Simply No Substitute?

Assessing and enabling realistic potential alternatives to key strategic materials in critical technologies

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Summary

The supply constraints on critical elements, from helium to rare earths is characterised by a fragmented and uncoordinated input from end users and policy makers. Current strategies of extracting more minerals or using alternative technologies do little to address the growing potential impact of shortages on future economic growth and carbon emission reduction policies.

So, a huge amount of research and development is currently taking place in academic and industrial research laboratories, with the aim of developing novel, innovative material substitutes or simply to 'engineer-out' critical materials with new designs. Whilst the search for substitutes for many critical materials is underway, the necessity and effectiveness of this activity is still unclear and requires greater insight.

This paper highlights the key issues, the required strategies and proposes the creation of a body to ensure the interests of end-users are represented across this increasingly complex and rapidly developing issue. This will benefit not just end-users, but also primary and secondary producers of critical materials, for who it is currently only feasible to have sporadic and inconsistent interaction with the diverse range of industries that use their materials.

Contents

Introduction

Minerals play an essential part in modern manufacturing and technology. For example, it has been reported that General Electric (GE) now uses at least 70 of the first 83 elements in the periodic table of elements and spends $40billion each year on materials, of which 10% is direct purchases of metals and alloys[1]. This diverse range of materials is used to create and define the performance of every product we encounter in our daily lives. Yet, it seems likely that we cannot assume the routine use of this same group of materials in the future.

In recent years there has been increasing emphasis on the deployment of clean technologies by Governments, industry and consumers. This increasing deployment of clean technology looks set to increase. All clean technologies use raw materials; in some cases commodity materials such as steel, but in other cases less well known materials, such as the lanthanide group of elements, more commonly known as the rare earth metals. There is increasing concern, particularly in Europe and the US that shortages and limited supplies of these metals and other critical minerals could hinder the deployment of clean technologies.

Some industry stakeholders believe the scale of the problem could be large. A team at MIT recently published work [2] that showed if the deployment of clean technologies is going to be at the targeted levels to meet mandated CO_2 reduction targets, industry will need an increase in the supply of neodymium and dysprosium (two of the rare earth elements) of more than 700% and 2600% respectively by 2037. This requires annual growth rates of 8% for neodymium and 14% for dysprosium, against an actual current growth rate of 6%. Some industrial parties are taking no chances. Recently, carmakers BMW and Daimler, electronic equipment group Bosch and 10 other German companies formed an alliance to secure key raw materials in the face of uncertainty over supply[3]. The US Materials Genome Initiative aimed at speeding up the deployment of new materials and launched in June 2011 also highlights the need to develop substitutes for critical minerals [4].

Global demand for rare earths has tripled from 40,000 tonnes to 120,000 tonnes over the past 10 years, during which time China has steadily cut annual exports from 48,500 tonnes to 31,310 tonnes according to one estimate[5]. The only way that a company can be exempt from China's rare earth export quotas is by manufacturing within China and that is what most companies, including Apple, are doing. Currently the only other alternative is to reduce consumption.

Although they have garnered most of the media attention in recent years, it is not just the rare-earth elements around which there are supply concerns. Even the simple elemental gas helium has been reported as being at risk of supply in the US [6].

For Governments and industries looking to mitigate their risks in using these materials, there are three broad strategies that can be adopted; diversifying raw material supply, using substitute materials or technologies and increasing recycled material content. The purpose of this white paper is to summarise the current technology and policy landscape with respect to attempts at developing substitutes for critical materials. These substitutes can be either alternative materials which are considered to pose less of a supply risk or re-designs of existing technology to avoid the need for such materials.

Which materials and clean technologies are potentially at risk?

Not all materials used in clean technologies have supply risks associated with them. For example, cerium, the most abundant of the rare earth elements is critical in the manufacture of environmental protection and pollution-control systems in cars; catalytic convertors. For the foreseeable future, there is no significant supply risk associated with cerium and catalytic convertors [7].

However, the supply of other materials has the potential to impact on technology deployment. To begin to address this issue, a number of Governments, agencies and research groups have recently studied and published lists of materials on the 'at risk' list. Due to varying geo-political influences and differing demand profiles within different geographical regions, there is no universal agreement on which materials are the most at risk. For example, the recent report by The Institute for Energy and Transport of the Joint Research Centre (JRC) of the European Commission [8] assessed whether there could be any potential bottlenecks to the deployment of low-carbon energy technologies in the EU due to the shortage of certain metals. It found that five metals commonly used in these technologies show a particularly high risk, with special relevance to the wind and photovoltaic energy generation technologies. These elements were neodymium, dysprosium, indium, tellurium and gallium.

A similar recent report, Critical Materials Strategy conducted by the U.S. Dept of Energy identified its own list of elements [9], and a joint report by the US Materials Research Society and the American Physical Society identified an even larger range of critical materials [10]. Other studies have produced graded risk profiles in this area [11,12], although these did not just focus on the clean technology sector.

In order to make sense of this rapidly developing landscape, we have summarised the key materials identified as being at most risk across the most comprehensive reports, Table 1. Given that each of these studies uses its own specific methodology, grading the important factors including supply risks, economic importance and technology demand, it is not particularly surprising that each report identifies a unique set of materials. It does emphasis the size and complexity of the strategic materials issue.

Table 1: Summary of materials identified at being 'at-risk' of supply disruptions, according to recent reports

	British Geological Survey[a] [11]	EU Joint Research Centre[b] [8]	EU ad-hoc Working Group[c] [13]	US Dept. of Energy[d] [9]	Institut für Zukunftsstudien und Technologiebewertung[e] [12]
Antimony	•		•		•
Platinum metals	•		•		
Mercury	•				
Tungsten	•		•		
Rare earth elements	•		•		
Niobium	•		•		
Dysprosium		•		•	
Neodymium		•		•	
Tellurium		•			
Gallium		•	•		
Indium		•	•		
Terbium				•	
Europium				•	
Yttrium				•	
Germanium			•		•
Rhenium					•
Beryllium			•		
Cobalt			•		
Graphite			•		
Fluorspar			•		
Tantalum			•		
Magnesium			•		

[a] risk rated at >8 (out of max. 10), [b] risk rated as 'high',[c] list of critical raw materials [d] risk rated as 'high' in medium term, [e] raw materials with the highest criticality (cluster VI)

For Governments looking to mitigate their risks in using these materials, there are three broad strategies that can be adopted; diversifying raw material supply, using substitute materials or technologies and increasing recycled material content. Not all stakeholders on the demand side of the rare earth market are working on substitution. For example, Rhodia are one company who have recently publicly declared that they are not investing in research on substitution, preferring to focus on recycling and conservation of materials [14]. Honda has recently formed a partnership with Japan Metals & Chemicals Co to begin extracting the rare earth metals. Yet many large organisations are committing substantial resources to finding alternatives to the rare earths.

Why substitution?

"Rare earths are to China as oil is to the Middle East," Deng Xiaoping (1992)

Many businesses and, in particular, non-technical senior management, view substitution as a relatively 'easy option' to overcome material supply challenges. In a recent survey conducted by consultancy PwC [15], over 60 % of senior executives believed increased substitution of critical materials was the correct response for their company to this major threat. However, the route to an alternative, commercially viable solution that does not use the 'at-risk' material will usually be long, costly and uncertain, often with no guarantee of a workable solution. Finding substitutes is not easy; the red colour in televisions is due to europium—it has been used for decades and no viable substitute has yet been found.

Despite the above caveats, a huge amount of research and development is underway in academic and industrial research laboratories and design centres to develop novel, innovative material solutions or simply to 'engineer-out' critical materials with clever new designs based on sound engineering principles. For this report a search of patent publications containing the words 'rare earth' and 'substitution' was carried out, Figure 1. It reveals a doubling of patent applications with these keywords, over the period 2008-2010. Given that the potential supply-side issues for many raw materials has only become apparent over the last few years, it is likely that this trend will intensify.

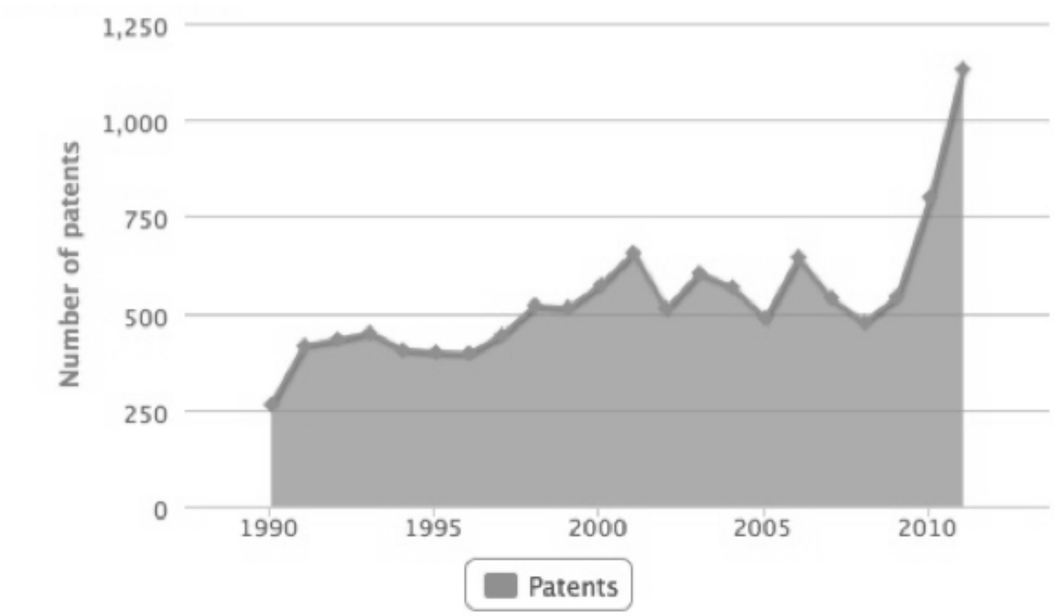

Figure 1 Number of patents containing the words 'rare earth' and 'substitution'

Some of the potential alternatives and substitutes to the most critical materials identified in recent studies are summarised below in Table 2.

Material	Key emerging technology use	Main products affected	Status on substitution
Dysprosium	High strength permanent magnets	Wind turbines, electric vehicles, electronics	No effective substitute yet developed, with research focusing on rare-earth free magnets and alternative motor and generator designs. Dysprosium increases the operation temperature so its use could be avoided for some lower temperature operations.
Neodymium	High strength permanent magnets	Wind turbines, electric vehicles, electronics	No effective substitute yet developed, with research focusing on reduced Neodymium content, rare-earth free magnets and alternative motor and generator designs. Wind turbines could, for example, use electromagnets instead.
Tellurium	CdTe photovoltaics (PV)	Next-generation solar panels	No effective substitute yet developed, although alternative use of silicon may reduce dependence in PV applications. Selenium can replace tellurium in some metallurgical alloying applications.
Gallium	GaAs for semiconductors, CIGS photovoltaics (PV),	Next-generation solar panels, advanced electronics	No effective substitute yet developed
Indium	GaAs for semiconductors, CIGS photovoltaics (PV),	Next-generation solar panels, touchscreen technology	No effective substitute for indium tin oxide (ITO) yet developed, but work focusing on other oxides, carbon, organic and ultrathin metallic alternatives. Current silicon prices may reduce dependence on PV technology using indium
Terbium	Phosphors for fluorescent lamps and LCD backlights	Next-generation solar panels,	No effective substitute yet developed, with research focusing on reducing terbium content.
Europium	Phosphors for fluorescent lamps and LCD backlights	Next-generation solar panels,	No effective substitute yet developed
Yttrium	Phosphors for fluorescent lamps	Next-generation solar panels, high power lasers	No effective substitute yet developed
Germanium	Fibre optics and IR optical technologies	Communications and electronics	No effective substitute yet developed, although silicon and germanium can be used in some applications.
Rhenium	Alloying for gas turbines	Gas turbines	Partially viable substitutes do exist depending on price of metal
Ytterbium	Laser technology	High power lasers	No effective substitute yet developed.

Example: Rare-earth magnets

A full analysis of efforts to substitute for all strategic materials is outside the scope of this report, but it is informative to look at how efforts are evolving to find viable alternatives in one example.

The use of REEs (mainly neodymium, dysprosium and praseodymium) in magnetic alloys confers excellent properties upon the alloy, most notably high resistance to demagnetisation, particularly high temperature resistance (from dysprosium). As a result the use of these properties material use has already become widespread and is growing, placing the REEs high on many organisations' risk-lists.

Significant efforts are underway to find both substitute materials and alternative design solutions. These broadly fall into 3 areas:

- Improving existing performance so that less REE is needed (so-called 'thrifting')
- Finding completely different material types
- Using an alternative technology or design

Turning initially to the first potential solution, reducing REE content, research advances in synthesis and production of these magnets has already led to improvements in magnet strength and other critical properties. The problem is that the basic composition has remained. At the University of Delaware research is focused on using nanostructured rare earth magnets with 30 to 40 percent lower neodymium content. Other efforts in Japan and the US are focused on reducing dysprosium content.

If, as one recent report suggests [16], each Toyota Prius requires an estimated 1kg of neodymium and praseodymium, along with 100-200g of dysprosium, thrifting would appear to be a viable strategy .Similarly, the magnets in large wind turbines can contain up to 150-200kg of neodymium and praseodymium, along with 20-35kg of dysprosium per MW of generating capacity. It is not difficult to see that even small reductions in rare earth content in an effective alloy could lead to substantial material savings.

In terms of finding alternative material types, at Northwestern University researchers, supported by a $3.5m grant from the US dept of Energy are looking to engineer new magnets that do not utilise rare earth elements. The research consortium includes General Motors whose vehicle electrification programme will depend on efficient magnets. The specific aim of this project is to manipulate material structures at the atomic level to develop superior magnetic properties. One potential alternative material currently under review is cobalt carbide, which the team have used to produce the world's fourth most powerful magnet, not relying on rare earth elements. A possible substitution of the rare earth permanent magnets in direct drive wind turbines that has been proposed is to use high temperature ceramic superconductors. One problem with this is that it substitutes one rare earth yttrium, for another - neodymium. Similarly, the reduced operation temperature of wind turbines in comparison to, for example, car batteries, could mitigate the amount of dysprosium required.

Finally, there are design solutions that engineers can pursue to mitigate the threat. Economising on the amount of magnet used is one option, but motor designers have to work harder and be more creative in order to economise on magnet usage. Wind turbines that are already connected to the power grid could use older-style induction generators, although this has a number of disadvantages including a reduction in overall efficiency. 'Engineering out' rare-earth magnets might also involve more time in testing and analysis of a motor design to determine the smallest motor (and hence minimum REE usage) that will fulfil the product requirements. In Japan Daikin Industries has partnered with Osaka University, to create an electric motor that produced high torque from hard ferrite magnets, rather than REEs. The newly designed prototype of this motor reportedly generates 30% more torque than a conventionally designed motor.

Recently the International Copper Association in alliance with the Copper Development Association has demonstrated the strength of the copper rotor motor for electric vehicles (SAE 2012 Powertrain Electric Motors Symposium for Electric and Hybrid Vehicles in Detroit). For some industry participants, the copper rotor induction motor is a strong alternative to the permanent magnet motor for electric vehicle traction when comparing overall cost, performance and reliability.

Does 'thrifting' provide one solution?

What is the likelihood of success in reducing the content of strategic materials in an end-application? Industry might consider the example of platinum use in two specific applications; automotive catalytic convertors and fuel cells. In both applications, platinum or its sister metals offer very advantageous properties. Platinum features on the list of materials in this report largely on its geographically concentrated supply from Russia and South Africa. In both catalytic convertors and fuel cells, industrial end-users have sought to reduce and minimise their use of platinum, due to the high relative price of the metal. How successful have industrial end-users been in this endeavour? For automotive catalysts reductions in platinum group metal loadings have largely been offset by increasingly stringent legislative targets that have necessitated higher PGM content. But in fuel cell catalysts, recently published work, Fig 2 below, shows that manufacturers have been successful in reducing their platinum loadings in line with the targets set by the US dept of Energy in order to help make fuel cell technology financially viable. So, 'thrifting' of a material type can be a viable strategy for reducing material content, whilst maintaining the inherent benefits of the material.

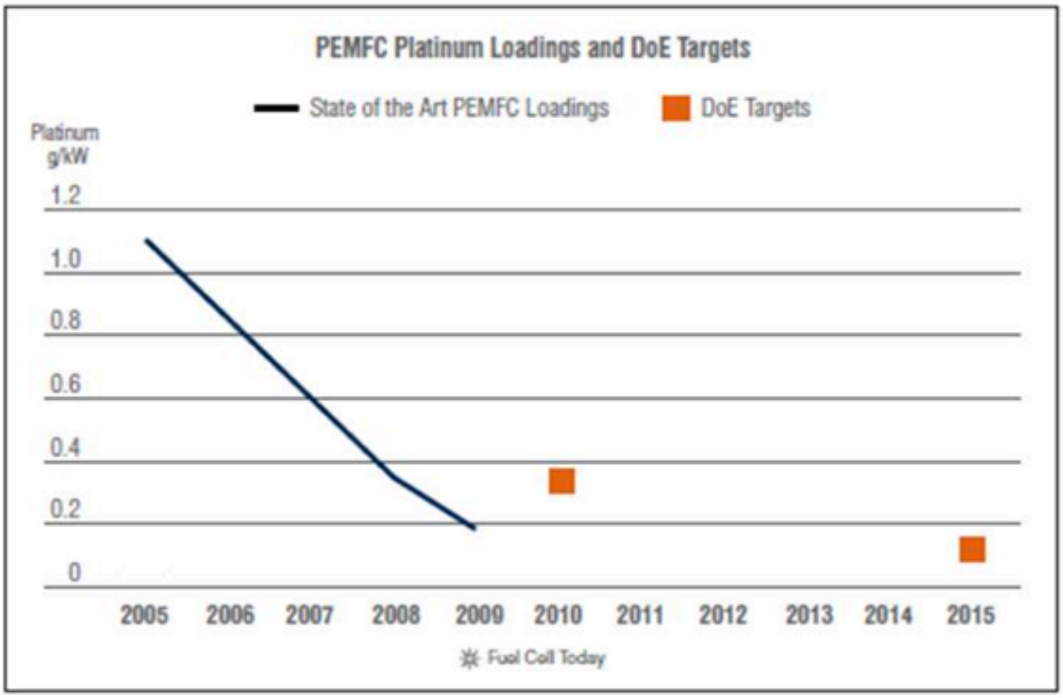

Figure 2 Reduction in platinum loading in state of the art fuel cell (PEM). Source: Fuel Cell Today, The Industry Review 2011

There has also been industrial success in thrifting other critical elements. Concerned about potential supply restrictions, GE recently undertook a program to reduce its usage of rhenium in superalloys used for turbine applications, while still maintaining the properties required for the finished parts. The programme focussed on alloy development and the results included a new alloy, that used less rhenium (1.5%) while providing the properties of other alloys that used significantly more rhenium (3%). The alloy has since been used in production. Interestingly, the research project used computer modelling, which is reported to have enabled the development and introduction of the alloy in two years, compared to the traditional developmental time of four years [17].

New uses ready for take-off?

The substitution of strategic materials is not a one-way street. Whilst there does not appear to be any large, co-ordinated attempt to research and develop new uses for strategic materials, there are some individual efforts by mining companies looking to grow and protect their markets, particularly in the rare earth industry. For example, in 2010, western rare-earth miner Molycorp launched a proprietary rare earth-based (ceria) water treatment technology known as XSORBX™, which is reported to be effective at removing pathogens, heavy metals such as arsenic and mercury, as well as organic toxins such as pesticides. The material is now being sold commercially in the pool, spa and recreational water filtration markets.

Other potential new uses for rare earths may emerge simply due to regulatory changes, For example, the Federal Aviation Administration regulations and restrictions have historically prohibited magnesium alloy for use in internal aircraft applications that would provide significant weight reduction. New magnesium alloys containing yttrium are reported to have now been approved for use in seat backs and may be incorporated into future aircraft seat designs, providing another source of demand for yttrium. Similarly, other emerging technologies that might create new sources of demand for materials already considered to be ‘at-risk’ include the long-term widespread use of so-called miracle material graphene derived from graphite or antimony’s possible use in novel liquid metal battery technology developed at MIT. What is certain is that in the longer-term new uses for critical materials will emerge, above and beyond those already widely reported and analysed.

Increasing Government focus on material substitution

Governments appear to be now focusing financial resources on the research and development of substitutional technologies. In the US, the Dept of Energy's REACT programme (Rare Earth Alternatives in Critical Technologies for Energy) focuses on 14 projects (total funding is $22million) that are developing cost-effective alternatives to rare earths, while encouraging existing technologies to use them more efficiently [18]. The EU has made some initial steps in this area and recently awarded 4 million Euros to a new research project dubbed Freecats, that deals with the development of new catalysts, potentially in the form nanomaterials. The aim is that the new materials will eliminate the use for platinum group metals and rare earth elements used in fuel cell technology, production of light olefins and in wastewater and water purification [19]. The EU's Horizon 2020 programme is likely to focus even more substantial resources in this area and the recently announced EU Innovation Partnership on Raw Materials has set a target of the development of at least substitutes for at least 3 applications of critical materials.

In Japan, METI is helping industries develop technology for magnets that reduce the use of dysprosium, with TDK Corp, Panasonic Corp, and Nissan part of the programme. Finally, in the UK, substitution forms part of the UK's Technology Strategy Board's Resource Efficiency strategy [20] and critical materials have been a topic of recent funding competitions.

Critical minerals are being addressed by governments, for example the US National Strategic and Critical Minerals Production Act of 2012, introduced by Rep. Mark Amodei (NV-01) notes that:

- 25 years ago the United States was dependent on foreign sources for 30 nonfuel mineral materials, 6 of which the United States imported 100 percent of the Nation's requirements, and for another 16 commodities the United States imported more than 60 percent of the Nation's needs;
- By 2011 the United States import dependence for nonfuel mineral materials had more than doubled from 30 to 67 commodities, 19 of which the United States imported 100 percent of the Nation's requirements, and for another 24 commodities, imported more than 50 percent of the Nation's needs.

However the proposed legislation does little to address the fundamental supply issues related to critical minerals, focussing more on permitting more mining and extraction in the US.

A number of countries including the US and Australia appear to moving towards the establishment of expert hubs or centres of excellence focused on strategic materials. These are likely to have concerted efforts on substitutional research. However, in many other countries there is still only a fragmented research effort.

A growing problem with no solution?

Supply constraints of critical minerals have been identified as a limiting factor in a wide range of technologies ranging from consumer electronics to clean energy, but policy responses are still lagging. As with oil, simply extracting more of the minerals guarantees neither the security of supplies nor price stability.

Two strategic approaches are currently being applied; substitution including thrifting and recycling.

The use of platinum is a prime example where thrifting has been a successful strategy for maintaining the inherent benefits accrued from using this material, whilst using nanotechnology and other precise manufacturing techniques to economise on the amount of metal used. This strategy may work well for some other material types.

Recycling presents great problems as many critical minerals are present only in very minute concentrations in electronic scrap. Currently the high volume and efficient processes required to enable recyclers to recover any reasonable amount of materials are non existent, making recycling economically unfeasible.

From reviewing the rapidly increasing volume of literature on the subject of critical materials, it is striking just how little work on the extent of substitution of critical raw materials by alternative materials and technologies has been estimated and incorporated into future demand projections. The recent work of the UK Energy Research Centre is a positive first step in a more rigorous approach to this issue [21].

Addressing the issue

Despite their name, REE are not that rare in the Earth's crust. What has happened in the past decade is that REE exports from China undercut prices elsewhere, leading to the closure of mines such as the Mountain Pass REE mine in California. Once China had acquired a dominant market position, prices began to rise. But this situation will likely ease. The US will probably begin REE production from the Mountain Pass mine later in 2012, and mines in other countries are expected to start operation soon as well.

Nevertheless, owing to their broad range of uses REE will continue to exert pressures on their supply – especially for countries without notable REE deposits. This highlights two aspects of importance for strategic materials: actual rarity and strategic supply issues such as these seen for REE. Although strategic and diplomatic supply issues may have easier solutions, their consideration for manufacturing industries will almost be the same – a shortage of crucial supply lines.

Furthermore, as the example of REE shows, the identification of long-term supply problems can often be difficult, and not every government has the same strategic foresight that the Chinese demonstrated. And as new technologies emerge, new elements may see an unexpected, sudden demand in supply. The vast majority of Apple's revenues comes from products that have been commercialized for less than five years. This means that strategic supply issues could arise suddenly, with little opportunity to address these. The only preparation is to establish procedures to mitigate supply issues.

For example, the combination of improved materials modelling, high throughput screening and nanotechnologies with initiatives such as the Materials Genome is creating increasing opportunities for materials substitution. However there is no body currently collating R&D activity or examining its implications for supply and demand. This is of critical importance where substitution of one material for another is somewhat blindly being pursued, without consideration of potentially creating new bottlenecks in supply for the substitute material.

Neither is the issue being communicated at a policy level. While governments are aware of the issue and some are gearing-up their policy responses, in many countries no concrete proposals have been submitted to alleviate supply issues, other than increased extraction of minerals outside China, and are largely driven by the mining industry.

A common problem with government programs addressing problems such as rare earth elements supply is furthermore that these often come too late – in case of the rare earths almost twenty years after Deng Xiaoping proclaimed their strategic importance for China. Being often set up in reaction to an issue arising, they only have limited effect on pressing industrial supply issues.

Fast developments in new technologies often change the landscape of critical elements. Schemes are only being developed in some countries on a national level (see Annex 1 in ref. [20] for a list of national initiatives). There are, however, no initiatives that provide an early warning system that links fundamental research to industrial applications with unlimited scope across all elements and materials.

Indeed, a more integrated approach is vital to improve both public perception around critical materials, and develop both industrial and policy responses designed to avoid supply constraints hampering economic growth and the shift to renewable sources of energy. Currently, most media coverage on this issue is being driven by the supply side of the industry with fragmented and uncoordinated input from users.

An end-users industry body?

To address many of the issues raised in this white paper we propose the formation of an industry body, nominally entitled the 'Strategic Materials End-Users Association' . This would provide a forum for discussion of the issues that affect industrial end-users of materials of strategic importance, including issues around substitution and alternative materials. This will benefit not just end-users, but also primary and secondary producers of critical materials, for who it is currently only feasible to have sporadic and inconsistent interaction with the diverse range of industries that use their materials.

The aim of the organisation would be

- To monitor the supply side of materials and commodity prices and to identify potential strategic issues, potentially publishing a regular definitive 'rating of criticality' for each element rather like the ratings agencies do for companies financial performance;
- To act as a neutral forum where industry, suppliers and policy makers can examine the issues;
- To help facilitate supply and processing agreements and appropriate integration of the supply chain to enable optimum use of critical materials;
- To collate current R&D efforts on best material use, substitution and recycling, and relate these to current and projected supply side issues;
- To make the case to policy bodies that focussed investment is required in this area in order to drive economic growth and meet clean energy targets;
- To publicise the issue and create engagement with both the general public and industry.

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Material Value

Material Value is a specialist consultancy focusing on the markets, technology and uses of metals and advanced materials. Led by Dr Richard Holliday, services provided range from R&D project management through to market intelligence, business development and communications.

Richard is the former Director of Technology at the World Gold Council and he also recently served as Board Observer at a silicon-valley based nanomaterials venture. A Fellow of the Institute of Materials, Minerals and Mining in London, Richard has extensive experience across the automotive, semiconductor, clean energy, chemical, metallurgical and mining sectors.

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Cientifica is led by Tim Harper who has built a twenty-five year career on identifying, understanding and acting on technology trends, from instigating and managing development projects to investment and eventual commercialisation of micro- and nanotechnologies.

Nature Materials

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Joerg Heber is a Senior Editor of Nature Materials, a journal published by Nature Publishing Group, the publisher of the weekly science magazine Nature and has written extensively on materials resource issues.