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Vol: 1, Issue: 3

Material Science and Engineering with Advanced Research

"Substitutionability" of the Critical Raw Materials in Energy Applications: A Short Review and Perspectives

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Article Type: **Mini Review**, **Submission Date**: 28 August 2015, **Accepted Date:** 18 September 2015, **Published Date:** 09 October 2015.

Citation: Evangelos I Gkanas, Yannis L. Bakouros and Sofoklis S. Makridis (2015) "Substitutionability" of the Critical Raw Materials in Energy Applications: A Short Review and Perspectives. Mater. Sci. Eng. Adv. Res 1(3): 1-9. doi: https://doi.org/10.24218/msear.2015.11.

Abstract

Among other turbulences in economic life, the availability and price of certain important raw materials have, in recent years, been subject to increasing uncertainty. The issues around these so-called critical raw materials (CRM) include strong and growing demand from industry as well as limited and volatile supply. Uncertainty surrounding the supply of raw materials potentially constrains economic growth as rising prices make key industries less profitable. This study broadly relates to the EU2020 Strategy and in particular to its sustainable growth objective, as well as to the EU Raw Materials Initiative, both of which aim to support sustainable growth in the EU. The objective of this study is to analyze current research, development and innovation policies in this area, which aim to substitute CRM with alternative materials or other solutions.

As the global economy continues to grow, there is an ever-increasing pressure on the Earth's resources. The European Union (EU) has the largest economy in the world, but it lacks the mineral wealth needed to sustain the growth. This is why the EU depends on imports of many critical raw materials [1]. The EU's supply of critical raw materials is further threatened by the fact that some emerging economies, in particular China, are limiting raw materials supply by means of export restrictions [2]. The potential supply difficulties with regard to industrial raw materials are also emphasized in the European Commission Communication on "Tackling the challenges in commodity markets and on raw materials" [3]. The ability to substitute raw materials may provide four advantages: Flexibility, which can insulate industry from the risk of sudden supply disruptions. Cost savings, which can allow industry to find more cost-efficient raw materials. Weaken monopoly power, in cases where a single supplier country controls the market for a given raw material. Environmental benefits, if the new substitute materials require less resource inputs to the production process and/or reduce emissions or resource consumption over the life-cycle of the product [4].

This particular study is one effort to understand the state of the art in the EU and Member States in their efforts to address the issues of critical raw materials. The aim of this study is to survey the policies and instrument that support substitution of CRM on the levels of EU and the Member States. The main research question of the study is: Which (policy) measures could foster the substitution of critical raw materials (as defined by the European Commission) as well as other metals that are mined as by-products of other metals, including in particular rare earths? The study focuses on the existing and foreseeable technical solutions as well as the policies and strategies to substitute the CRM in the value chain. The particular focus is on the policies that can support substitution.

Analysis on the Substitution of Critical Raw Materials

The approach aims to analyze the studies both in terms of technology and policy, and includes some key interviews in both directions. As illustrated in Figure 1, the study is based on the analysis of available policy and technical documents and supporting interviews, which are subsequently analyzed by the authors who then compile the report on the state of the art in substitution of the CRM and the recommendations for action to support substitution. An often cited fact is that China as of 2011 held a market share of 97% of world REE production in 2011, which illustrates the concentration of supply. The drivers for growth in demand for CRM are general economic growth and demand for goods which contain CRM as raw materials or manufacturing of which use CRM. One of the most common examples is petro-chemical products, where platinum group metals play a key role in manufacturing. The global growth of consumer demand will project to demand for raw materials with some delay due to stockpiles in various parts of the value chain. However, the production of REE or other CRM does not scale up in the short run, as estimated lead time from a confirmed deposit to a working mine may be as long as ten years. The rise in price will increase competition in the supply of CRM and naturally direct funding for Research, Development and Innovation (RDI) to substitute present solutions.

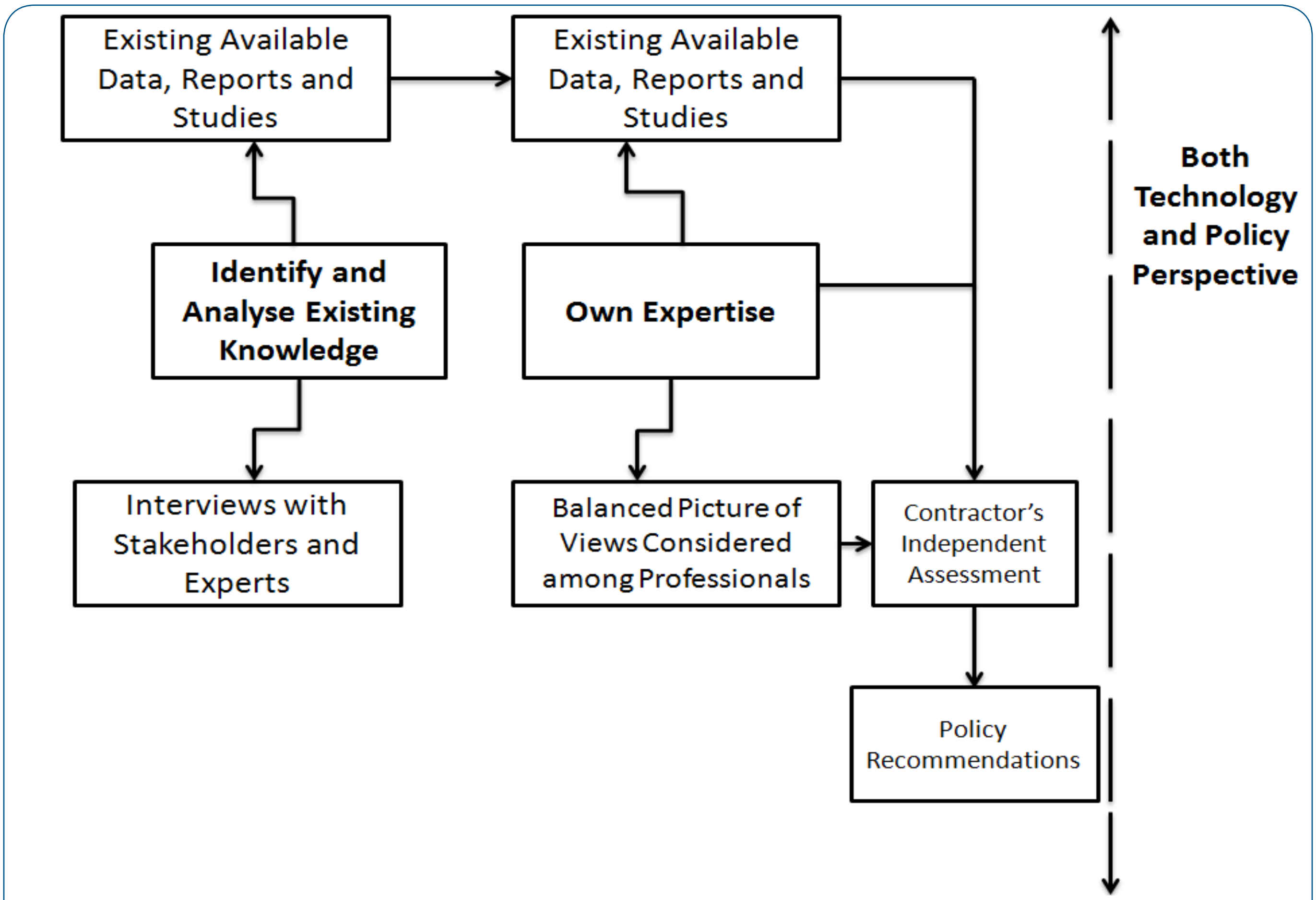

Figure 1: Workflow diagram of the study

In many cases the actual criticality ranking is complicated (and varied) by the fact that some of the critical elements availability depends on demand for and extraction of other materials, as the former are found mixed-in with the latter and it is not economically feasible to extract the critical elements on their own. This is particularly pertinent to gallium, germanium, indium and cobalt. Furthermore, the criticality ranking is also dependent on the relative ease (or difficulty) of increasing the rates of recycling of each element and any new recycling technologies. For example, platinum and palladium (the most important of the platinum group metals) are much more easily (and profitably) recycled than many of the other critical materials such as most of the REE and especially materials that are mostly used-up during their use. From the 14 critical materials identified by the Raw Materials Initiative, REE and the Platinum Group Metals (PGM) were regarded as being the most critical at the moment. Indium, Germanium, Gallium and Lithium ranked second in criticality. Important application areas that depend on the supply of critical materials are electronics, lighting, displays, photovoltaics, e-mobility, batteries and catalysts for automobile and chemical industry. The majority of these applications are related to clean energy technologies.

Some substitutes have already been developed, e.g. new electric motors without REE have been developed and luminescent phosphors are replaced by LEDs. For automotive catalysts: palladium and platinum are mutually substitutable, and the choice of metal is based on the current price. The same applies for example for cathode materials for accumulators/storage batteries, which employ cobalt: the cathode material is developed with inherent flexibility to increase or decrease concentration of the metal. These are market ready examples. However, the industry has been trying to find replacements for PGMs for 30 years in catalysis, and has not achieved substitution with the same success. One of the reasons is the very high efficiency and ease of use of PGMs for most catalytic applications. The other is the apparent inability of the scientists to fully understand the actual micro mechanisms taking place during catalysis at the atomic level.

Research on substitution is above all risky and lengthy endeavor taking anywhere from 5 – 15 years without any guarantee of success due to unforeseeable fluctuations in raw materials prices and at the same time customer demand as well as new products and services introduced by direct competitors and other companies. A person from industry stated that true substitution research, meaning the discovery of disruptive and not incremental innovations, would have to try to fundamentally understand materials properties first (such as atomic-level catalysis) and answer why certain elements are needed and in what ratio to obtain those properties. The first step in substitution is to carry out research, and if successful, the RDI process will move to industrial applications. However, a prerequisite for obtaining and applying a substitute material are industrial lengthy endeavor, it would potentially also enhance material efficiencies as an intermediate gain. The other approach to substitution would be to replace the existing value network with altogether different products and/or services. For example, development and wide adoption of electric vehicles for consumer use together with a well functioning public transport would considerably lower the demand of PGMs for catalytic converters both upstream in petroleum refining as well as in the automotive industry. However, on the flipside, with the present technology this would increase dependency on REE considerably.

Existing Policies for the Substitution of Critical Raw Materials

Policies, measures and policy targets for substitution in the EU and its Member States

EU Level: The European materials policy has a principle aim of increasing self-sufficiency, sustainability and competitiveness of European industry and economy, by reducing dependency on third countries for raw materials and energy. The rationale is at least twofold: financial and security-oriented. The European economy cannot be competitive and grow to create welfare for everyone as projected in the general EU2020 Strategy if the industry is constrained by lack of resources necessary to keep on the path of sustainable and sustained growth. Besides constraining growth, serious shortage of resources could result in withering of the industries where the value chain depends on CRM, which in turn may turn into loss of vital know-how within EU.

Furthermore, especially in times of crisis self-sufficiency is important as one cannot rely on outside sources for political and logistical reasons. Especially the Americans are quite aware and explicit about the fact that their defensive capability depends directly on REE and other CRM supplies [5].

While EU institutions are active in policy making within the union, the EU also has engaged in a dialogue with US and Japan to discuss the options to lessen the demand for REE and increase efficiency of raw materials use [6] The issues of CRM policy are intertwined with energy policy, not least because REE are vital ingredients in powerful permanent magnets utilized in high-performance electric motors and generators as well as in batteries, which in turn are the building blocks of e.g. wind turbines, hybrid and electric vehicles, not to mention their use in chemical catalytic converters for the petro-chemical industries [7].

Besides these strategic initiatives, the EU institutions and the Member States have set up a host of policies and instruments to support substitution of CRM. The European Commission has paid attention to the importance of uninterrupted supply of raw materials since "The raw materials initiative" [8] of 2008 when raw materials were seen primarily as an issue of growth and jobs. However, on the EU level the thrust for replacing/substituting CRM through innovation is a major theme since 2011, with a slightly altered agenda of sustaining the present level of use and present value chain until new solutions can be developed. It seems that the current level of interest in CRM can be largely traced back to first the Chinese decision to mandate export duties for REE back in 2009 [9], second to the simultaneous production and export limits in China (the provider of almost all of worlds REE as of today [10] and third to the rise in demand for CRM, which have caused the raw material prices to rise sharply during 2011. However, at the moment of writing, the idea of improving specifically CRM/REE supply security or substitution is relatively new, and the main focus in many countries' materials technology programs seem to be general development of new technologies and solutions to existing technical and commercial programs, rather than explicitly replacing the use of CRM.

On a more practical level, the objectives are also implemented down to the EU 7th Framework Program for Research and Innovation (FP7). Especially the Specific Program Cooperation includes several relevant funding themes, including environmental research and energy research. The FP7 environmental theme contains strands such as conservation, sustainable management and recycling of natural and human-made materials. Energy research aims to create new sustainable technologies, which have largely relied so far on CRM. The most relevant theme or sub-division seems to be however the Nano- and materials technology theme, as exhibited particularly in the 2012 Work Program on Nanosciences, nanotechnologies, Materials and new Production technologies – NMP [11] of the EU FP7. The NMP 2012 call includes, among others, the following themes/calls: "Rational design of nano-catalysts for sustainable energy production...", "Innovative recycling technologies of key metals in high-tech applications" and "Development of advanced magnetic materials [completely] without [or with less CRM]". Besides the flagship RDI program, the EC also commissions technical studies to research the feasibility of substitution of CRM [12].

The major emerging issue in EU RDI policy is the phase-out of FP7 and the emerging Horizon 2020 – The framework program for Research and Innovation (H2020), and its interplay with the partially overlapping EIP on Sustainable materials resources and a possibly emerging KIC administrated by EIT. Starting 2014, H2020 supersedes FP7, while it is foreseeable that some of the themes found in the H2020 proposal might be introduced to FP7 during its last year. The present FP7 is split into 7 specific programs and altogether 25 subdivisions inside the specific program. The largest specific programs are Cooperation for collaborative RDI projects, Ideas for top academic research, and People for international researcher mobility, and these specific programs are split into subdivisions that concern different themes or aspects of RDI activities. Differing from FP7, H2020 is planned to have four pillars called 'Excellent science' (Pillar I), 'Industrial leadership' (Pillar II), 'Societal challenges' (Pillar III), as well as 'Non-nuclear direct actions of the Joint Research Centre (JRC)' (Pillar IV). 158 Comparing the structures of FP7 and H2020 proposal, within Pillar I the first specific objective of strengthening European research through the European Research Council is analogous to the FP7 specific program 'Ideas' and the objective of strengthening skills, training and career development through Marie Sklodowska-Curie actions corresponds to the FP7 specific program 'People'. The Pillar II and to some extent Pillar III then are rather close in content to the FP7 specific program 'Cooperation'.

Looking at the relevance of the H2020 proposal to CRM substitution, the most relevant specific objective in Pillar I would be the 'Future Emerging Technologies' program which is open to various thematic fields, while in the second pillar funding to RDI on 'Nanotechnologies', 'Advanced materials' as well as 'Advanced manufacturing and processing technologies' under the specific objective of boosting Europe's 'Industrial leadership' are the most relevant. The CRM issues are also being addressed under the third pillar by the specific objective of achieving a resource-efficient and climate change resilient economy and a sustainable supply of raw materials including recycling and resource efficiency. As an overall observation, however, it could be suggested that while there is potentially a substantial funding for CRM substitution, the structure seems rather dispersed with multiple and to some extent overlapping actions that all potentially address the CRM issues.

The member states: Looking at the national level, the Member States at large have not been that active specifically on substitution of CRM. In a recent publication surveying raw materials and minerals strategies around the world it is confirmed that as of 2011 only three Member States have an explicit minerals strategy: Germany, France and Finland [13]. Two of the raw materials strategies mentioned above are publicly available, the German Raw Materials Strategy [14] and Finnish Minerals Strategy [15]. Especially the latter strategy aims to boost the traditional minerals sector, including mining and extraction, processing and refining and production of metals. One interpretation for the finding that there are relatively few explicit raw materials strategies, and that at least some are more concerned with developing minerals and mining industry than raw materials supply is that due to a period of liquid global minerals market, there has been relatively little concern over supply security until recently and the Member States have pursued a passive strategy toward minerals.

European Strategies: As is apparent from the analysis presented above and from the more detailed overview of the relevant strategies and programs in Annex III, the EU has been very proactive both in creating a strategy to tackle issues in raw materials supply as well as operationalising the strategy to its RDI instruments. On the national level there is considerably more variation on the implementation of the EU strategy and the government role in raw materials. For example, in Finland, the raw materials strategy was created in response to the EU strategy, while in Germany the Federal government has been active in making raw materials strategy since 2007 and has implemented a host of policies to support the strategy and secure raw materials for the nation, whereas e.g. in The Netherlands the Government has apparently chosen a relatively *laissez faire* approach, in the sense that the Government positions itself as a facilitator for the private sector and markets. In UK and France, the policy making concerning raw materials supply is in its infancy, as both countries have recently set committees to investigate implications of CRM situation in national policy, but neither have explicit raw materials policy. Table 1, illustrates the summary of policies in the EU and member states directed toward substitution of CRM.

Further, most of the national strategies address only the two of the three main points of EU Raw materials initiative, namely they support freedom of movement in global markets and also reinforce supply of raw materials, but considerably less has been said about lowering the use of primary raw materials. The analyzed strategies do not in general set tangible quantitative targets, with the partial exception of the EU Raw Materials Roadmap.

International Situation: In summary, the strategies in the US, Japan and South Korea are broadly similar to the approach in the EU, in that they aim to balance short and long term interests by minding the supply security of the raw materials most important to each respective nation in immediate term, while encouraging efforts to develop recycling techniques and substituting CRM in the industry through product and component innovation, new products and services. Both Japan and USA have implemented policies and programs for substitution of raw materials. Japan especially has been working on the issue quite strongly and for a relatively long time already, and programs to support substitution research have been operating since 2007. The US program on advanced research on energy technology has been running since 2009, but substitution of CRM has been raised as a topic on interest only later in the more recent Critical Materials Strategy.

The difference in response might have something to do with different governance structures, as the US House of Representatives (Congress) is interested in raw materials security, but the Federal Government does not have a track record of similar interventions for RDI as the EU. That is, the US Government has not historically been as active as the EU in installing policy instruments such as RDI funding programs or other measures to correct market failures. Differing from the USA and Japan, the ROK is approaching the raw materials issue by supporting the expansion of Korean minerals sector to secure supply.

Besides national programs, international efforts on strategic metals have been initiated through the G8 research councils on multilateral research funding, one of which is the interdisciplinary program on material efficiency and sustainable use of materials. This joint funding initiative is aimed at supporting excellent research on topics of global relevance best tackled through a multinational approach, recognizing that global challenges need global solutions. Funding should support researchers to cooperate in consortia consisting of partners from at least three of the participating countries. Participating countries are Canada, France, Germany, Japan, Russia, United Kingdom and the US (out of established G8 countries, Italy is not participating) [16].

At the moment, as far as can be deduced from public sources, substituting CRM is under discussion in many countries. Nevertheless some efforts have already been launched particularly in Japan and in the USA. Out of the examined countries Japan has undertaken the strongest efforts to substitute CRM across industries, while in the US the main public effort is confined in the energy sector. In Japan programs to support substitution of REE have been running since 2007 and a national research institute for materials science has been founded 2001, which has started a new strand of research called 'Elements science and Technology Center' where a large component of research is related to substitution of CRM [17]. One presumable driver behind these different policy responses is industry structure. For example, presumably the economy and infrastructure in the ROK is structured differently and may be in different stage of development, and the industry is more dependent on mineral imports, e.g. Korean steel industry that supports its burgeoning shipbuilding and machinery industries has to import practically all raw materials, not only CRM. This need is also mirrored in Korean raw materials policy, which aims to broaden the base of raw materials supply rather than conserve materials. Table 2 presents the summary of policies directed toward substitution of CRM in the USA, Japan and Korea.

Also others have probed existing minerals strategies and policies across countries [18], including some of the world's foremost mineral producers and also EU Member States. Their review

Table 1: Summary of policies in the EU and member states directed toward substitution of CRM

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
European Union				
Raw Materials Roadmap	European Commission	EU	Policy objectives/milestones by 2020 (directly relevant to CRM) [27]Citizen and decision makers have incentives to choose most resource efficient productsMarket and policy incentives reward business investments in efficiency Waste is managed as a resource. Waste generated per capita is in absolute decline. Scientific breakthroughs and sustained innovation efforts have dramatically improved how weunderstand, manage, reduce the use, reuse, recycle, substituteand safeguard and value resources. Means:Enhancing dialoguesInvesting transition Developing indicators	
EU-FP7 Specific programme on Nanosciences, nanotechnologies, Materials and new Production Technologies (NMP)	European Commission	EU	Goals include [28] DevelopmentofcatalystsbasedonnanotechnologiesTechnologies for recycling REE and other key metals Replacing REE in key technical applications	Calls for Proposals still open
EU-FP7 NMP 2012.4.1-3: Development of advanced magnetic materials without, or with reduced use of critical raw materials	European Commission	EU	Goals include: [29] Development of catalysts based on nanotechnologies Technologies for recycling REE and other key metals Replacing REE in key technical Application	Calls for Proposals still open
EU FP7 NMP.2012.4.1-4: Substitutionofcriticalraw materials: networking, specifying R&D needs and priorities; including substitutions for CRM (PGM, REE), NMP-2.2-4	European Commission	EU	Goals include:[30] Substitution of 14 CRM from Raw Materials Initiative Create competence cluster in CRM substitution area Draft Roadmap with Activities, actors,timing, selection and networking ofexisting national activities/centers	Calls for Proposals still open
European Technology Platform on Sustainable Mineral Resources (ETPSMR	European Commission	EU	Goals: [31] To modernize and reshape European extraction and processing sector of energy and non-energy minerals, including: Providing RTD strategy and maintaining a research base Focusing public and private investment Contributing to resource efficiency, supply and reduction of materials use	Major projects Launched under FP7 (undisclosed)
European Innovation Partnership on Raw Materials (EIP)	European Commission	EU	Goals by 2020: 10 pilot plants Secured raw material supplies International cooperation, substitution of critical materials Improve infrastructure and know how basis on raw materials [32]	Starting 2012

Table 2: Summary of policies directed toward substitution of CRM in the USA, Japan and Korea

Strategy/ Programme	**Owner/ Implementing body**	**Country**	**Aims/goals**	**Projects/Results (such as are available)**
Critical Materials Strategy	Federal Government, US DOE	USA	Diversifying supply, Developing substitutes and Improving recycling [33]	Workshops to discuss the issues regarding CRM supply and use[34]
ARPA-E	DOE	USA	Funding of transformative research on advanced energy technologies, not specifically on substituting CRM[35]	122 funded projects through 12 open calls, worth approx 370MUSD 12 programmes to develop high performance innovative technologies for power generation, distribution and use.[36]
An elemental strategy project	Ministry of Education, Culture, Sports, and Science and Technology	JP	Rare and harmful elements, aims for drastic or complete substitution Aims to propose a new paradigm for materials research May be continued as a METI RDI project after the first 5 year of programme	Projects kicked off since 2007 include: [37] High Performance Anisotropic Nano composite Permanent Magnets with Low Rare Earth Content Self-forming Nano-particle Catalyst without Precious Metals Development of TiO2-based Transparent Electrode
Rare metal substitution material development project	Ministry of Economy, trade and Industry (METI), New Energy and Industrial Development Organization (NEDO)	JP	Aims for reduction in the use of critical metals by 30-80% during the programme period Promotes RDI activities to develop practical substitutes [38]	Projects since 2007 include: [39] Development of Substitute Materials for Indium in Transparent Conducting ElectrodesDevelopment of Technology to Reduce Dysprosium Use in Rare Earth Magnets Development of Technology to Reduce Platinum Group Use by Utilizing Substitute Transition Elements and Aggregation Inhibitor of Platinum Group Development of Technology to Reduce Platinum Group Use in Catalysts for Diesel Exhaust Emission Development of Technology to Reduce Cerium Use for Precision Polishing by utilizing the Substitute Abrasive
Korea Resources Corporation - KORES	Government of ROK, Ministry of Knowledge Economy	ROK	Further Korea's access to strategically important mineral resources Engaging directly, or indirectly through joint ventures or in the form of investments, in overseas exploration, development and production of strategically important mineral resources Managing Korea's stockpile of rare mineral resources.	

supports the finding that EU Member States have not, by and large, been active in making minerals policy. While in the 1980s governmental regulation and interventions were commonplace, liberalization of markets became standard practice in the 1990s also in the minerals sector and this thrust is mirrored in most analysed policies. Niemeläinen et al. [19] summarize these policies, revealing that mining laws and raw materials policies have been revised in the 1990s in many countries, and thus the content and objectives are in many cases from that era, with the exception of recent policies from Germany (2007-2011), India (2008), China (2003) and South Africa (1998). The common themes over many strategies are primarily: Subsidising or supporting exploration/prospecting and mining.

Sustainable development of mining and minerals sectors, ensuring transparency and liquidity of global commodities/ raw materials markets. And secondarily: RDI for prospecting, extraction and mining and refining minerals, Attracting domestic and foreign investments, Creating a regulatory framework for minerals sector, Development of institutions and international collaboration. Analysing the strategies, three groups of countries arise; (large) minerals exporters, (large) minerals importers, and the rest. Each group has their own response, which could be hypothesized to be dictated by the relationship of each country's mineral demand versus their domestic supply and vulnerability of their industry and raw materials supply.

In the first group each country is apparently anxious to boost exports and create jobs in the minerals sector. Particularly the large minerals exporters, e.g. China, India or South Africa, have little incentive to attempt to change the value chain from existing, as they are in the possession of the valued resources and they have also *de facto* monopoly or oligopoly power over the market price, which may be a considerable economic benefit as well as a diplomatic leverage. These countries in fact benefit from the *status quo* where demand of minerals exceeds the present production capacity, as this disparity is directly reflected positively in their trade balance as well as their international importance, while the domestic production keeps the industry in relatively good supply despite international market difficulties. To some extent this applies also to Finland and Sweden, which are countries with relatively good minerals resources, and which in Finland have been hitherto relatively little prospected. In contrast, countries which are large net importers of raw materials and have relatively small minerals resources compared to demand, such as the EU countries in general and Germany in particular, seem considerably more anxious to find alternative supplies or substitutes for CRM. This finding arises from the comparison between the strategies of the large minerals producers like China and India, and also a smaller producers such as Finland or Sweden, which are mostly focused on developing the mining industry, and e.g. Germany, which is considerably more geared toward multi-faceted action to secure present and future supply of resources that keep the industry in production. The German strategy could be said to be most comprehensive and advanced on the level of the Member States. The German strategy embraces the EU objectives to increase market transparency and knowledge about minerals resources, as well as increasing sustainability of resource use. Differing from the EU initiatives, the strategy also includes a component which could be called up-stream integration in value chain, that is, establishing bridge head position in overseas mineral deposits and securing supply of minerals by domestic suppliers (see also the Raw materials alliance and *Deutsche Rohstoff AG* above), developing foreign minerals deposits, and the complementing element of securing bilateral agreements with selected countries together with integration with development policy. This strategy is actually quite similar to the one adopted by the Republic of Korea, which puts extensive efforts to create a mining industry that is active in explorations and mining overseas to supplement the relatively few domestic resources.

Policy Recommendations

Possibilities for supporting further substitution efforts through EU RDI programs

The EU, and in particular the European Commission, has been very active as regards the raw materials initiative in recent years. Indeed, the Commission spearheaded a strong strategy tasked with securing the supply of raw materials. The EU has also integrated its raw materials strategy into the existing funding programs, e.g. FP7, as well as ERA-NET (European Research Area Network) for materials and the emerging European Innovation Partnership (EIP). In the RDI policy field, the EU is already consolidating RDI instruments; the proposal for the RDI instrument Horizon 2020 – The Framework Program for Research and Innovation will proposedly integrate the current FP7 with parts of the Competitiveness and Innovation Framework Program (CIP) and the European Institute of Innovation and Technology (EIT), as well as the sector specific Information Communication Technologies Policy Support Program and Intelligent Energy Europe Program [20]. H2020 is likely however to continue to implement EU policy objectives in general and specific objectives, such as CRM substitution, in particular. While consolidation potentially simplifies RDI policy, the internal structure of H2020 may present a number of challenges to the RDI consortia seeking funding for their efforts in respect of CRM substitution. The immediate question that arises when looking at the proposal for H2020 from the CRM substitution point of view is that the potential sources of funding are quite fragmented across the three pillars and also across the specific objectives within the second pillar, 'Industrial leadership'. Research relevant to CRM substitution could potentially fall under each of the pillars. For example: Under Pillar I CRM substitution could be a Future and Emerging Technology project or even a flagship project, as substitution can be positioned as a "grand interdisciplinary science and technology challenge"[21]. However, looking at the specific objectives under the pillar, there are three or four separate relevant research themes; Nanotechnology, Advanced materials, Advanced Manufacturing and Processing, and to some extent also, Biotechnology. All of these fields can contribute to CRM substitution in their own right, but there is little incentive for multidisciplinary research to develop integrated solutions as the research fields have different silos in the program. Finally, under Pillar III one of the main themes is "Climate action, resource efficiency and raw materials", which includes the sub-themes "Sustainably managing natural resources and ecosystems" and "Ensuring the sustainable supply of non-energy and non–agricultural raw materials" [22]. The themes under the third pillar are, at least in the proposal stage, parallel with those of the second pillar, but supposedly can envelop a multidisciplinary approach. In sum, from the perspective of an RDI consortium looking to develop CRM substitutes, the structure of H2020 is in fact more fragmented from this specialised perspective than FP7, where most of the RDI specifically for CRM substitution falls under one or two sub-divisions of one specific program, namely NMP for technology development and Environment for research on recycling under specific program Cooperation. It is foreseeable that positioning multi-disciplinary efforts to substitute CRM may present challenges for funding applicants, starting from choosing between pillars, and also within a pillar positioning the proposal between the specific actions. For example, comparing NMP sub-divisions under the FP7 specific program Cooperation, one finds most if not all relevant calls for proposals to develop new materials to substitute CRM under one sub-division.

Maintaining up-to-date information about raw materials resources and their criticality

The EU has taken a considerable interest in raising awareness of the CRM issue and in implementing policies that will kick-start substitution. However, as pointed out in the interviews, the availability and importance of any individual raw material in the CRM list or outside it may become, or cease to be, critical as a result of e.g. the development of new technologies, materials and products; extensive substitution; through changes in customer preferences; or the finding of unforeseen new deposits. The EU can create an important resource for substitution by maintaining up to date information on the current situation of various minerals resources, the global trade situation and the criticality of different raw materials. Further, information could be disseminated on the current use of CRM and the structure of value chains, highlighting the risk associated with the use of CRM and the potential economic and/or technical benefits of substitution.

Creating an RDI roadmap for substitution

While the raw materials strategy provides a clear direction in respect of where European industry should, in general, be headed, substitution efforts could be aided by a more specific roadmap for research on substitution. Side by side with the previous recommendation, the research roadmap should look at interdependence between materials efficiency, the recycling of end-of-life products and materials and the substitution of each critical material and application separately and in conjunction with each other. Another crucial point worthy of further analysis is whether substituting materials with currently noncritical ones creates negative externalities, e.g. by making currently abundant materials critical in cases where the existing production of the substitute material cannot satisfy the demand for the new application, or by creating environmental hazards in the event that recycling the substitute material or product is not feasible. Ideally, CRM should be replaced by abundant materials and minerals. For example, initiatives exist where new semiconducting properties are obtained in iron through clever manipulation of micro- or nanostructures [23], potentially replacing silicon and germanium in some applications. However, managing funding on this level of detail requires a thorough socio-economic as well as a technical analysis in order to decide which CRM and applications to focus on.

Recognizing the different dimensions of substitution

As illustrated in "[The] guide to substitution" developed by the UK Chemicals stakeholder forum [24], the substitution of any material is a multidimensional issue and the various possible perspectives to substitution should be recognised when developing further policy and instruments for CRM substitution. Stereotypically, the goal is to find abundant materials and processing technologies that offer the same efficiency and the same essential properties as materials that include CRMs. However, that is only one angle to substitution; substitution can include innovation on all fronts besides developing direct material-for-material substitutes, including process-for-process, substance-for-substance, mechanism-for- mechanism, product-for-product and service-for-product solutions in addition to the most obvious [25]. The plethora of potentially available substitutes was illustrated by the example of digital versus film photography outlined above, illustrating product-for-product substitution in equipment and service-for-service substitution in printing.

Strengthening mechanisms to bring the EU to the forefront of materials science

Bringing the EU and the European Research Area (ERA) to the forefront of science is an overarching EU policy objective. CRM substitution not only provides an important economic challenge; it is also entails a large multidisciplinary scientific effort. To support substitution oriented research, establishing strong materials science centers and programs may be in order. Looking at the international benchmarks, for example, in Japan the National institute for Materials Science has been running since 2001. In the US, the policy response has thus far not been that strong with some US scientists arguing publicly that the intellectual infrastructure and knowledge base requires strengthening to enable successful CRM substitution [26]. The existing and foreseen European funding instruments, including FP7, the emerging H2020 and EIP on raw materials already represent an extensive effort, but additional specialized research may be called for in order to bring European research to the cutting edge and to avoid loss of competence in various fields around materials science and CRM through 'brain drain. One way to organize such an effort and to ensure a critical mass of researchers could be by mimicking the Japanese NIMS set up, the Helmholtz Institute for Resource Technology in Freiberg, Germany, or the Energy technologies institute in the UK. Such an institute could be organized as a Joint Research Centre (JRC) under Pillar IV in H2020, or under Pillar I as research infrastructure, or through other means, and would act as a nexus of materials science research within the EU as well as a meeting point for top materials scientists around the world. The institute could cover a broad range of RDI activities from basic to applied research and ideally also demonstration, with a focus on broadly used technologies and applications.

Acknowledgements

Authors would like to thank Professor Xiaoyan Song, Beijing University, China for the extensive discussions on the topic of EU-China rare earth supply.

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