **W** are serious candidates for Plasma Facing Components (PFCs). Substitution unlikely or not a priority. These material choices are the result of long trade offs and small solution spaces. Motto: 'Use critical materials for critical applications'.	
High electric voltage:		
Electrical contact in high voltage breakers	Substitute refractive metals and other scarce metals (W-Cu, **W-Ag**)	To be defined
Radiation (ionizing radiation, light):		

Medical equipment (e.g. grids, collimators in X-ray, CT)	Substitute **W** in shielding against ionizing radiation. (possibly difficult as W is already substitute for Pb)	To be defined
High pressure:		
Subsea instrumentation / Materials for deep-sea applications Downhole instrumentation (deep drilling)	Substitute refractive metals In most cases **Co**, **Ni**, Fe based coatings on steel and high strength structural steels (commercial grade 316L or low carbon S690). Both are low alloyed steel grades with elements like **Nb**, **Cr** and **Zr**.	To be defined
High mechanical loading, wear and friction:		
Cutting tools and wear parts - Cemented Carbides For machining (turning, drilling, milling, cutting) and wear parts in automotive, aerospace, mining, gas/oil exploration and wood machining industry. Exhibit an outstanding combination of hardness and toughness which make them irreplaceable materials in many manufacturing operations.	Reduce the use of critical materials **W**, **Co**, **Nb**, **Ta**, possibly **Cr** and **Ru**.	Alternative alloys and processes
		Use of recycling. (input for recycling agenda - WG2)
Dredging materials - cutting and wear parts		Development of new production concepts to reduce the use of raw powders.
Tools	Substitute refractive metals in hard-coatings (Ti, W, Cr)	Novel materials for coatings with abrasion resistance
Lubricant coating in bearings	Substitute mica wear-resistant coatings (TPT and UL)	
PVD wear resistant coatings	Reduce use of Cr, Nb, Ta, Zr as cathode (source) material. PVD uses cathodes of pure metals. Substitution of exotic metals may be considered.	
High electromagnetic field:		
Corrosion (vapour, steam, chemical environment):		
Pipelines, pipeline inspection, ship building, offshore platforms	Substitute refractive metals (W,Mo,Ta, Nb, Hf, Zr, Re, Ti) and other scarce metals (e.g. V, Cr) in stainless steels and superalloys	
e.g. industrial equipment, pipelines	Substitute refractive metals in corrosion resistant coatings	Novel materials for coatings, with chemical resistance

Table 3 - Critical materials in bulk applications - Grey marked topics show a first prioritization		
APPLICATION/ PRODUCT	**REDUCTION GOAL**	**TECHNOLOGIES**
Glass:		
For cars, buildings,…	Remove monopoly of alkaline elements -Li, Na, K (input for roadmap Primary Resources - WG1)	Substitution of alkalines in glass matrix expected to be a long term development. More feasible is to improve the availability by stimulating/ developing local production. Alkaline resources available in Europe (e.g. Li mines in Serbia, but will need help in further development.
For housing and mirrors for solar cells	Increase local sources for low iron sand (input for roadmap Primary Resources - WG 1)	Further development of magnetic techniques to reduce iron content to ppm level.
For electronic devices (LCDs, touchscreens)	Reduce use of cerium as a polishing agent in the glass substrates	-
Ceramics:		

Cooling equipment:		
Magnetic refrigeration at room temps (future technology, energy efficient and environmentally friendly)	Reduce use of Gd (prototypical room temperature refrigerant) Gd5(SiGe)4 the first giant magneto caloric material both with obvious criticalities, alternatives are: La(FeSi)13 or Fe2P type compounds (MnFePAs --> MnFePGe --> MnFePSi)	Fe-based amorphous alloys as magnetic refrigerants, but possible only limited cooling performance. (for FE based amorphous alloys the direct adiabatic temperature chance delta T is expected to be very low)
Heat-electricity generators		
Steel grades:		
High alloyed steel grades for automotive and other applications- alloying with 10 % or more.	Reduce use of alloying elements (Cr, Ni, Mg, others) Criticality of alloying elements to be checked	Metallurgical models New alloying processes Increased (alloying) process efficiency
Steel grades with scarce elements - alloying elements in the order of 0.1 %.	Reduce use of alloying elements (Co, Nb, Be, Mg, W, B)	Metallurgical models Increased (alloying) process efficiency
		New elements or processes to take over precipitation effect of **Co** a.o.
		De-alloying in recycling (input for roadmap Recycling - WG2)
	Reduce use of Nb in micro alloyed steels	New grades of steel with addition of V

Coatings:		
Coating of bulk materials	Reduce use of critical materials in coatings Criticality of coating elements (Zn, Cr, Ni, Sn)	Thinner scarce elements containing coatings
		Avoid delamination of coatings (longer lifetime)
		Organic coatings to replace metal based coatings
		Concepts for de-coating (recovering materials) (input for roadmap Recycling - WG2)
	Reduction of PGM in glass industry equipment	Use of PGM coated ceramics
Magnets:		
Materials for permanent magnets (for electric vehicles, wind turbines, hard disks, disk drives, electronics, power hand tools, ear buds)	Reduce use of critical elements: Nd, Sm, Dy. Most critical is Dy (for high temperature applications).	Reducing drastically LRE and especially HRE in NdFeB type magnets by grain boundary diffusion processes.
		Make rare earth free magnets which are better than best hard ferrites.
		Use nano-materials and structures to better reach the function with less REE → power density.
		Further development of other existing permanent magnet systems
		More use of induction magnets -> Cu
		Use powder metallurgy technologies with SPS consolidation techniques (MW.
		Develop structural Fe-based and Ni-based materials replacing Nd-based and SmCo magnets especially for generators and traction motors.
		Other novel magnetic materials without critical elements
Brazing alloys and contact materials:		
Brazing alloys and contact materials	Reduce use of scarce elements (e.g. silver, tin, rhenium)	-
Superconductors:		
Superconductors	Reduce use of Nb in superconducting cables (MW) About 3 % of Nb is used in superconductors. Not negligible, but often used in special applications. Possibly need for substitution is limited. Motto 'Use critical materials for critical applications'.	New high temperature superconductors

<table>
<tr><td colspan="3">Table 4A - Materials for electronic devices and medical applications- Grey marked topics show a first prioritization</td></tr>
<tr><td>APPLICATION/ PRODUCT</td><td>REDUCTION GOAL</td><td>TECHNOLOGIES</td></tr>
<tr><td colspan="3">ELECTRONIC DEVICES</td></tr>
<tr><td rowspan="2">Printed Circuit Boards</td><td>Replace use of In in solders –

In in solders is 10% of total In market (priv. comm. from Indium Corporation) -

Relative importance of In-solder market, compared to other solder markets to be defined.</td><td rowspan="2"></td></tr>
<tr><td>Replace Ag, in current substitutes of Pb-free solders.

Ag is more abundant in these products, but not alone. Also Au and Pd are present in smaller quantities – see previous notes</td></tr>
<tr><td rowspan="2">Displays

(focus on LCD+CCFL, LCD+LED and

take into account the future role of ORGANIC electronics - AM-OLED rigid displays are already used in smartphones by Samsung)</td><td>Reduction / substitution of In, Sn used in transparent conducting oxide ITO (tin-doped indium oxide)</td><td>Possible substitutes of conducting inorganic oxides with In, Sn: Conductive polymers; nano carbon, both stand-alone (graphene) and embedded into transparent polymers.

OLED displays save 50% In, compared to LCD displays of the same size.

Point to FLEXIBLE In-free conductive layers, in order to match the future needs of organic electronics: flexible displays.

Synergy with substitution research for other appls: solar, lighting, etc..</td></tr>
<tr><td>RE in phosphors of LED backlights. Mainly Y, Ce, Eu.

(the market share is < 12%)</td><td>Quantum dots</td></tr>
<tr><td rowspan="7">Sensors and actuators</td><td>Replace Ag in RFID, if the market will really take off in the future, and RFID chips will become a universal device</td><td>Electrically conducting steels</td></tr>
<tr><td>IR night-vision equipments (based on Ge-wafer microchips)</td><td></td></tr>
<tr><td rowspan="2">Piezoelectric devices (with Nb, Zr, Bi)</td><td>Produce piezoelectric without the use of Lead or early 4d/5d elements such as Zr by using thin film properties</td></tr>
<tr><td>Doped graphenes</td></tr>
<tr><td>Thermoelectric devices (with Sb, Ge)</td><td>Electrically conducting steels</td></tr>
<tr><td>Optical fibres (Ge-doped silica fibres)</td><td></td></tr>
<tr><td>Ga in future sensors for smart cities - same situation as for power solid state electronics; see below</td><td></td></tr>
</table>

Semiconductor for microelectronic devices (for high-frequency appl. and power solid state electronics)	Without or with reduced **Ga** (also used for POWER solid state electronics - 10^2-10^3 volts)	Novel material concepts or micro-/nano-structuring
	Without or with reduced **Ge**	
	Without or with reduced **In**	
Cables and wires	Replace/reduce **Cu** (and **W** in chip pins)	Aluminium, Graphene, Carbon Nanotube, nanocomposites
Spring connectors	Replace/reduce **Be** in Cu:Be (**Cu** + **Au** play also role in many other types of connectors)	
Electronic Product Cases and cables	Replace/reduce **Sb** in Flame Retardant Plastics	
Batteries	Replace/reduce **Co**	Exploit synergy with substitution research for other applications: automotive, etc..
	Replace/reduce **Li**	
Magnetic devices (magn. sensors, loudspeaker, disk drives, etc..)	Replace/reduce **Nd** and **Dy**	“...high-strength magnetic material from neodymium, iron, and boron nanoparticles. .....is thought to be able to yield as much magnetization using smaller amounts of rare earths” Iron nitride and other alloys candidate Exploit synergy with substitution research for other applications: wind turbines, MRI, etc..
Solid State Light Sources (the <u>future</u> generation of energy efficient light sources)	Replace/reduce **Ga** in present generation GaN-epitaxy LED, and those of next generation especially if on GaN wafers	
	Replace/reduce **In** in OLED, if the advent of next gen. OLED lighting will be confirmed	Exploit synergy with substitution research in displays
	RE in phosphors: YAG:Ce; (oxy)nitrides:Ce, Eu (the market share is < 12%) Phosphors coat small die area; area increases in.remote phosphor configurations	Quantum dots
Fluorescent lamps (tubes, energy saving lamps) (the <u>present</u> generation of energy efficient light sources)	**RE**-containing phosphors (**Y, Eu, Ce, Tb**, …). Phosphors coat large glass areas. **W** for electrodes	If CFL will decline with the takeoff of LEDs, no substitution is necessary
Metal-insulator-metal capacitors Resistors, thermistors, humistors	Replace/reduce **Hf, Zr, Ta, Y** Replace/reduce **Ta, Ru, Cr, Ir**	High-k materials with less REE and more SiO_2 or Al_2O_3 (Jorel et al. 2009, Appl. Phys. Lett. 94, 253502 (2009) Carbon in resin/organic matrix based materials

Table 4B - Materials for electronic devices and medical applications- Grey marked topics show a first prioritization		
APPLICATION/ PRODUCT	**REDUCTION GOAL**	**TECHNOLOGIES**
MEDICAL APPLICATIONS		
Implant materials of Ti or steel alloys	Substitute **V**	Adapt foundry processes + finishing. Challenges: legal authorities.
	Substitute **Nb**	
	Substitute **Cr**	
Contrast agents	Reduce current use of 3 ton **Gd**`/year. (market share of contrast agents is 100 % ! for Gd applications)	Use iron oxide nano particles. Challenges: legal authorities.
MRI = Magnetic resonance imaging	**Nb** in superconducting MRI magnets	
	Rare Earths (**Nd, Dy**) for permanent magnets in open MRI	"...high-strength magnetic material from neodymium, iron, and boron nanoparticles. .....is thought to be able to yield as much magnetization using smaller amounts of rare earths" Iron nitride and other alloys candidates Exploit synergy with substitution research for other applications: wind turbines, MRI, etc..
PET and other tomographies	Scintillator materials, containing **RE** (es: **Lu** orthosilicate); **Ce**-based LSO for PET; **Gd**, **Pr**, **Ce, Y** and other materials for Computed Tomography (the market share is < 12%)	
X-ray tubes	**Mo**	
	Graphite	
	Re	
	W	

Table 5 - Enabling technologies & research infrastructure - Grey marked topics show a first prioritization	
TECHNOLOGY/ INFRASTRUCTURE	**EXPLANATION**
Infrastructure	**European infrastructure which is equivalent to the Materials Genome Initiative as established by president Obama in 2011**
Computational tools and databases	
Integrated Computational Materials Engineering (ICME)	Integral model relating the properties, chemistry, microstructure, and processing techniques of materials
Microstructural model with all inputs to define/ design material properties	Detailed models describing the evolution of the microstructure during processing of materials based on physical principles. Examples are phase-field and cellular automata models. These models require input from a data-base.
Data-base for the thermodynamics, kinetics, and properties of materials	Data-bases with the thermodynamic properties materials and a data-base with the kinetic properties of materials, e.g. nucleation, grain growth, re-crystallization, precipitation kinetics. Data-base with the mechanical, optical, electrical, magnetic properties material.
Computational materials center	This center will integrate computational models.
Experimental tools	
High throughput screening to test substitute materials	A fast method (e.g. x-ray diffraction) to test material characteristics (e.g. crystal structure and composition) of materials.
Diagnostic tools/ characterization technology	Tools to characterize the structure, chemistry, and properties of materials
Large scale characterization facilities	Neutron scattering and synchrotron radiation facilities like the European Spallation Source (ESS) and the European Synchrotron Radiation Facility (ESRF) provide unique probes to study the evolution of the microstructure in-situ during processing of materials
Advanced microscopy centre	Different microscopes to characterize the structure of materials: high-resolution electron microscopy (HREM), 3D atom probe, transmission electron microscopy (TEM), environmental scanning electron microscopy (SEM), etc..
Technologies	**Enabling technologies which are needed as a generic basis for substitution related research in a wide area of applications.**
Overall	
Method for evaluation of substitution concepts	Method to verify if a substitute is more sustainable than the original material based on ecological impact, availability of materials, energy demand, recyclability etc.. For example: life-cycle analysis
Define and construct substitutability matrix	Systematic and scientific method the identify potential substitutes for materials
Self-healing techniques	Make materials in such a way that the life-time of damaged materials is enhanced by a self-healing effect of the material
Synthesis and manufacturing	
Joining technologies of different materials to enable substitution	For example joining ceramics to metals
Net shape technology for metal components to increase material efficiency	For example metallic foams reduce weight.
Technologic approaches using “elements of hope” instead of scarce elements.	The elements of hope are chemical elements that are abundantly available, e.g. oxygen, silicon, aluminium, iron, calcium, sodium, potassium.

Innovative routes for carbo-reduction of oxides for steel and carbides	
Repairing technology	For example high rate sputtering instead of substitution of components

Prioritization, validation

In order to collect as many ideas as possible, the working group has kept an open mind and a broad scope when filling in each of the five key areas. A first prioritization has been done, but in all cases further validation is necessary. Stakeholders from outside the working group should be involved here.

The following criteria are considered to be important for prioritization and validation of entries in the substitution roadmap:

Application/ product	Reduction goal	Technology
The applicability of the application/ product depends on: a. Amount and role of critical materials in application of products b. Projected need for application or product in (near) future c. Role of application or product in industrial sector, EU economy or national economy.	Reduction goals should pertain to d. Critical materials with real need of substitution • subject to supply risks and essential for the product performance, and/ or • subject to increasing costs and impacting margin of products • with low recycling possibilities. e. Feasibility of reduction	Technologies should be f. Ranked on low and high hanging fruits

Applications and products are to be validated by industry and government	Reduction goals are to be validated by industry and government.	Technologies are to be validated by academia

Table footnote:

a. *Applications and products with large amount of critical materials or in which critical materials greatly determine essential product properties will have a higher priority for working on alternatives.*
b. *One should not only look at the current situation but also at new products and technologies which may require critical materials. Furthermore it is important to look at the projected needs of products considering the considerable time needed to realise substitution:*
c. *How large is the current and future market for the products seen from the perspective of EU economy, national economy or the related industry sector? Is it relevant to invest in substitution?*
d. *How critical are the materials? Are they (expected to be) subject to strong prices increases or even supply interruptions? Is recycling an option to provide substantial secondary resources for the critical materials?*
e. *The feasibility of reducing or substituting specific critical materials in applications should be taken into account when defining reduction goals. For instance, based on on-going research and the physical properties of Nd, it is not expected that current high quality permanent magnets are possible without Nd, at least in the foreseeable future. The same applies to selecting technologies for reducing or substituting specific critical materials. One should look at work done in earlier stages at the proposed technologies and assess whether enough progress can be expected.*
f. *If possible a division should be made of technologies which are close to applications and others which require more time. Work on both categories is needed, but in first calls one could go for low hanging fruits.*

Future Work

Considering the novelty of the subject and the available time, the working group has chosen to focus on the basic elements needed to set-up a Substitution Roadmap. The resulting Substitution Roadmap presented here provides a good basis to discuss the role of substitution, possible priorities and first steps to define relevant research. However more elements have to be added in the future.

The working group identified the following topics for future work:

- Involve industry & government to select & validate the true substitution targets. For good decisions on investments in substitution, one needs to take into account scarcity forecasts, economic challenges and opportunities (domain of industry) and policy and societal challenges (domain of government).
- Involve material research community for broad input on new technologies. The ideas and solutions for substitution challenges can come from anywhere in the wide field of material research. It is crucial to tap the material research community for viable technologies to work on, once the substitution target has been defined.
- Include 'Technologies for increasing material efficiency in products and production' in the scope of the roadmap. Using fewer raw materials for the same amount of materials, or recycling waste back into the production process of materials, can contribute to reduced dependence of raw materials in the same way as substitution.
- Include 'Functional substitution' as way of reducing the dependency on critical materials. Re-designing products to eliminate the need (function) for parts containing critical materials all together can be a powerful way of substitution and can have effect on a short timescale (a few years).
- Define the time path for R&D on substitution. If viable technologies for substitution and their maturity level are identified, it is possible to define a time path and the required research activities.
- Broaden the materials scope for the Substitution Roadmap. Almost all critical materials currently considered for the Substitution Roadmap are metals. This is indeed an important category of critical materials, but ERA-MIN is asked to also consider industrial minerals and building materials as well. It is also advised to broaden the field of solutions further to include for instance also bio-based materials as substitutes.

Key performance indicators

Because of the novelty of the subject and the uncertainties associated to the definition of pertinent materials or elements to be substituted (will the critical materials to be replaced still be critical and expensive 10 years from now? And will the R&D route taken for substitution not become obsolete by a whole new material or a whole new products?), defining Key Performance Indicators in the field of substitution should be made with caution. This requires know how and knowledge which are not available yet.

The research on substitution should be split into a few phases: 1) an exploratory phase in which several (material) technologies are researched further to prove the feasibility and provide the essential processing and application parameters, 2) a proof of principle phase in which the most viable technologies (technology) are (is) proven in an exemplary application , 3) a prototype phase in which the most viable technology is applied on a pre-industrial scale.

For the development of substitutes, the Technology Readiness Levels (TRLs) can be used as performance indicator, at least for the first phase. For the second phase, the Key Performance Indicators should be on a successful proof of principle. For the third phase, the KPI should be a positive industrial investment in production of the new material.

WG 4: Public policy support and mineral intelligence

Rationale

Sustainable management and use of mineral resources, taking into account criticality issues are vital for competitiveness of industries in the EU. A possibly major issue is the lack of an EU non-energy mineral raw materials policy and of a legal basis to develop it. The lack of an EU legal competence to develop such a policy may have far reaching consequences, especially in the context of globalisation and of sustainable management of mineral raw materials, as the industry and its impacts are global in scale. At present, the EU can only look at non- energy mineral raw materials issues from certain perspectives such as competitiveness, development co-operation, environment, energy, maritime affairs, research, trade, Specific research is needed to identify what costs and benefits could arise from a harmonised EU policy, what it would mean in terms of legal and institutional development and how and where the subsidiarity principle could be applied. The just started EIP High-Level Steering Group comprising several Commissioners, Member State Ministers, CEOs and representative of the European research community could possibly play a role in this.

At a time when raw materials and resource efficiency are at the forefront of the EU political debate, public and private sectors must work together in a spirit of partnership to attain the goals set out in the EU Raw Materials Initiative. A series of trends will shape the future supply of raw materials needed by the EU economy in the global context. To enable the paradigm shift to come, towards eco-efficiency and a circular economy, consistent resource efficient policies, based on public data and knowledge, are needed to base decision-making. Data, knowledge and processes must be available and tailored regarding specific constraints:

- While designing Raw Material strategies, policy makers have to gather trustworthy data and information on the national and EU deep geological potential and at a global scale, on minerals and metals stocks, flows, projects, demand and supply, on the drivers and scenarios that will, within a 20 years perspective steer demand and supply, capitalistic and intellectual property controls, trade;
- While developing economically, environmentally and socially responsible mining, industrial stakeholders have to cope with lingering negative public perception due to historical damages such as ground subsidence above old workings or air, soil and/or water pollution;
- While developing circular economy, industrial stakeholders throughout the value chain need to secure product value and quality with new range of raw materials. Consumers need to be informed on the environmental performance of the goods they purchase, commitment of minerals and metals to transparency and auditable sustainable performance need to be rewarded by EU and national mechanisms.

The mineral industry has many stakeholders such as geological surveys, research institutes, academia, technology providers, authorities at all geographic scales (from EU to local scales), primary and secondary minerals and metals industries, added-value manufacturing industries, civil society (neighbours, consumers, associations)…

Capacities, expertise is needed both in the public and in the private sector to address the numerous sustainability challenges related to minerals and minerals, delivering the many irreplaceable benefits they provide through the functionalities they make possible, while reducing at a maximum negative economic, environmental and social impacts that may arise in relation with the industry current or past operations (fig. 5). Research in social and human sciences is equally important, to analyse public perception and behaviour about the issues related to Europe's raw material demand, supply, industrial competitiveness and related sustainable development issues.

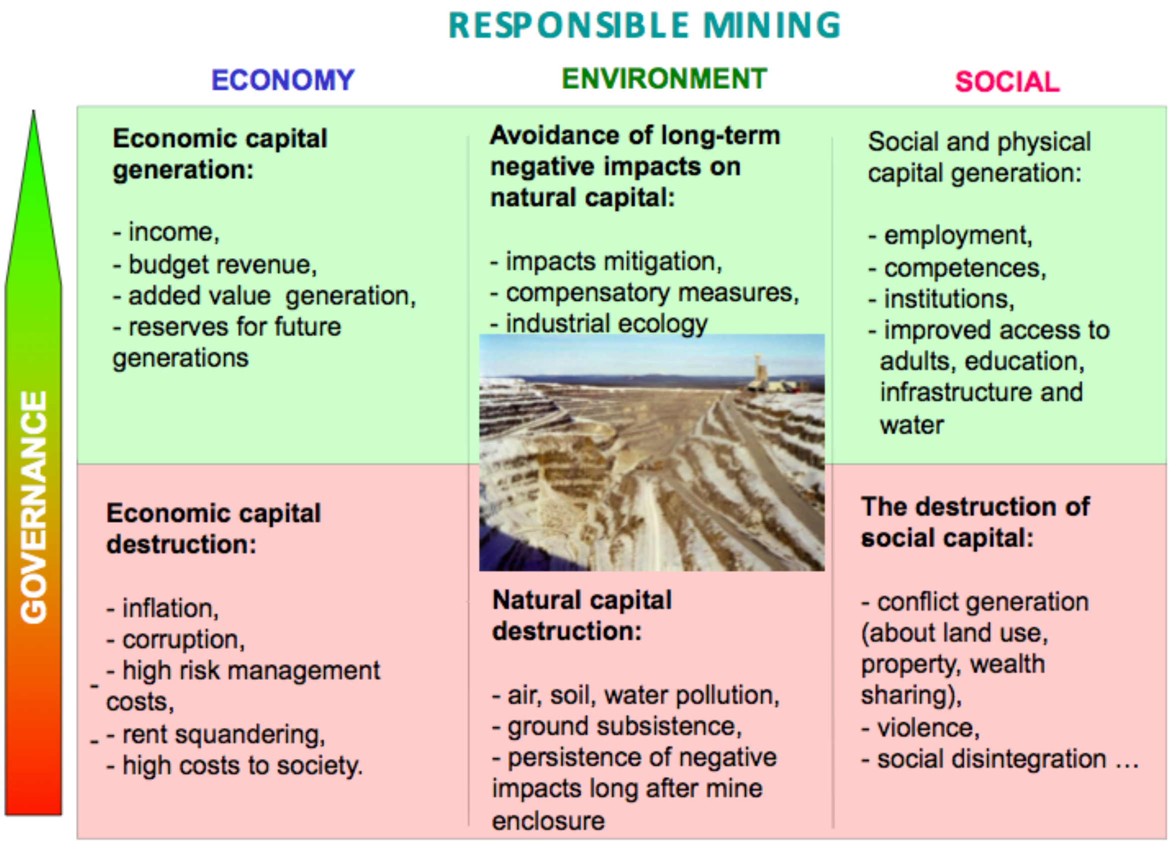

Figure 5 - Positive or negative impacts of the minerals and metals industry: governance matters.

General challenges

From an EU, national or regional policy-making perspective the challenges related to minerals and metals are manifold. They relate to the need to ensure, in harmony with the concerned economic stakeholders and the expectations of society the flows of primary and recycled minerals and metals needed by the economy, and ihe sustainability of these flows.

The challenges to be addressed include:

- Sustainability challenges related to the production and recycling of minerals worldwide, as much of their supply to the EU comes from beyond its borders. Emissions of greenhouse gases, of pollutants to air, water and soils including by the energy sources needed to supply energy to the industry are part of this challenge. Much of the EU environmental footprint is located beyond its borders;
- The important issue of all stakeholders awareness-raising and engagement, with regard to the development of a sustainable EU minerals and metals industry, requires comprehensive, cross-sectorial policy responses (competitiveness, development cooperation, education, energy, environmental, trade, and professional training, social sciences …). These must be supported by:
  - The availability of accurate, up to date public mineral intelligence derived from data and information on the global mineral resources industries (deposits, exploration, current and future mining projects, location and main characteristics of metallurgical and refining plants, recycling and related facilities, capitalistic controls, intellectual property, market

drivers, life-cycle and material flow data ...); So far, current EU minerals intelligence is essentially limited to open source production data available from national/ regional sources (for some countries/ regions) or from producing companies. Very little data is available for high-technology minerals ([5], [6]) and for many industrial minerals;

- The development of public, digital, 3D/ 4D geological data and knowledge on Europe's subsurface. It is hampered by very limited data acquisition efforts over the last twenty years in many EU countries. A protracted public effort over a few decades would be necessary to develop a 3D/4D data, knowledge and formation infrastructure on the EU's subsurface down to 3 to 4 km depth (see also WG1 on exploration). Moreover, such data and knowledge has a range of other applications in the energy, construction (underground infrastructure), natural hazards impact mitigation, water resources domains;

- The development of trade and non-trade barriers undermining EU competitiveness; An identification and assessment of existing best practices in the mineral resources domain;
- The availability of expertise needed to analyse and transform this intelligence for use in formulating policies, investment decisions and more generally to inform the society and the minerals and metals industry stakeholders;
- The development of modelling, integrating economic, environmental and social factors as well as objective functions controlling them;
- The development of educative curricula needed to develop and maintain such expertise over the long-term;
- Outreach actions to communicate mineral raw materials and sustainable development issues to the broad public;
- Public policies rewarding transparency, eco-efficiency based on improvement of global sustainability;
- Corporate, public and individual governance are needed to maximise the contribution of the minerals and metals industry to all dimensions of sustainable development (Fig. 5).

Finally a possibly major challenge is the lack of an EU non-energy mineral raw materials policy and of a legal basis to develop it. The lack of an EU legal competence to develop such a policy may have far reaching consequences, especially in the context of globalisation and of sustainable management of mineral raw materials at a global scale.

Addressing these challenges will require :

1) The development of EU-level public mineral intelligence and eco-efficiency frameworks and more specifically:

- the EU public database of primary and secondary resources and flows;
- the development of the EU 3D/ 4D geological database on deep geology (down to a depth of 3 to 4 kilometres), to document the potential for deep-seated, hidden deposits;
- the long-term and comprehensive assessment and monitoring of criticality factors impacting mineral raw materials supply chains;
- the life-cycle assessment as public good; encompassing the comparative impacts of the key process routes available to produce a same mineral or metal and the impacts of trade;
- the development of indicators to measure the progress towards eco-efficiency.

2) Capacity-building and engagement of all stakeholders i.e:

- Reducing demand for raw materials and increasing the re-use of materials
- Enabling sustainable extraction of raw material.

Several of the actions proposed below relate to the development of data and information systems needed to support life-cycle thinking, for policy making and industrial decision taking, to drive research, to guide the development of new mineral deposits and to facilitate environmental assessments, for instance to compare the environmental footprints of different production routes. .

Research in social and human sciences is equally important, to analyse public perception and behaviour about the issues related to Europe's mineral raw material demand, supply, industrial competitiveness and related sustainable development issues, in the EU and globally. Obstacles to securing a social license to operate for the minerals and metals industries need to be identified and, if feasible, addressed.

Enhancement of mineral intelligence and eco-efficiency frameworks

Availability and validation of resource and reserves data as public good

Challenges

Current intelligence from the global primary and secondary mineral and metals industry is essentially limited to:

- Data on production, available from several open, free of charge, sources. Global production data is available as well as national data (for some countries) or for many producing companies but mostly only for the more common minerals and minerals. Data on many minerals and metals produced in small quantities, frequently of great importance to the development of high-technology applications [5] and [6] is scarce or unavailable;
- Open source trade data is available from UN COMTRADE (global trade), EUROSTAT and national statistical authorities. However, this data only allows to assess apparent EU or national consumptions as, for instance, metals and minerals contents hidden in traded manufactured or semi-manufactured goods, in alloys, in concentrates, in waste, in scrap or in end-of life products are not individually identified and recorded in trade statistics; conventional material flow analysis, as done at EU level, is widely based on the Direct Material Consumption, which only measures the total amount of material directly used in an economy (domestic extraction plus imports minus exports,. The DMC indicator also ignores the environmental and social burdens that may result from mining or metallurgy in poorly regulated countries or due to transport, potentially major issues form a sustainable development perspective.
- Data on resources, reserves and mining projects at various stages of development is mostly available for companies financing their exploration or development projects via the issuance of shares on stock market where there are obligations to report resources and reserves data according to specific reporting codes such as the JORC (Australia), the NI 43-101 (Canada) or the SAMREC (South Africa) codes. A similar code exists for the European Union, the Pan-European Reporting Code (PERC).
- Data and information on projects financed through private equity or taking place in certain regions such as Asia or Russia is much more limited and data on secondary materials resources is scarce.
- Data on the sustainability performance of companies is available only for a growing selection of Western mining and metals products companies. In 2011, 133 companies worldwide reported their sustainability performance according to one of the three Global Reporting Initiative application levels (A, B, C).

The availability of public data on global primary and secondary resources and reserves data on the diverse metals and minerals required by the EU economy remains too limited to efficiently guide public policy making and investment decisions. Data acquisition and EU information system are needed to support EU level policy-making in fields such as competitiveness, development, environment, marine policy, research, trade. This information system should also include information on the ownership of these resources and reserves.

Key performance indicator

Within 5 year launch of a sustainable, financed, public EU mineral intelligence capacity and appropriate databases and instrumenrs.

Innovation needs

- Collection of public data and information, traceable and validated:
    - Regarding the production of all categories of minerals: construction materials, industrial minerals and metallic minerals (ore minerals);
    - Addressing economic, environmental, governance and social aspects all along a mining project's lifecycle (from exploration to post-mining) or urban mining;
    - Targeting both listed and non-listed companies with appropriate means (e.g. on a voluntary basis, through regulatory developments…).
- Development of the infrastructure and tools to process the collected data. This is a necessary step to e.g. process, integrate and model the various kind of data necessary to efficiently guide public policy making and investment decisions.
  For instance, infrastructures and tools remain to be built in order to process geological data of the EU's subsurface (see WG1) and set up an EU 3D/4D data, information and knowledge infrastructure to identify Europe's potential for deep-seated, concealed mineral deposits, and to provide guides for later investment in mineral exploration. Building on the INSPIRE Directive implementing rules for geological and mineral resources, the development of common EU geological and mineral resources data models is suitable for high resolution (1:200,000 scale and larger scales) mapping, to entail, at least schematic interoperability between national/ regional datasets. The achievement of semantic or conceptual interoperable would be an important step in support of a harmonised European geological data infrastructure.
- Development of statistical tools, definition of proxies, and data analysis models to provide a range of projections so that scientists and decision makers can understand the uncertainties of the projections, appraise the impact of raw materials use on our environment, quality of life and sustainable (or not) development.

Research goals

Short-term goals (2 years)

Improvement of imports-exports data of minerals, metals, products and waste, crucial to Material Flow Analysis, through the development of statistical proxies to gain a better understanding of national/ EU level real consumption of minerals and metals:

In dialogue with industry organisations, it is recommended to build an EU material flows database taking into account not only Direct Material Consumption (DMC) but also the Raw Materials Equivalent (RME) [2] and the related environmental global footprint of the EU minerals and metals consumption. While it is impossible to determine it precisely on the basis of current trade statistics, the concept of "statistical proxies" could be developed to describe the average minerals and metals content of main minerals intensive products and semi-products, including concentrates and scraps. Minerals and metals contents of products representing a large share of the minerals and metals use as statistical proxies to better assess the real EU material consumption would be very useful to improve the current material flow analysis practice, to understand EU's global environmental footprint and to better assess EU's dependence on minerals and metals production beyond its borders.

Medium-term goals (5 years)

On the basis of the findings of these projects and of other requirements, such as the development by the European Commission of a framework of resource efficiency indicators, engage into dialogue with key stakeholders such as the International Council on Mining and Metals, World Business Council for Sustainable Development, the International Metals Study Groups, OECD, the Global Reporting Initiative, the Committee for Mineral Reserves International Reporting Standards, specialised UN bodies such as UNEP, UNFC and UNCTAD, key stock markets regulatory bodies on ways and means to enhance the international reporting framework and standards, building further on existing developments and initiatives.

Many areas of the natural and social sciences involve complex systems that link together multiple physical or intellectual sectors. This is particularly true for environmental problems, which have strong roots in the natural sciences and require social and policy sciences. Integrated assessment models (IAMs) are necessary to integrate knowledge from these contrasted domains into a single framework (see the developments in IAMs for climate change; e.g. Nordhaus, 2011[10]) so that a decision or analysis can consider all endogenous variables that operate simultaneously. Integrated assessment models are valuable because they provide a range of projections so that scientists and decision makers can understand the uncertainties of the projections, and they can help to appraise the impact of raw materials use. The developpement of these models requires collaboration between contrasted fields of expertise including « hard » and social sciences, comprehensive databases, and an EU dedicated infrastructure.

Long-term goals (2020 and beyond)

Achieve an internationally agreed framework of indicators describing all the dimensions of the global minerals and metals industry and have a sustainable, operational EU minerals intelligence capacity in place.

Physical criticality through Material flow analysis and life-cycle impact assessment as a public good

Challenge

In a context of growing raw material demand, the necessity to develop tools to inform political and industrial choices with the aim **to secure the availability of resource for the future generations**. Hence, many-fold indicators informing resource availability/criticality have been developed over the last two decades addressing physical issues and other economic (protectionism, monopolies) and geopolitical (conflict zones) in the medium-long term.

Regarding physical criticality analysis, one can consider both Life-cycle impact assessment methodologies and Material flow analyses, which are complementary. However, even if they can both contribute to inform policy or industrial decision-making with respect to resource criticality, research challenges to be tackled are very specific and must be addressed separately.

Challenge 1: Life-cycle impact assessment

LCIA methodologies aims to assess environmental and sanitary impacts of production and consumption in a Cradle-tp-cradle approach. Hence, they provide relevant measurement of resource efficiency. Yet, given the complexity of the impact on resource, many LCIA resource depletion indicators have been developed relying on different methodologies (principles, bases).

With a view of informing decision-makers, it is important to improve reliability and relevance of the various methodologies regarding specific policy or industrial objective. Compatibility of various LCIA resource depletion indicators is in progress and preliminary results show important result variability when applying different assessment methodologies to the same flow inventory (9). Therefore, it is important to benchmark these methodologies from a user point of view. A key issue is to identify their relevant use by clarifying the specific environmental objective they address.

In addition, with the development of recycling industries, the introduction of "anthropogenic stock" (i.e. from the urban mine), which was missing in all assessment methodologies so far, becomes of high importance and relevance for research.

Finally, when dealing when resource criticality, it is important to remind that LCIA-resource depletion indicators do not differentiate between the various forms of resource consumption in manufacturing processes. Yet, some processes "consume" resource in a dispersive way (e.g when using small quantities of metals for micro-electronics of mobile phones). It affects the resource concentration raising environmental and economical costs of resource accessibility. Such considerations should also be taken into account in the evolution of assessment methodologies.

Challenge 2: Material flow-analysis

Develop the analysis of industrial supply chains linking key industrial goods to geological and urban mining knowledge as well as substitution solutions (element, material or functional) and identification of criticality issues at each stage.

Key performance indicators

Within 5 years:

- Develop a comprehensive public European Life-Cycle impacts database for minerals and metals used in the EU;

- The public Material Flow Analysis database approaching real consumption;
- The methodology to assess the EU real consumption environmental footprint beyond its borders.

Innovation needs

- Create an improved EU data base on minerals and metals material flow analysis approaching real minerals and metals used by the EU and its economies and assess its global environmental footprint;
- Develop the European Life Cycle Database (ELCD) for all economically important minerals and metals, organising data to document the various key processes, considering their main production routes;
- Create an EU industrial ecology database on material flows and life-cycle inventories for the production of non-energy mineral raw materials, for selected products
- Develop long-term supply/ demand scenarios (foresight studies looking 20 years ahead); Develop the analysis of industrial supply chains linking geological data to industrial goods (see fig. 6) and identification of criticality issues at each stage;
- Assess the vulnerability of supply chains to political decisions and to regulatory changes (collateral damage: ban on landfilling, ban on mercury and arsenic; inappropriate application of the precautionary principle; promotion of certain technologies ...);
- Develop indicators to measure the sustainability performance of minerals and metals production;
- Choice and use of methodologies for assessing impacts considering the options to develop a broadly acceptable reporting framework.
- Analysis of the economic considerations of the operator with regard to investment and supply chain;
- Negative externality issues such as legacy costs from waste which are transferred from one generation to the next; Life-cycle costing;
- Design, experiment and assess impacts of new innovative management, business models (including online reporting systems); and reporting mechanisms;
- Potential for the development of industrial symbiosis (zero emission industrial parks);
- Flow-sheet re-engineering, taking an established method, such as wet process phosphate processing and reengineering the flow sheet to extract a number of other minerals of interest in the same overall process, at the same time converting saleable waste streams into products.

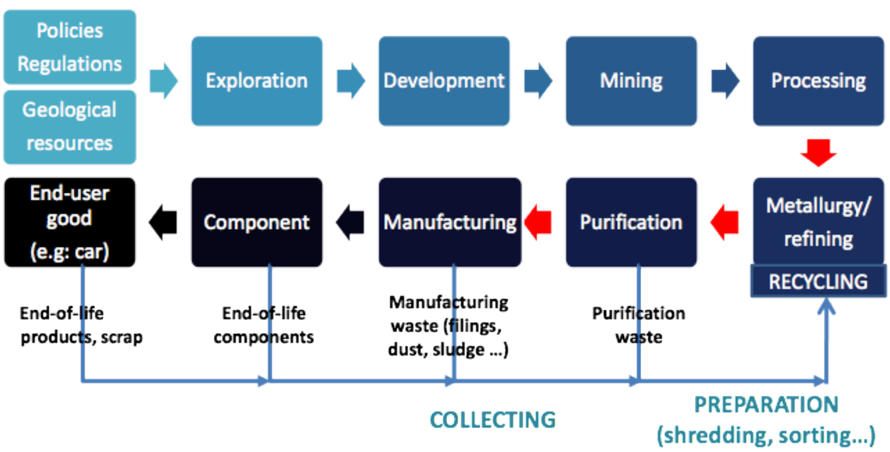

Figure 6 - Theoretical components of a supply chain. Not all stages may be necessary for the production of a given product. Red arrows designate trading houses that in a number of cases play a key role in marketing concentrates or metals

Research goals

Short-term goals (2 years)

- Develop a cradle-to-gate (from geological resources to the marketed minerals and minerals) materials flow analysis and database, including energy, land and water use, for minerals and metals, as a public good. This analysis should as far as possible allow to compare the main production routes (mining, processing, metallurgy, recycling) available for the production of a same metal or mineral to serve as a reference for the possible development of eco-labelling;
- Support the update/ integration of the results of key material flow analysis projects related to minerals and metals at UNEP, in national institutions and from past projects such as the collaboration between the German Federal Institute of Geosciences and Raw Materials and the Volkswagenstiftung [1], the Mining Minerals and Sustainable Development Project, the University of Aachen (Germany); the Wuppertal Institute (Germany); the Yale School of Forestry & Environmental Sciences (USA) and other similar projects/ institutes;
- Develop indicators to track and compare the performance of global mining operations, processing plants and smelters building on the already widely used mining and metals sustainability reporting guidelines developed by the Global Reporting Initiative;
- Develop international partnerships with Australia, China, India, Japan, and USA to pool efforts with mining and metals industry companies and international organisations (ICMM, OECD, WBCSD, GRI ...) to achieve the stated goals.
- Benchmark assessment methodologies choice and use considering the options to develop a broadly acceptable reporting framework. The impact of such benchmark on the inventory data set should also be addressed.
- Develop or improve assessment methodologies to introduce anthropogenic stock and collect inventory data (see WG 2) to develop new LCIA resource depletion indicators

Medium-term goals (5 years)

- On the basis of the outcomes of EU funded projects such as Minerals4EU and CRM-INNONET, develop the analysis of supply chains for individual minerals and metals, linking key industrial goods to geological and urban mining knowledge. Assess the potential for substitutions (by the use of more abundant elements, different materials, or a different management of the functionalities provided by rare minerals and metals,
- Assess the feasibility of a primary and secondary minerals and metals eco-labelling system, including recycled minerals and metals, based on the above indicators,
- Develop knowledge regarding the dispersive use of resource and develop assessment methodologies to incorporate such dimension,
- Understand geological stocks available to mankind and Progress towards an harmonised resource depletion assessment methodology fostering cooperation with UNEP-SETAC (similar approach as Usetox).

Long-term goals (2020 and beyond)

- Develop Eco labelling of primary and secondary resources to inform customers and allow for sustainable procurement.

Long-term mineral raw materials criticality assessments

Challenge

In 2010, the European Commission's ad-hoc working group on Critical Raw Material coordinated by DG Enterprise identified a first set of 14 Raw Materials. To qualify as critical, a raw material must face high risks regarding its availability to it, i.e. high supply risks or high environmental risks, and be of high economic importance. The 1st revision of the 3-yearly assessments of Raw Materials critical to the EU economy (DG Enterprise project) is in progress and is to be released later in 2013;

This section deals with more longer-term strategic issues with potential high impacts for the whole EU economy.

Innovation needs

Due to the lack of elasticity of the supply side, caused by the very long lead times needed to open new mines, develop effective recycling chains or industrial-scale innovation, all needing from 10 to 20 years, there is need to develop long-term analysis to assess the challenges that the EU's mineral raw materials supply may face, based on the determination of long-term supply and demand scenarios. On the supply side, there is need to consider factors such as:

- the global mining industry project portfolio at various levels of advancement;
- the perspectives for recycling of individual metals and minerals, for substitutions;
- trends in global raw materials investment and trade;
- trends in controls over production and intellectual property all along the supply chain.

On the demand side, the following factors s will need to be considered.:

- compound annual growth rates over different periods of the demand for individual minerals and metals;
- material composition and intensity of different technologies;
- regulatory issues and their impacts);

Identification of factors for determining metals and minerals prices and their potential impact on criticality is needed as well.

On-going or soon to be launched EU-funded projects will look at these needs. It is suggested to await the outcomes of these projects, and evaluate them to adjust the proposed ERA-MIN research roadmap.

These projects are:

- the 1st revision (in progress) of the 3-yearly assessments of Raw Materials critical to the EU economy (DG Enterprise project);
- the Study on structured statistical information on quality and quantity of EU raw materials deposits, to be launched in January 2013;
- the 2013 FP7 Work Programme project "NMP.2013.4.1-3 - European Intelligence Network on the Supply of Raw Materials)", which is expected to be launched during the second semester 2013, further to the evaluation process in progress at the time of writing these lines (March 1st, 2013).

Research goals

Short-term goals (2 years)

- Demand scenarios: developing and linking foresights consumption studies with prioritary goods and deriving technology-driven demand scenarios for individual minerals and metals. compound annual growth rate over different periods of the demand;
- Assess the vulnerability of supply chains to political decisions and conflicts and to regulatory changes (collateral damage: ban on landfilling, ban on arsenic, cadmium and mercury; inappropriate application of the precautionary principle; promotion of certain technologies...);
- Assess the incentive or deterrent characteristics of policy measures on recycling or re-use (ERP, VAT differential between materials,..);

Medium-term goals (5 years)

- Develop a stable, suitably funded, EU minerals intelligence capacity (institutional goal, not research) and derived services (EU Minerals Yearbook, minerals and metals criticality assessments) as a public good.
- Develop Market-tool analysis mapping urban mining deposits (including operators, geographical areas)

Developing eco-efficiency

Challenge

Eco-efficiency is a concept that has been developed since 1982 by the World Business Council on Sustainable Development (WBCSD). It means "creating more goods and services using fewer resources, waste and pollution" [4] in other terms doing more with less resources use. It is at the heart of the "zero waste" circular economy thinking.

The WBCSD is actively engaging with the Global Reporting Initiative (GRI), the latter having developed a voluntary sustainability reporting framework, with 6 groups of indicators, including reporting guidelines specifically tailored to the mining and metals initiative. The use by this reporting framework is growing rapidly, from 12 companies in 2002 to 80 companies today. In 2012 a large share of the global mining or metals companies has reported their sustainability performance using the GRI reporting guidelines. The GRI has entered in a global alliance with OECD, the United Nations Global Compact, the United Nations Environmental Programme and ISO.

Innovation needs

- There is a need to document progress over time towards eco-efficiency throughout the global minerals and metals industry, by main centres of production and by countries/ regions, in terms of progress to date and the outstanding challenges;
- There is a need to assess, from a sustainability perspective, the current status of the main available eco-efficiency indicator frameworks such as the GRI reporting guidelines for the mines and metals industries and the scope for further development, for instance to better characterise solid waste streams for their potential impacts on the environment (air, biodiversity, energy, soil, water ...);
- A number of ore deposits comprise "main" ore minerals, such as copper, iron or zinc bearing

minerals, but they may also contain various technological metals (Ga, Ge, In, Se...) as by-products that can, so far, only be recovered at the level of smelters, who may, or not, recover them, according to their own market strategy. Three of the quoted metals are on the European list of critical minerals [7]. As a result a significant share of these metals may end up in slags or in flue gas. Comprehensive extraction of all the valuable elements included in ores would be in line with eco-efficiency targets and help to reduce waste, and the presence of potentially ecotoxic elements in the waste.

Research goals

Short-term goals (2 years)

- Building on existing initiatives such as the GRI, ISO 14045-2012, or the European Commission's provisional resource efficiency indicators framework, assess the need to further develop such an indicator framework for individual minerals and metals, key production technologies available for the production of specific minerals and metals [1] or for the development of specific innovative technologies such as fuel cells, photovoltaic cells or high-strength low alloy steel [5], [6];
- Define a methodology to develop such a framework together with key organisations such as the European Commission, ICMM, the GRI, the WBCSD, OECD, UNEP and ISO , the International Metals Study Group to document key impacts on sustainability at various scales (from local to global) of the activities of the minerals and metals industry;
- From a sustainability perspective, assess the feasibility of fostering, possibly through EU regulatory measures, the full use of by-products contained in ore;
- Assess the value of encouraging end-uses in safe-to-use industrial products, backed by well controlled recycling chains (such as photovoltaics) of metals that could have negative environmental impacts if left in ore processing tailings or mining waste, such as cadmium, mercury, selenium or tellurium (linkage with ERA-MIN WG 2 and 3).

Medium-term goals (5 years)

- Assess the feasibility of developing eco-labelling of primary and secondary minerals and metals flows;
- Further strengthen sustainability performance monitoring and reporting for individual mines, plants and companies. Make performance data available as a public good to support policy-making and to foster public trust in the minerals and metals industry;
- Develop a system to reward good performance, for instance by developing rules of access to the EU market as well as to public procurement and assess the use of market instruments in this context.

Capacity-building and resource efficient economy

Challenge 1 : Reducing demand for primary mineral raw materials and increasing the re-use of materials

Achieving absolute decoupling between EU growth and its global environmental impacts, managing resources of mineral origins in a sustainable way requires research as well as flanking policy measures. Some authors (see (8)) argue in favour of decoupling growth from mineral raw materials use, but this may be an unachievable target due to demographic trends and the growing material intensity of developing countries. While there is no scientific evidence for mineral resource depletion at the global scale in a foreseeable future, sustainable development ethics command to reduce the material intensity of products and services without compromising growth.

Challenge 2 : Enabling a sustainable extraction of raw materials

Even if demand for minerals and metals can be reduced, there still will be for primary mineral resources. Their production through mining and, where needed, processing and metallurgical activities will remain an important industrial activity.

Innovation needs

Research can contribute to design policy tools to reduce material intensity by:

- Understanding consumption triggers for resources of mineral origin. Consumers' behaviour when buying, consuming and discarding products could be studied across the value chain (from industrial clients to final individual consumers). This could include studying the way consumers react to different policy tools designed to curb demand (information regarding the environmental impacts of products, regulatory measures, fiscal incentives…), the reasons they choose to buy a product, the way they deal with their waste or the objects that they do not need anymore;
- Fostering the creation of new value chains and new business models. Current business models designed for linear economy are not suited for investors interested in developing eco-designed solutions due to the lack of reporting tools to measure return on investments generated by resource savings and reduction of environmental burden. Research can contribute to develop policy tools that foster these new business models, for instance by developing new quadruple accounting and legal models integrating the economic, environmental, governance and social dimensions of performance;
- Studying technical and social innovations. Eco-designed products using less primary resources or recycled materials; industrial or territorial symbiosis developing new linkages between actors are being developed that contribute to reducing demand for natural resources including mineral resources, to reduction of emissions and waste. Research can help foster these innovations by analysing current global scale best practice and strategies at company or communities level, markets, value chains and the strategies. It can also identify obstacles that these innovations face when they develop, and formulate recommendations to improve their large-scale development.
- Understanding public perception of mining activities. This could enable project developers to better understand the representations that the general public, or local communities, have of their activities;
- Studying the governance of mining projects. As any project, mining projects have both positive and negative impacts, over all their lifecycle stages (project development, mine operation, post-closure). The way project developers manage these impacts, through identifying them and designing mitigation strategies at the early planning stage of the mining project (at the level of the conceptual or of the prefeasibility study) is crucial in gaining a social license to operate. Research (see also WG1 on mining/ quarrying/ metallurgy, p. 17 ff.) is crucial to the continuous improvement of industrial practices through the study of past and existing experiences, that of participatory processes and of risk management practices. It can further drive best available technologies (see[3]) and tools that contribute to a smoother integration of mining and metal extraction activities within the local communities. Examples include good practice in sharing economic and social benefits of mining activities or corporate transparency by means of quadruple bottom line performance reporting and stakeholder involvement. It can also study the uptake of these good practices among all stakeholders involved in mining activities (project developers, authorities at local, regional or national levels…) in order to contribute to the capacity-building of stakeholders.
- Measuring economic, environmental, governance and social impacts of mining activities, building on existing sustainable performance reporting practices such as the Global Reporting Initiative and ISO 26000. This could include cost-benefit analysis or any other method that enable to gauge

impacts and the way they are distributed among stakeholders.

Research goals

Short-term goals (2 years)

Identify, document and assess case studies with key products, trial corporate eco-design tools and reporting systems, pilot policy measures, innovative business models, industrial symbiosis experiments

- Identify through an appropriate survey of specific categories of citizens (by age, education,, exposure to active mining or metallurgical operations) their perceptions about the activities, benefits and impacts of the different segments of the mines and metals industries. This research should identify the hurdles to overcome and ways to overcome them including through education at different ages (primary and secondary school) and media;
- Improve the understanding of the variability of public perception through the assessment of historical patterns since the 19th century in written and visual documents (press, literature, prints...);
- Document good practice in mine development, operation and post-closure management.
- Develop knowledge on the incidence of speculative financial instruments, such as over-the-counter trade and exchange traded commodities (ETCs) or funds (ETFs), on minerals and metals prices, their volatility and the financing of the industry's development in order in support to policy making.

Medium-term goals (5 years)

Develop guidance and tools for policy makers and industries to enable dissemination of new value chains and business models etc. with a view to achieve growth / raw material decoupling.

- Follow public perception of extraction activities.
- Provide stakeholders a clear overview of challenges and solutions associated with mining activities and supply of primary and secondary resources.

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WG 5: Education and International Cooperation

Rationale

To assure a sustainable supply of mineral products and metals for European industry requires a multi-faceted approach. More efficient and rational consumption, enhanced substitution and improved recycling will play increasingly important roles but to fully meet future needs, metals and mineral products from primary sources will need to be fed into the loop. Most of these metals and minerals will continue to be imported from sources outside Europe; but others can, and should, be produced domestically.

The activities of WG5 focus on two main issues. The first issue is the need to promote education and training in all parts of the geomaterials life cycle in order to: a) contribute to Europe's overall expertise in the field; b) increase the public awareness of the importance of raw materials as part of the foundation of modern society's material quality of life, and c) maintain the supply of professionals (geologists, materials scientists, engineers, designers, teachers) needed to support both traditional and high-technology industries in Europe. The second issue is to foster international cooperation in research and education between European countries and between these countries and the producers and consumers of raw materials throughout the world.

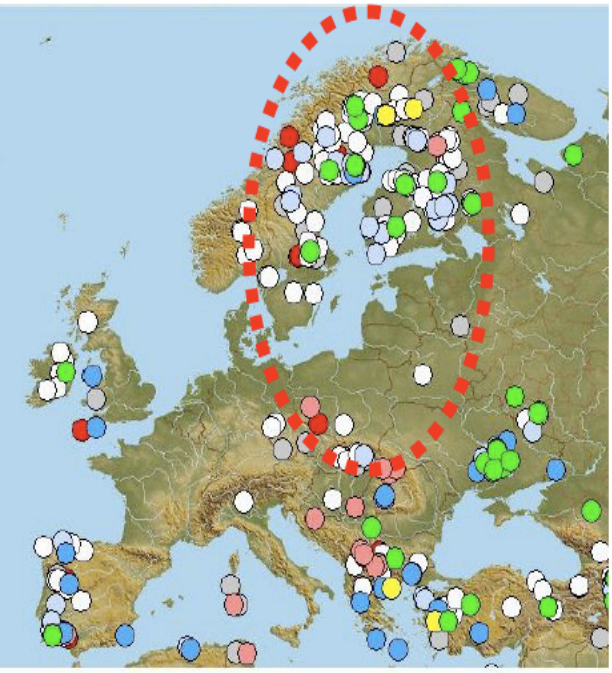
Education and training

In past decades, activity in many parts of the geomaterials life cycle has declined. During this period, the mining of metals had virtually ceased in most countries in the geographic core of Europe (France, Germany, the Netherlands, etc; Figure 7) and has continued only at low ebb in other European countries. In the past 2-3 years, however, renewed interest in the minerals sector has led to an expansion of mining, particularly around the fringe of Europe, from Ireland through Scandinavia and eastern and southern Europe to Portugal (Figure 7). In parallel, activity in mineral processing and particularly in recycling has increased, and concerns about the security of supply of raw materials are gradually leading to an increased interest in materials science and engineering. The need to increase the amount and scope of recycling is bringing out major changes in the design of high-technology materials. However, although today's state-of-the art technologies are very different from methods used in the past, memories of mineral industry in much of Europe stem from the period when local mines closed, before modern techniques were employed. The sceptical European public will need to be convinced that modern society requires a secure supply of mineral products and that there are compelling economic, social and environmental reasons for promoting within Europe production of these materials. It must be explained that when modern technology is applied, the extraction and distribution of these materials can be performed in a sustainable and ecologically sound manner through the entire geomaterials life cycle. The important issue of the public perception of the raw materials industry is treated mainly in WG4; in WG5, we focus on the need to provide teachers, administrators and the general public with accurate and complete information about all parts of the geomaterials life cycle.

In many sectors, researchers, teachers and professionals in both the public and private sector are approaching retirement; there is already a scarcity of trained specialists and a lack of infrastructure and teachers to train their replacements. Future activities in the raw-materials sector will require that the new generation of professionals is educated and trained. Revitalized research in the geomaterials life cycle must also be coupled with improved and expanded teaching and training, particularly in the latest clean technologies. In following sections we describe the measures to be taken, including revision of university curricula, promotion of short courses for specialists and for a broader public, and schemes to encourage closer cooperation between the public and private sectors.

International collaboration

Europe currently imports between 60 and 100% of all metals, either as raw and refined ores, or within components of manufactured goods (see reports by other Working Groups). Mining in Europe is limited to a few countries and active research programs between the public and private sectors are to some extent restricted to these countries. The production of high-technology materials and consumer products, on the other hand, is spread throughout Europe (Figure 7).



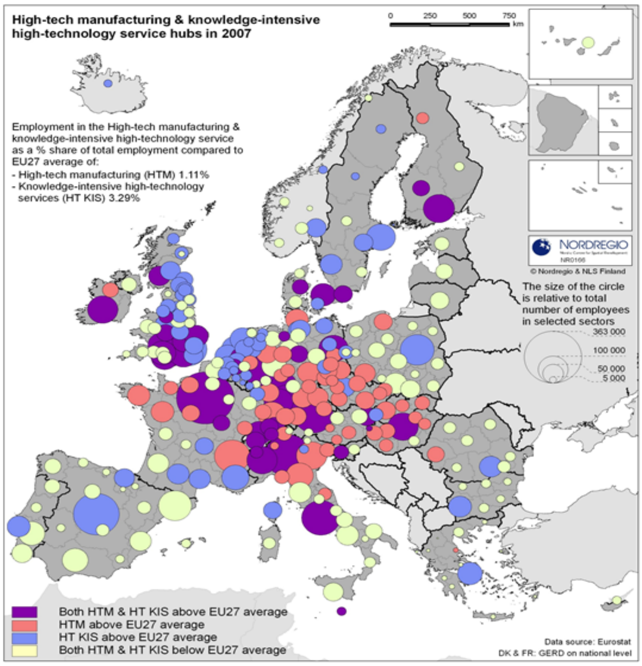


Figure 7: Map contrasting the distribution of planned and active mining sites in Europe (left, diagram from "Raw Materials Group, Stockholm", M. Ericsson, 2012) and with centres of high-technology manufacturing (right – data from Eurostats). With the exception the eastern part of Germany and neighbouring countries, mineral production is absent from regions where the mineral products are consumed.

Research and development on the geomaterials life cycle is commonly limited to initiatives in single European countries instead of within networks that mutualise costs, risks and basic knowledge. Centres of research and teaching programs in universities, governmental agencies and the private sector are scattered and their level of activity is commonly far from optimal.

On the other hand, Europe maintains several areas of specialized expertise in the minerals domain, notable examples being in the fields of mining technology in Scandinavia (Atlas-Copco, Sandvik), the GOCAD program developed in France, processing of raw materials (Umicore, KGHM, Boliden, Alcan, ArcelorMittal, Corus, Thyssen, Outokumpo, Outotec) and tunnelling techniques in Austria and Switzerland. Given sufficient support, these could develop on a worldwide basis, to become, or to strengthen their current position, as world leaders in their field, and thereby help improve Europe's competiveness.

The global materials scene has changed dramatically in the past decade, driven by the soaring demand from China, fuelled by the opening up of new areas for mineral exploration throughout Asian and Africa, influenced by the growing worries about the availability of materials, and nuanced by increasing globalization of the recycling trade and the treatment of mineral and industrial waste. To assure a secure supply of mineral products for European industry and to develop a materials sector that can compete on the world stage, various types of international collaboration will be required. These include the reinforcement or establishment of research and training networks, support of multi-partner research projects, and schemes to promote mobility between different countries and between various sectors of the geomaterials life cycle. The collaboration will also entail enhanced interaction among European countries and between Europe and four groups of countries: 1) industrialized, resource-deficient countries (Japan, Korea, USA); 2) mineral-exporting countries (Canada, Australia, South Africa); 3) developing countries in need of European aid and expertise; 4) China and other populous developing countries.

Finally, the currently low degree of interaction between the public and private sector in many European countries and in certain sectors of the geomaterials life cycle must be improved. Incentives for a deeper, more coherent and consequential dialogue between all parts of the cycle should be developed, incorporating both public and private viewpoints, as well as industry and academia perspectives, in order to realise a European strategic agenda on research and education programmes on raw materials.

To realize the goals outlined above, we must:

- Revitalize European education in all parts of the geomaterials life cycle in order to train future generations of students and assure the continued education of current professionals
- Improve the level of research in all parts of the geomaterials life cycle by fostering interaction between key players, both between member states of the EU and between public and private sectors.
- Help develop a high-technology and competitive European materials industry capable of supplying a significant proportion of Europe's metals and of competing on the global research, training and industrial scene.
- Develop links with academia, government agencies and the private sector in non-European countries.

Education and training of future professionals

Challenge

The major challenge is to develop a system of education throughout Europe and in all sectors of the raw materials cycle capable of training the scientists, engineers, technicians and teachers needed to meet current and future needs of the materials industry (Figures 8 and 9)

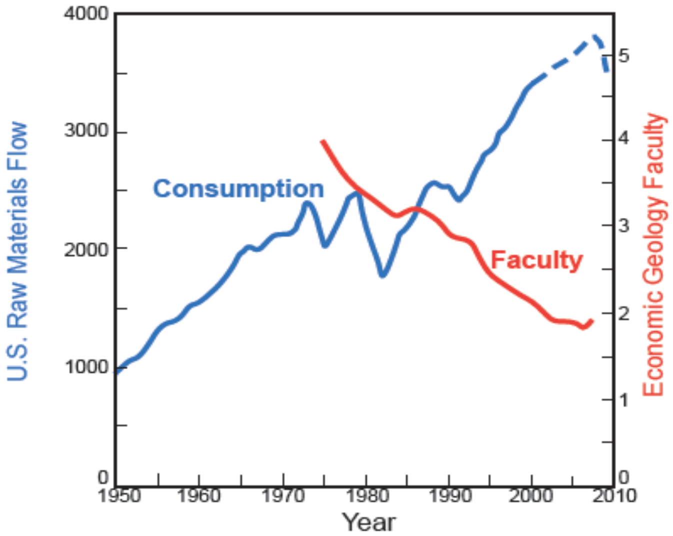


Figure 8: Graph illustrating a steady increase in US consumption of raw materials (Wagner, 2002) and a steady decline in economic geology as a percentage of the total geoscience faculty (from Hitzman et al., 2009, GSA Today).

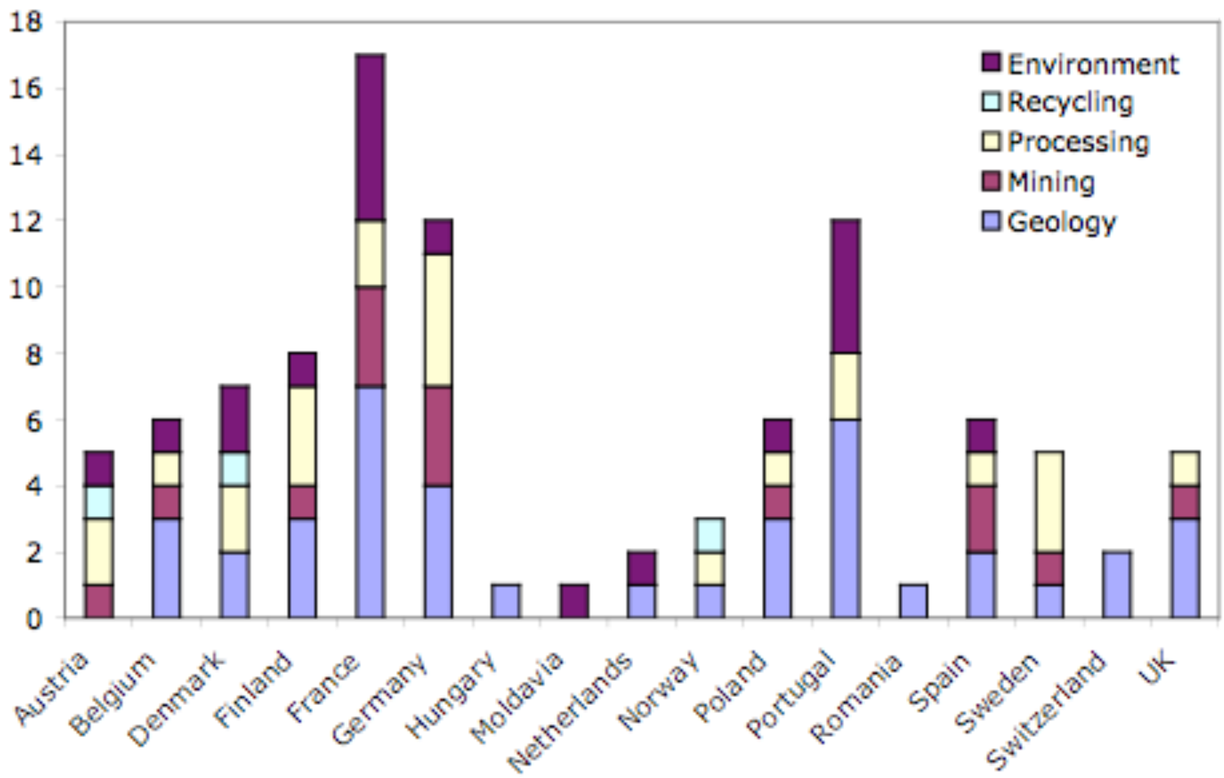


Figure 9: Graph presenting preliminary results of a survey of courses in the geomaterials life cycle proposed in European universities. The results were obtained on a part-time basis by Karin Tynelius and are clearly incomplete; but they illustrate the type of data that should be obtained as a part of the ERA-MIN program.

Goals

- Establish databases of European education in all disciplines related to the geomaterials life cycle. These will include catalogues of courses at universities and other educational institutes; a list of masters and other high-level programs, and information about teaching in schools. This work should be done in close collaboration with other European agencies and programs, where much of these data already exist. Cooperation with the other ERA-MIN working groups is essential to identify minimum standards in all fields of interest (exploration geology and geophysics, mining engineering, mineral processing, materials science and engineering, recycling and substitution, environmental issues), as well in numerous complementary disciplines.
- Promote teaching about the raw material cycle at all levels. Activities include incentives to support or introduce specialized university courses at the Masters level; insertion of basic courses on materials in all earth science and materials- and product-design curricula; and development of courses encompassing a broader spectrum of disciplines, including the economic, environmental and social sciences. The development of the curricula of these courses must take into account industry concerns and interests and promote collaborative work and exchange programs with non-European countries.
- Develop innovative methods of education along the lines of Massive Open Online Courses (MOOC), which will allow a limited number of teachers and professionals to reach large numbers of students throughout Europe and elsewhere in the world.
- Identify and support specialized, high-level short courses for graduates and professionals from both academia and industry at national and international meetings; promote broad-spectrum courses and applied workshops courses on the entire raw-materials cycle; encourage participation and sponsorship from the public and private sector; identify gaps and initiate proposals to fill these gaps.

- Identify current skills shortages and develop or modify training programs to meet emerging needs. The analysis should also include the offer of intensive courses on geological and/or technological issues critical to industrial activities in non-European countries, ideally conducted in collaboration with European companies.
- Develop links with European institutions and professional societies such as geological surveys, EuroGeoSurveys, Society of Geology Applied to Ore Deposits (SGA), Euromines, European Materials Research Society (E-MRS), and the Federation of European Materials Societies (FEMS)
- Support existing and proposed pan-European research and teaching networks (e.g. ERASMUS - Liège- Luleå -Freiberg-ENSG Nancy; ITN - Southampton, Freiberg, Luleå, NHM London); identify gaps and initiate proposals to fill these gaps; expand the networks to include other groups.

Key performance indicators

- Establish databases - catalogues of courses at universities and other educational institutes [year 1]
- Promote teaching – insertion of new geomaterials courses into science programs; development of new broad-spectrum courses [for each, one new course by year 3; three new course by year 5]
- Development of a Massive Open Online Courses (MOOC) [preparation of a proposal in year 1; realization of a course by year 5]
- Support specialized, high-level sessions or short courses at national and international meetings [from year 1; at least two sessions and one course per year]
- Identify current skills shortages [produce a preliminary list in year 1; develop and update this list each year]
- Develop links with European institutions and professional societies [establish a list of target institutes in year 1; establish formal links in year 2]

Dissemination of information to a broad public

Challenge

To compile complete and unbiased information on all parts of the geomaterials life cycle and make this information available to all stakeholders and to the general public.

Goals

- To coordinate and facilitate the dissemination of information and to increase public awareness of the geomaterials cycle on a Europe-wide scale. This task includes the conception and edition of a booklet designed to guide teaching of topics on the geomaterials life cycle in schools and universities. The establishment of a European network committed to "science for citizen/education at large" and dealing with all parts of the geomaterials life cycle (Figure 10). To achieve these goals will require the involvement of academic, industry and government agencies.

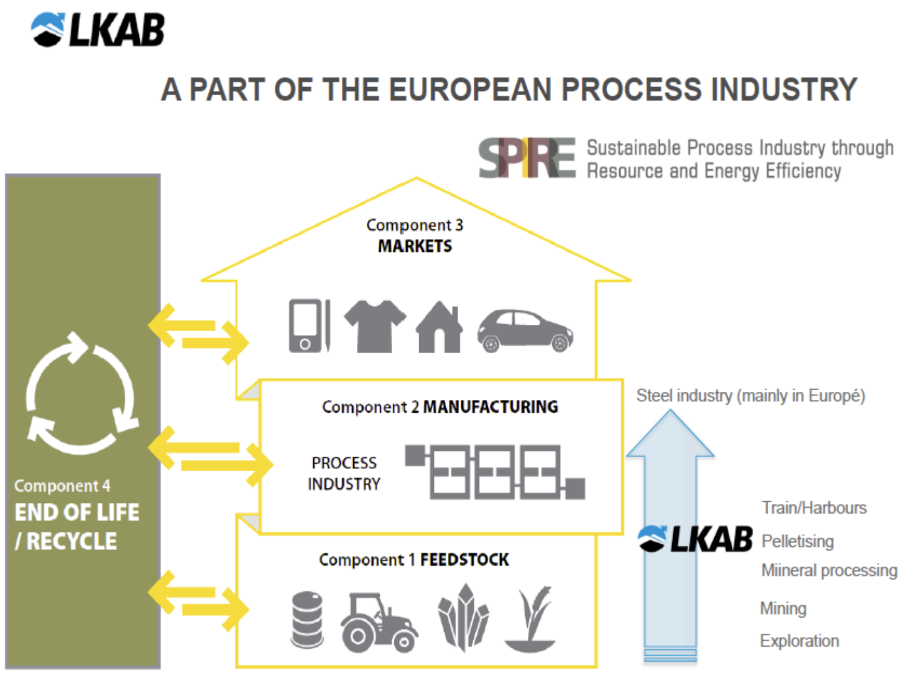


Figure 10: An example of communications from a European steel company emphasizing the links at all stages of the geomaterials life cycle

- Organization of high-level short courses for graduates and non-specialist professionals and courses on raw materials for non-specialists (lawyers, economists, political scientists, journalists, teachers). An example of this type of course is "Geology for Non-Geologists" http://lg.eage.org/course_description.php?courseid=290 proposed by the European Association of Geoscientists and Engineers. Similar courses should be supported for other sectors of the geomaterials life cycle and linked with activities such as field trips or guided visits to mines, industrial sites and recycling plants. The development of Massive Open Online Courses should form part of this effort.
- Establish links with media agencies (e.g. Science Media Centre), outreach committees in programs and unions (e.g. geological surveys, professional societies, the GIFT (Geosciences Information for Teachers) program of EGU) and journalists to help address the question of public perception of the minerals industry.

Key performance indicators

- Establishment of a European network committed to "geomaterials for citizen/education at large" [preparation of a proposal in year 1; realization of a network by year 3]
- Organization of high-level short courses non-specialist professionals [one new course by year 3; three new courses by year 5]
- Establish links with media agencies [establish formal links with five major agencies in year 1]

Pan-European research networks

Challenges

The major challenges are to: coordinate and improve competitiveness in research at a Europe-wide scale; to encourage innovation; attain a leading position in state-of-the-art materials technology for selected academic and industry centres; encourage co-financing of research and development from public and industry sources.

Table 6: The position of ore-deposits research in Europe as illustrated by the number of publications in the principal journals in the field (EG - Economic Geology; MD – Mineralium Deposita; OGR – Ore Geology Research). Top-level research is conducted in scattered centres, not necessarily in ore-producing countries. Despite the dispersion, the contribution of these centres remains high on a global scale: increased collaboration between these centres would improve the situation.

	COUNTRY	EG	MD	OGR	TOTAL
1	AUSTRALIA	85	59	36	**180**
2	CANADA	99	37	10	**146**
3	USA	77	16	9	**102**
4	CHINA	12	23	64	**99**
5	GERMANY	**11**	**22**	**16**	**49**
6	UK	**24**	**11**	**8**	**43**
7	SOUTH AFRICA	11	15	6	**32**
8	BRAZIL	3	9	17	**29**
9	FRANCE	**6**	**14**	**7**	**27**
10	SWITZERLAND	**16**	**10**	**1**	**27**
11	NEW ZEALAND	12	8	5	**25**
12	CHILE	3	16	0	**19**
13	SPAIN	**5**	**7**	**5**	**17**
14	TURKEY	**3**	**2**	**12**	**17**
15	BELGIUM	**2**	**7**	**5**	**14**
28	MEXICO	1	4	2	**7**

Site	Nr	EG	MD	OGR	total
Geological Survey of Norway, Norway	**1**	8	7	12	**27**
Natural History Museum + Imperial Coll, UK	**2**	11	4	10	**25**
University of Geneva, Switzerland	**3**	11	12	2	**25**
Nancy CNRS + Univ, France	**4**	3	13	5	**21**
ETHZ, Switzerland	**5**	10	9	1	**20**
Munich, LMU+TU+Geol Surv, Germany	**6**	3	8	7	**18**
Hannover BGR + Univ., Germany	**7**	4	8	5	**17**
GFZ Potsdam, Germany	**8**	4	11	2	**17**
Glasgow , UK	**9**	4	6	5	**15**
KULeuven, Belgium	**10**	5	6	2	**13**
University of Leeds, UK	**11**	5	7	1	**13**
RWTH Aachen University, Germany	**12**	1	6	4	**11**
Technical University of Clausthal, Germany	**13**	3	3	5	**11**
Orléans (BRGM, France + Univ)	**14**	0	5	6	**11**
Univ Oslo, Norway	**15**	1	0	10	**11**
University of Southampton, UK	**16**	3	4	3	**10**

from Lluis Fontboté

Goals

- To coordinate and reinforce research and teaching throughout Europe, which currently is dispersed between many relatively isolated and independent centres (Table 6). To achieve this goal will require interaction on a Europe-wide scale between various pan-European programs (e.g. ERA-MIN, ETP-SRM, EODI, EuroGeoSurveys, EuroMines, Eurometaux). Fruitful interaction should be encouraged between mineral-producing countries such as in Scandinavia and Eastern Europe, where industry-academia collaboration is well established, and with other European countries where mining is absent but where metal-consuming industries, and research in mineral processing, substitution and recycling, are strong. Programs to inform decision-makers and the general public about the minerals industry must be created both at a local and European level.

- Initiate and support proposals for infrastructure projects such as European Strategy Forum on Research Infrastructures, Joint Programming Initiatives, and European Innovation Partnership on Raw Materials. Combine these with existing programs developed within university networks andgovernment surveys

- Facilitate access to specialised higher education and/or professional training in the EU, through fellowship grants in all domains of the geomaterials life cycle.

- Establish a European Centre of Research and Training in Sustainable Use of Materials complemented by an Infrastructure Research Network on Raw Materials (within the framework of ESFRI, European Strategy Forum on Research Infrastructures). The Centre could be sited in a single country with strong contemporary mining or materials-processing activity; or it could be multi-site, extending to several countries. It could form part of the pilot plants proposed by other Working Groups and it could be linked to existing national or regional centres of excellence. Because of the social implications, the centre must include researchers and teachers from the economic and social sciences as well as from the fundamental and applied sciences and engineering. The Centre could therefore obtain support from three sources: the science and engineering programs that traditionally have supported research and teaching of the minerals sector; the minerals and metals producing industry, which in the past and in other countries provides substantial support for research activities; and non-scientific programs, which are rarely if ever involved in such projects. The Infrastructure Research Network on Raw Materials would provide a link between existing and new facilities and would include not only physical equipment but also databases, reference collections/knowledge-based resources, and information and communication facilities; the overarching goal will be to develop the groundwork for a sustainable minerals industry in Europe.

- The development of the research and teaching centre will draw on the experience of some very successful centres in the Netherlands (M2i), Belgium (SIM), the Scandinavian countries (MEFOS, GTK), Australia (CODES, CET) and Canada (MERC) where the participation of academia, state and private sectors produces synergy – coordinated research and an exchange of data, methods and ideas – that cannot be realized in a purely academic setting. In European context, where high population density, administrative hurdles, and diverse cultural or social norms build a climate that is commonly hostile to the extractive industries, the centre must promote a new type of activity. Drawing on the help of companies such as Atlas-Copco and Sandvik and working together with the Finnish "Green Mining" program, the goal should be to build models of new, clean, safe, energy-frugal mines, refineries and materials-producing industry. A major goal of this centre must be to develop new processing alternatives that will allow the treatment of ores that cannot be processed today. If successful, European materials activity will be recognized as a leader in cutting-edge technologies, a knowledge-based, sustainable, environmentally and socially conscious minerals industry that will enhance international standards.

Key performance indicators

- Establish Europe-wide research and education networks [preparation of 3 proposals addressed to different programs (ITN, Marie Curie, etc) in year 1; realization of at least one new network by year 3]
- Establish Europe-wide infrastructure projects [preparation of a proposal in year 1; realization of a project by year 3]
- Establish a system of grants to facilitate access to specialised higher education and/or professional training [preparation of a proposal in year 1; realization of a program by year 3; exchange of 10 participants per year by year 5]
- Establish a European Centre of Research and Training in Sustainable Use of Materials [preparation of a proposal in year 1; acceptance of program by year 5; realization of project by year 10]
- Promote the activities of companies such as Atlas-Copco and Sandvik and the "Green Mining" program. Reinforce the position of European companies as leaders in a knowledge-based, sustainable, environmentally and socially conscious minerals industry [preparation of a proposal in year 1; realization of formal agreements with 3 companies by year 2]

International programs

Challenges

Establish a framework in which Europe will be assured of a sustainable supply of metals, raw materials and high-technology materials.

An issue that is commonly not addressed in an open and frank manner in current programs is the mechanism and instruments that must be developed to supply metals to European industry. Improved recycling, more substitution and reduced consumption must be strongly supported, as explained in detail by WG 2 and 3. These actions will form an essential part of the solution but they are not panacea – new metals must also be fed into the loop. Even in the most optimistic projections, production from European deposits or from "urban mining" will supply only a small fraction of Europe's primary metal needs (Figure 11). Some of these metals will come from reliable foreign suppliers (Canada, Australia, South America) but even from these sources, their availability will be subject to market forces and political or societal vagaries. To assure a continued supply of metals and other mineral products at stable prices requires that, in addition to the development of within-Europe programs, direct contact must be made with government agencies, international organisations and NGOs, and, above all, with metal producers, in countries throughout the world. These countries can be grouped as follows:

Group 1: industrialized, resource-deficient countries that face the same challenges as Europe (Japan, Korea, USA);

Group 2: mineral-exporting countries with strong research programs in the fields of mineral exploration and mining (Canada, Australia, South Africa);

Group 3: developing countries and European Neighbourhood Policy countries in need of European aid and expertise;

Group 4: China (and in the near future, India), populous countries whose enormous and growing domestic demand for metals strongly influences the entire global situation.

Some of the measures taken to promote and improve international cooperation apply to all four groups of countries. These include:

- Creation of a European raw-materials board that can speak for European industry and consumers at an international level. Only by creating a structure with the full backing of EU member states will the interests and needs of European consumers be heard at a global level.
- Support for measures fostering transparency and governance, such as the Extractive Industries Transparency Initiative and the Global Reporting Initiative, reporting of resources and reserves in line with widely accepted reporting standards (PERC, NI 43-101, JORC, UNFC …). Transparent, well-functioning markets would benefit all players in the global market, including the EU.

However, because each group of countries has very different needs or offers specific benefits and challenges to the ERA-MIN program, a different approach must be adopted in each case.

For **Group 1 (**industrialized, resource-deficient) **countries**, appropriate measures include:

- Participation in international agencies and organisations conceived to protect the interests of raw-material-importing counties and regions. Participation in programs designed to establish respect of international trade rules, and environmental and societal norms
- Development of cooperative research and training programs dealing with the processing of raw materials, recycling and substitution – the fields of activity of WG2 and 3.

In most **Group 2** (mineral-exporting) **countries**, research and training in the fields of mineral exploration and mining are currently far ahead of that in most (but not all) European centres. Establishment of exchange programs, joint participation in teaching programs and eventually establishment of joint research projects will boost fledgling programs in Europe. Specific links could be established, for example, with the centers and agencies listed in Table 7

Table 7: Partial list of research and training centres in Group 2 countries

Centre or agency	**Location**	**Address**
Centre of Excellence in Ore Deposits	Tasmania, Australia	www.utas.edu.au/codes/
Centre for Exploration Targeting	Perth, Australia	www.cet.edu.au/
Mineral Exploration Research Centre	Sudbury, Canada	http://merc.laurentian.ca/
Mineral Deposits Research Unit	Vancouver, Canada	www.mdru.ubc.ca/
Wits Mining Research Institute	Johannesburg, South Africa	http://www.wits.ac.za/
AMIRA	Melbourne, Australia	www.amira.com.au/

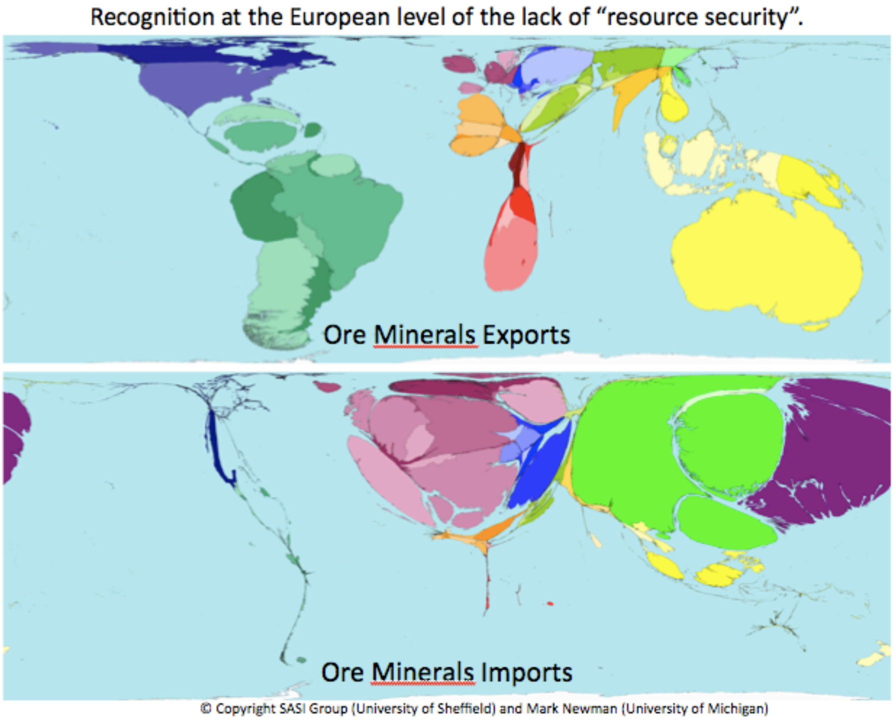


Figure 11. Cartoon illustrating the dependence of Europe on foreign supplies of metals. The distorted size of each country illustrates the proportion of total mineral products that are exported or imported.

Group 3 (developing) **countries** commonly have an active mining industry and/or a high geological potential. Those surrounding the EU; i.e. Greenland, Norway, Russia, Ukraine, Turkey, Albania, Kosovo and other Former Yugoslavia Republic countries, Egypt, Libya, Tunisia, Algeria and Morocco generally lack strong research and training programs and would benefit directly from the establishment of such programs within the ERA-MIN framework, Farther afield, links should be developed with countries in sub-Saharan Africa, Asia and South America. All of them could benefit from EU know-how to further develop their institutional capacities to promote and regulate the development of their mineral resources sector, for instance through twinning actions with relevant EU-based institutions such as geological surveys and participation to EU research action. This could help these countries to identify and assess their mineral resources in a modern and efficient way and develop a level-playing field for the development of their minerals and metals industries in line with sustainable development ethics. In this case, the following specific measures can be considered:

- Development of direct links with the companies and other agencies in these countries that produce metals. Following the lead of Japanese or Korean companies, direct interest in foreign mining operations could be acquired. Appropriate actions include the development of exploration programs co-financed by the public and private sector in Europe and the host country; acquisition of interests in or the development of partnerships with mining companies; notable examples being the involvement of ERAMET or Toyota in Li mining in Argentina,
- Support to EU companies willing to engage in exploration in EU partner countries (Figure 12), possibly within a scheme comparable to that developed by Japan (Japan Oil, Gas and Metals National Corporation, established under the Ministry of Economy, Trade and Industry of Japan)..

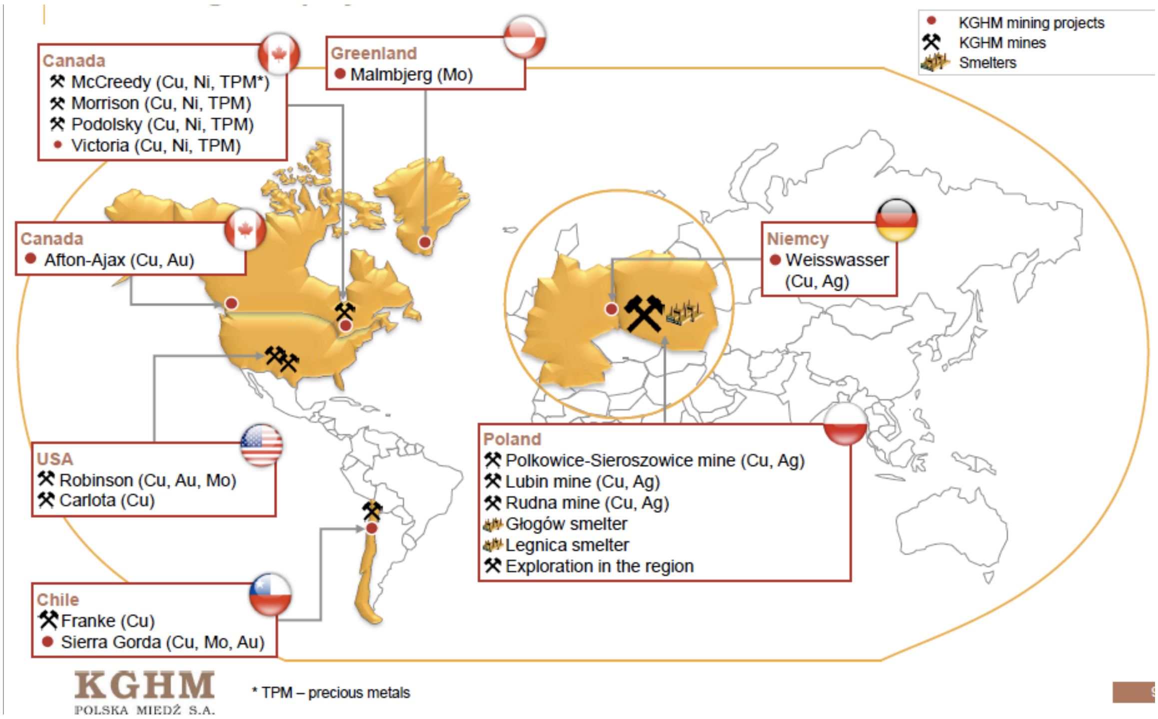


Figure 12. Global activities of KGHM, a Polish mining company with interests in North and South American and in Asia. This type of expansion should be encouraged and extended particularly to Africa.

- Additional benefits include the preferential access by individuals and government agencies from developing countries to 1) EU minerals related research; 2) specialised higher education and/or professional training in the EU, through fellowship grants in all primary and secondary mineral raw materials related domains; 3) training on EU legislation and best available technologies related to mining, metallurgy, recycling, life cycle and material flow analysis, mining waste management, geographic information management, energy and water management and conservation; ecosystems protection; environmental management, etc; 4) technical support for public sector projects such as inventories of regional/ national mineral potential; inventories of derelict mining sites and related possible geotechnical and/or environmental, development of databases and GIS, of laboratories.
- The European Union has specific cooperation agreements with the Africa Union and its member states, materialised by the 3rd Joint Africa – EU Action Plan 2011-2013[12] and to Africa-Caribbean-Pacific (ACP) Group of States. The main goals of these programs are listed in Table 8

Table 8: Comparison of the outlines of the Africa Union « Africa Mining Vision » and of the ACP Group of States « Framework of action for the development of the mineral resources sector in ACP countries » outlines – Both strategies have comparable, complementary, objectives and outlines

« Africa Mining Vision »	**« Framework of action for the development of the mineral resources sector in ACP countries »**
Mining Revenues and Mineral rents management	Enhancement of the capacity of Public Mineral Institutions
Geological and mining information systems	Development of Mineral Exploration and Geoscientific Information Systems
Building human and institutional capacities	Development of the Small- and Medium-Scale Mining Sectors
Artisanal and small-scale mining	Reduction of the Social and Environment Impacts of Mining

12 Available here : http://www.africa-eu-partnership.org/sites/default/files/doc_jaes_action_plan_2011_13_en.pdf

Mineral sector governance	Improvement of the Energy and Transport Infrastructures for the mineral industry
Research and development	Development of Industrialisation and Diversification of ACP Economies
Linkages and diversification	
Mobilising mining and infrastructure investment	

In addition to the Africa Union and the UNECA, the Geological Society of Africa and the Southern and Eastern Mineral Centre (SEAMIC) are robust institutions, given Africa's conditions. The Organisation of African Geological Surveys (OAGS) requires support, and other regional organisation, as does the Southern Pacific Commission and the Caribbean Community (CARICOM). The needs in the ACP region are immense, to start with education and training in all the disciplines related to the minerals and metals sector. The development of e-learning multilingual training modules (in English, French and Portuguese as a minimum) could be one way to address some of the huge needs in higher education and professional training. However the particularities of the minerals and metals industry require hands-on training in geological data acquisition, exploration methods, feasibility assessments, mining, ore processing and metallurgical activities.

Group 4 (populous, rapidly developing) countries. China is becoming increasingly important in mineral exploration and mining in most parts of the world. Chinese actions have received considerable publicity in past months, mainly negative. It is claimed, in some cases with ample justification, in others less so, that Chinese activities in Africa are entirely self-promotional, aimed solely at gaining access to Africa's mineral resources; that China persistently flaunts international rules and norms, and that its investments provide few jobs, but distort the local economy and prop up corrupt governments. Less publicized is China's specific position in the global diplomatic and socio-economic scene – as the world's leading importer of mineral products, it particularly vulnerable to market pressures, cartel-like behavior of multinational companies, and global distrust of Chinese actions. Although it is claimed that "Australia has become China's quarry", Chinese investment in that country, as in most mineral-producing regions, still lags far behind that of Europe and the USA.

In most European programs that address global supply of mineral resources, China's actions are either criticized or ignored: very rarely are measures proposed to develop cooperative programs or actions. This ostrich-like behavior is not constructive: China will remain a major player on the global raw-materials scene for the next decades, and means of constructive engagement between Europe and China must be sought. Ways must be found to reduce destructive competition and establish cooperative R&D programs with Chinese universities and governmental agencies. Specific actions could include:

- Development of joint research and development programs in all parts of the geomaterials cycle with Chinese universities and institutes. Given the large sums currently on offer by Chinese agencies to support scientific and industrial research, collaboration with Chinese institutions could constitute a major source of funding. Extreme care should be taken, however, to select the appropriate Chinese institutions; only a few have the level of expertise and experience required to function in partnership with European researchers. Care must also be taken to assure that any joint research is carried out in a fair and equilibrated manner.
- Joint programs could also be established with government ministries and agencies. Programs of cooperative research or minerals exploration in Africa, for example, would be beneficial to all partners (China, Europe and the African host country) and would help to break down the distrust that currently exists.
- Because of the opacity and complex of mineral exploration undertaken by Chinese industry, any

form of collaboration with this sector is likely to be complicated.

Although India has been far less active in the global mineral exploration and mining scene, Indian companies are playing an increasing important role in mineral processing. For example, ArcelorMittal, formed when the Indian company L.N.Mittal took over the Spanish-French-Luxemburg company Arcelor, is now the world's biggest steelmaker, producing about 10% of global output. Steps should also be taken to foster constructive partnerships or joint programs with companies such as this.

Key performance indicators

- Creation of a European raw-materials board that can speak for European industry and consumers at an international level [preparation of a proposal in year 1; creation of the board by year 3]
- Participation in international agencies and organisations conceived to protect the interests of raw-material-importing counties and regions [formal agreements with 3 agencies in year 1]
- Development of cooperative research and training programs dealing with the processing of raw materials, recycling and substitution [preparation of a proposal in year 1; realization of a program by year 3]
- Establish research and training programs on mineral exploration and mining with minerals-exporting countries. Develop exploration programs co-financed by the public and private sector in Europe and the host country [preparation of 3 proposals in year 1; realization of a program by year 3]
- Development of joint research and development programs in all parts of the geomaterials cycle with Chinese (and Indian) universities and institutes [formal agreements with 3 agencies in year 2]

Expanding the spectrum of ERA-MIN activities

Challenges

The majority of ERA-MIN activities are restricted to the academic or government domains while links to the private sector are, with some notable exceptions, poorly developed. In addition, most of these activities centre on science and technology whereas links with other more diverse disciplines must be initiated or reinforced if the major issues related to minerals production, recycling and substitution in Europe are to be addressed. In particular, to improve public perception of the minerals industries and to obtain social licence to mine, refine or recycle metals in Europe, the expertise of professionals in sectors as diverse as design and engineering, ecology, economics, banking, trading and finance, law, politics, journalism and communication must be brought into the picture.

The exchanges between ERA-MIN network and the other disciplines should operate in two directions. As is clearly explained in the reports of the other working groups, the participants of the ERA-MIN network have much to offer both European industry and other sectors of European society. To achieve the goal of assuring a supply of metals for European industry will require complete and efficient use of the data and expertise in geoscience and engineering of European universities and governmental organisations. Yet it must also be recognised that the other sectors can contribute immensely to the activities of ERA-MIN. Companies in all parts of the geomaterials life cycle possess vast amounts of data and diverse types of expertise that must be tapped; and, as explained above, the involvement of experts from the economic and social sciences is essential if the goals of ERA-MIN are to be realised. In particular, professionals from industry and from the other disciplines must be fully consulted and their expertise brought into play at all steps of the development of the roadmap and during the realisation of the program.

Goals

- Encourage exchanges between universities and government agencies throughout Europe small to large companies in all parts of the geomaterials life cycle. Develop capacity-building courses co-sponsored by funds from the public and private sector. Define existing and future possibilities for internships for students and 'sabbaticals' for researchers and teachers in all sectors of the minerals industry. Explore programs for joint university-industry PhD projects (e.g. Marie Curie European Industrial Doctorate). Develop participation of industry professionals as both teachers and experts in universities and other governmental agencies.
- Explore new teaching methods designed to produce courses available on line to global audiences (Massive Open Online Courses)
- Identify the specific needs of industry in the domains of research and education; define current skills shortages in all raw-materials fields, anticipate future needs; develop or modify training programs to meet the needs of industry. (What does industry expect from the European research/ education system? What skills are sought or required in graduates? What skills are lacking?). Build on previous surveys; interact with professional groups such as the Society for Geology Applied to Mineral Deposits, Euromines, European Association of Geoscientists and Engineers, Federation of European Materials Societies.
- Develop links with European mineral exploration and mining companies and (potential) producers of strategic metals (e.g. Boliden, KGHM, ERAMET). Investigate jointly how joint public-private programs can help to increase the extent of mineral production from European ore deposits.
- Develop schemes to allow companies in all other parts of the material life cycle to contribute directly to ERA-MIN activities. To have access to the wealth of data and expertise in European and foreign companies will require the development of instruments to assure that the needs of all partners are respected. Methods must be found to share data in a manner that provides access to all participants while respecting the needs of confidentiality of the private sector. These issues are discussed in the report of the other working groups, particularly WG4.
- Encourage the participation of teachers, researchers and professionals in courses, workshops, and meetings that focus on the geomaterials life cycle; engage economists, social scientists, lawyers and journalists in the definition of joint research and development projects designed to address problems related to the supply of materials to European industry; support national or Europe-wide networks or research centres where these subjects are treated (e.g. the new initiative of the French CNRS or the Centre for Energy, Petroleum and Mineral Law and Policy at the University of Dundee).

Interdependencies and transversal issues

The distribution of topics related to raw materials into different working groups that worked in parallel on the preparation of the Research Agenda should not hide the necessity of integrated research, as well as research that goes beyond the specific topics addressed by the working groups. These issues generally require research efforts involving contrasted scientific communities and have often a potential to emerge as breakthrough discoveries. It also emerged from the working groups discussions that several research themes show strong interdependencies and common features. Some of them are listed hereafter, and emphasis is also put on the issues that need integrated research involving contrasted research communities and/or stakeholders.

Energy and environmental issues

Humanity remains totally dependent for its survival on the same natural resources it already depended over hundreds of thousands of years: fertile soil, biodiversity, clean and abundant water, climate, clean air as well as the availability of affordable energy and mineral resources. Consequently, future research activities should not only address competitiveness and security of supply issues, but they also need to target sustainable development. Research efforts must be made to improve existing technologies by reducing the input of water, energy and chemicals, as well as the output of all kind of emissions to air and water as well as of any harmful solid waste. To sustain and increase current production rates, resources will have to be extracted at more distant locations (including deep mining and ocean floor mining) and most probably lower ore grades. To extract and process such ores requires an exponential use of energy which is only partially compensated by the development of new, energy-frugal technologies. In this sense metal minerals scarcity aggravates energy scarcity.

Research has to be conducted to develop new environmentally friendly technologies. These technologies should not rely solely on fossil energies but should tap alternatives such as geothermal energy in deep-seated mines, or the thermal energy stored in anhydrous minerals. Industrial slags and ashes can be used as a secondary source of raw materials and as a source of hydrogen as well, from the reduction of water that accompanies a thermally activated oxidation of Fe^{2+}. Such reactions, which are known to occur in nature and can be reproduced in laboratory, might ensure a sustainable production of a non-carbon energy source from solid wastes. The possibility of industrial symbiosis aimed to achieve utility sharing and symbiosis among diverse sectors of the raw materials industry located in the same area must be studied as well.

Mineral and element separation, substitution and biomimicry

The working groups dealing with primary and secondary resources both address common issues related to phase and element separation. Physical and chemical processing of primary and secondary materials, and the metallurgy processes considered by WG1 and WG2 have many similarities, as they should both be developed to facilitate the extraction of a wide range of substances from different kinds of multiphase starting materials. One important challenge is the need to refine ever lower grade ores and materials while reducing energy consumption and environmental impact; the need to develop methods for extracting all valuable metals from currently-mined ores and recycled materials, including minor elements that are commonly now rejected; the need to find methods of extracting metals and other valuable products from unconventional ores and secondary sources (waste); the need to extract a full inventory of metals to anticipate future demand for hitherto unwanted metals.

Beside classical approaches (crushing and grinding, flotation followed by pyro- and hydrometallurgic treatments), alternative approaches like geo- and bio-inspired processes need to be considered. Research in bio-mineralogy must be actively pursued with the objective of extracting metals from new natural or engineered starting materials, and for the remediation of polluted sites. Geo-inspired inorganic processes of separation have to be studied as well. An important underlying question is whether natural processes can be reproduced artificially over short periods of time and their efficiency be increased to be economically viable. A positive answer to these questions would mean that elements might be successfully extracted from low-grade concentration rocks (primary resource) or other starting material like mining & smelting residues from historic landfills and tailings (secondary resource) with environmentally friendly technics. The efforts of research include research in thermodynamic and kinetics of rock and mineral-fluid interactions, mineralogy of bearing phases and structural environment/speciation of elements, biomineralogy, and experimental studies in systems under mechanical, thermal and chemical disequilibrium.

Besides the specific issues regarding mineral and element separations, biomimicry (science that studies Nature's models and then emulates these forms, processes, systems, and strategies to solve human problems – sustainably), can also offer breakthrough concepts and approaches with lots of applications in the fields of material science, energy production, storage, and substitution[13]. For example:

- Plant-inspired solar cells mimic photosynthetic dyes and processes to generate solar energy many times more cheaply than silicon-based photovoltaics, while having the flexibility to be integrated with a building skin.
- Researchers the Angstrom Laboratory at Uppsala University in Sweden have developed a prototype battery consisting of cellulose from algae, conductive polymers and salt water. The advantage of these batteries is that they are much more environmentally friendly compared to the metal-based batteries used today, which continued demand for rare-earth metals. Sony has recently gone a step further by presenting a cellulose-based battery that has been in development for several years,
- Sony developped bio-batteries based on enzymes that degrade glucose to generate hydrogen ions and electrons. and for the first time demonstrated a proof-of-concept of their bio-battery at the Eco-Products 2011 exhibition in Tokyo.

Need for Databases

Regularly updated and reliable information is necessary to assess the European Union real consumption of minerals and metals, the potential of secondary resource, the need of substitution, the effect of developing new technologies and products in terms of future raw material demand, the assessment of element criticality, and the environmental and sustainability implications of projects, policies, products or programs taking into account complex supply chains. A lot of this information already exists but in separate places and often in incompatible formats. A first step must be to make an inventory of where the data are. For instance, companies in all parts of the geomaterials life cycle possess vast amounts of data and diverse types of expertise that must be tapped. The second step is to develop a plan on how to incorporate all the data into a system that can be accessed by all potential users. Efforts must be made to develop, at EU level, extensive databases on:

- The global minerals and metals projects pipeline, production and trade as an essential input to policy making in support to EU competitiveness and sustainable development. It is recommended

[13] see http://www.asknature.org

that an EU mineral raw materials information system includes the mining activities locations and the ore processing, smelting and refining/ purification activities.

- Trading activities, to determine international material flows. Reliable information on the amount of metals and minerals included in numerous categories such as alloys, ashes, cinders, concentrates, final goods, semi-products, scrap or waste have to be documented.
- The energy, water and materials inputs and outputs for the widest possible range of industrially produced minerals and metals.
- Metals and minerals embedded in key end-products to move an important step from apparent consumption to a closer understanding of real consumption.
- Teaching courses on the mineral chain in universities and other educational institutes; short courses, training schemes; material for teaching
- An inventory of supply and demand of the professionals at all stages of the minerals chain; identification of current and future shortages; plans to remedy the shortages.

Information for decision-makers, the citizens, and the industry

There are numerous reasons for supporting an active mining and mineral-processing and recycling industry in Europe. Some of these are purely economic and range from the ERA-MIN's principal goal – to assure a sustainable supply of raw materials from European industry – through to balance-of-payments arguments or the need to create new jobs and domestic sources of wealth. Other arguments come from environmental and societal concerns. Lessons could be drawn from the "locivore" movement which promotes the idea that food and other materials should be sought close to sites of consumption so as to reduce transport costs (both financial and environmental and to support the local economy. On this basis, it can be argued that metals should also be produced locally and not imported from far-flung sources. Likewise, there are strong reasons to argue that mining and mineral processing should be conducted in Europe under the control of stringent European environmental and societal norms and regulations, rather than in an uncontrolled manner in politically unstable and commonly corrupt foreign countries. These arguments must be made clearly and brought to the attention of European citizens and decision-makers.

A major barrier in the place of enhanced domestic metals production is the generally negative public opinion of the minerals industry Although today's state-of-the art technologies are very different from methods used in the past, memories of mineral industry in much of Europe stem from the period when local mines closed, before modern techniques were employed. It follows that most citizens have a very negative image of the minerals and metals industries, leading politicians to oppose their development in several European countries.

Research in social and human sciences is needed to understand how these issues could be addressed and how European industry could gain the "social license to operate" needed to access European mineral resources. This point is fundamental because opening new industrial facilities not only require proper administrative permits but also the appropriate social licences to operate. Such licences can only be obtained if the citizens and politician are informed on the issues relating to raw materials, the benefits and the costs of mining, metal processing and recycling, and the progress of research and technology to develop cleaner and less disruptive methods for mining and treating ores and wastes. To this end, research in social and human sciences is important to raise public awareness about the issues related to Europe's raw material supply, competitiveness and related sustainable development issues. Research is needed to identify and describe best practices and foster public support to reuse and recycling and the eco-efficient use of minerals and metals.

Education, training and formation

In many sectors, researchers, teachers and professionals in both the public and private sectors are approaching retirement; there is already a scarcity of trained specialists and a lack of the infrastructure and teachers needed to train the next generation. Centres of research and teaching programs in universities, governmental agencies and the private sector are scattered and their level of activity is commonly far from optimal.

Future activities in the raw-materials sector will require a new generation of trained and educated professionals. Revitalised research in the geomaterials life cycle must be coupled with improved and expanded teaching and training, particularly in the latest clean technologies. There is a need to promote education and training in all parts of the geomaterials life cycle in order to: a) contribute to Europe's overall expertise in the field; b) increase the public awareness of the importance of raw materials as part of the foundation of modern society's material quality of life, and c) maintain the supply of professionals (geologists, materials scientists, engineers, designers, teachers) needed to support both traditional and high-technology industries in Europe. The measures to be taken include revision of university curricula, promotion of short courses for specialists and for a broader public, and schemes to encourage closer cooperation between the public and private sector. Given sufficient support, this could develop on a worldwide basis to help improve Europe's competiveness.

Integrated research and cross fertilization potential

The many-faceted nature of issues raised by the raw materials supply poses a challenge to the industry, scientists, economists and lawyers, which must incorporate a wide variety of earth, material and environmental, economic, and political disciplines into their diagnoses and prescriptions. It is also necessary to develop research activities involving contrasted technical and scientific disciplines as well as various stakeholders that may have opposite objectives. Research on raw materials should not be limited merely to supply problems and profitability. It should also assess the conditions of the supply, which must be sustainable and acceptable to society.

There is a huge potential to be gained from:

- pushing the industry and the academic earth and material sciences to work together with social sciences, economists, in order to determine and predict development of the mine (including urban mine) inventory, understand and impact consumer behaviour, develop business models to close the loop, create knowledge/education, and inform the decision-makers and citizens about the need of mineral raw materials in their every day's life and about the evolution of technologies and their linkages to the mineral and metal extraction industries.
- Developing schemes to allow companies in all parts of the material life cycle to contribute directly to identify the specific needs of industry in the domains of research and education, define current skills shortages, and anticipate future needs in research and education. The access to the wealth of data and expertise in European and foreign companies will require the development of instruments to assure that the needs of all partners are respected. Methods must be found to share data in a manner that provides access to all participants while respecting the needs of confidentiality of the private sector.
- Encouraging the participation of teachers, researchers and professionals in courses, workshops, and meetings that focus on the geomaterials life cycle; engage economists, social scientists, lawyers and journalists in the definition of joint research and development projects designed to address problems related to the supply of materials to European industry; support national or Europe-wide networks or research centres where these subjects are treated.
- putting together recycling industry and product developers in order to create knowledge about design for recycling requirements and integration into first-principles models and develop tools how to combine design for recycling/ disassembly with product functionality.

- Gathering natural sciences, ecology, economics, political science, computer programming (e.g. game theory), and international law in order to model and understand how the use of raw materials and the behaviour of economic and environmental systems will shape global futures. Many areas of the natural and social sciences involve complex systems that link together multiple physical or intellectual sectors. This is particularly true for environmental problems, which have strong roots in the natural sciences and require social and policy sciences. Integrated assessment models (IAMs) are able to integrate knowledge from these contrasted domains into a single framework (see the developments in IAMs for climate change; e.g. Nordhaus, 2011) so that a decision or analysis can consider all endogenous variables that operate simultaneously. Integrated assessment models are valuable because they provide a range of projections so that scientists and decision makers can understand the uncertainties of the projections, and they can help to appraise the impact of raw material use on our environment, quality of life and sustainable (or not) development.
- Crossing social and political sciences, diplomatic forces of Europe combined with development initiatives and the private sector in order to develop and reinforce contacts in ore-producing countries, to match what Asian countries are doing now and what the USA and Europe had done in the past.

Annex

Additional information on the Substitution Roadmap

Definition of Materials

Three terms related to materials are used in the Substitution Roadmap. To avoid confusion a short definition is given here:

- Raw materials: The ores and industrial minerals and metals which are extracted by mining, recycling and other activities.
- Critical materials: The list of materials which are considered as critical according to the EU (see next section) due to supply risk of the raw materials from which they are derived. The critical materials are mostly defined in terms of elements.
- Materials: Base metals, alloys and engineered materials which are produced using raw materials.

Substitution definition

It is good to define the term substitution more clearly. What does it mean in the context of defining a roadmap on substitution? Substitution should also include reduction of the use of critical materials – not only strive for 100 % substitution.

Substitution is about reducing the use of critical materials in products. One can distinguish the following ways of substitution:

Element substitution

- Substitute the critical elements in alloys or other materials by less scarce elements. Instead of elements one can also substitute larger constituents (molecules, nanoparticles, etc.) in materials.

Material substitution

- a. Replace materials with other (new) materials which contain less or no critical materials.
- b. Functional substitution (or system substitution)
- c. Redesigning products (or systems) to eliminate the need (function) of the parts containing critical materials altogether.

The substitution type c. is primarily located in the domain of product design, where by clever redesign and making good use of existing materials the quickest wins can be made in terms of reducing the dependency of critical materials. This does not work in all cases. The roadmap on substitution will focus on substitution types a. and b. which require long term decisions in terms of research and development.

Critical materials

EU list of critical materials with room for other materials

Element:	PGM group:	REM group:
☐ Antimony (Sb)	☐ Platina (Pt)	☐ Yttrium (Y)
☐ Beryllium (Be)	☐ Iridium (Ir)	☐ Neodymium (Nd)
☐ Cobalt (Co)	☐ Osmium (Os)	☐ Cerium (Ce)
☐ Fluorspar	☐ Palladium (Pd)	☐ Lanthanum (La)
☐ Gallium (Ga)	☐ Ruthenium (Ru)	☐ Scandium (Sc)
☐ Germanium (Ge)	☐ Rhodium (Rh)	☐ Dysprosium (Dy)
☐ Graphite (C)		☐ Samarium (Sm)
☐ Indium (In)		☐ Terbium (Tb)
☐ Magnesium (Mg)		☐ Praseodymium (Pr)
☐ Niobium (Nb)		☐ Promethium (Pm)
☐ Tantalum (Ta)		☐ Europium (Eu)
☐ Tüngsten (W)		☐ Gadolinium (Gd)
		☐ Holmium (Ho)
		☐ Erbium (Er)
		☐ Thulium (Tm)
		☐ Ytterbium (Yb)
		☐ Lutetium (Lu)

Above is the list of critical materials as defined by the EU[14]. Although this is a good and obvious starting point for the Substitution Roadmap, it may not cover all materials for which substitution efforts are required. Furthermore for each country or industry sector a somewhat different set of critical materials applies. Therefore the EU list was used as a core, but some room has been taken to add materials if necessary.

Bi	Zn
V	Hg
Cr	Ag
Re	Mica
Sn	He

The above materials have been added by the working group to the list of critical materials to be considered when defining the roadmap for substitution. These materials are frequently mentioned as critical in other reports[15].

14 Critical raw materials for the EU, Report of the Ad-hoc Working Group on defining critical raw materials, June 2010. In 2013 an update of this list will become available.

15 Rohstoffsituation Bayern: Keine Zukunft ohne Rohstoffe", vbw 2009, "Rohstoffsituation Deutschland 2009", Deutsche Rohstoffagentur, 2010 or I. Erdmann, S. Behrendt, M. Feil, "Kritische Rohstoffe für Deutschland", Studie des IZT and adelphi für die KfW Bankengruppe, 2011, Kritische materialen voor de Nederlandse technologische industrie, April 2012, M2i en TNO.

Approaches for structuring the Substitution Roadmap

Substitution and material efficiency both span up a very wide area of research. Starting with a large number of 35 critical materials[16], each of these materials can be applied in many different ways in engineered materials and components, which on their turn are integrated into a myriad of products. Finding substitution and material efficiency solutions for each and every product is not possible, and not always necessary.

There are at least three approaches for selection of challenges for research on substitution and material efficiency:

- Top down approach: From the list of critical materials, the most urgent or critical ones are chosen. From this 'reduced' list, the applications containing these materials are derived. As final step a selection of the most important applications is made on which the roadmap should focus.
- The top down approach depends on good knowledge on current and future criticality of materials and of all the applications in which these materials are used. This knowledge is not available or at least still subject to debate.
- Product approach: Here the central question is what are the important products? What is needed to have a prosperous and sustainable European industry and society? Examples are the report on Key Enabling Technologies products of the High Level Expert group17 and Emerging Technologies by IZT Fraunhofer18. The roadmap should focus on important products which require substitution research to enable a sustainable production in Europe. The product approach results in a very broad set of products and does not really help to get a focus. Furthermore the emphasis is mostly on new technologies, and in this way we may overlook the need to safeguard existing technologies which are currently and perhaps also in the future the basis of the European industry.
- Functional approach: Which functions are important for society and need to be realized in a sustainable way? This leaves room to choose different technologies and product designs to fulfill for instance the function 'mobility'. Viable technologies which rely on critical materials can be targets for the roadmap on substitution. The functional approach gives room to express what is really needed by society, but is difficult to translate in related technologies. Furthermore the link with economic value of EU related industrial production is not clear.

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16 The critical raw materials list of the EU defines 14 materials which include the REE group and PGM group. In total there are 35 materials.

17 High-Level Expert Group on Key Enabling Technologies (to the EC), June 2011

18 Raw materials for emerging technologies, IZT/ Fraunhofer, February 2009

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