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Critical Materials For Sustainable Energy Applications



Resnick Institute Report

September 2011



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+ About the Resnick Institute

The mission of the Resnick Institute is to foster transformational advances in energy science and technology through research, education and communication. The Resnick Institute strives to identify and address the most important outstanding challenges and issues in the generation, storage, transmission, conversion and conservation of energy.

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**Critical Materials For
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+ About This Report

Caltech's Resnick Institute fosters transformational advances in energy science and technology through research, education and communication. Through its activities, the Institute strives to identify and address the most important outstanding challenges and issues in the generation, storage, transmission, conversion and conservation of energy.

To this end, the Institute provides leadership in brokering discussions on energy and sustainability issues among panels of international experts in government, academia, and industry. As part of its outreach, the institute issues summary reports documenting these compelling events.

The Resnick Institute is solely responsible for the content of this report. The views expressed herein do not necessarily reflect the views of participants in these discussions. This report has been independently prepared by the Resnick Institute to support our efforts to communicate critical energy issues to a broad range of stakeholders.

We would like to thank the experts who contributed time and information for their willingness to engage in the candid discussions and debate that informed this report.

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Executive Summary

This report examines the current and future outlook for critical materials used in sustainable energy applications. These are materials that have the capacity to transform the way we capture, transmit, store or conserve energy. Its conclusions are based in part on facilitated discussions among domain experts on how to set a research and development agenda across the supply chain to mitigate the effects of material criticality on achieving a sustainable energy future. Those discussions were, in turn, informed by several recent reports on this issue.

The recent focus on this topic has centered on a number of elements, including silver, platinum, indium, tellurium and of course the rare earth elements. Clean energy technologies currently constitute about 20% of global consumption of these technology metals. As these technologies are deployed more widely in the decades ahead, their share of the global consumption will likely grow rapidly, and the supply of certain critical materials may not be sufficient to meet the increased demand. Examples of the affected sustainable energy technologies include wind, photovoltaics and solar fuel generation, fuel cells, electric and hybrid vehicles, and lighting. However, this report makes clear that there are other materials in addition to these such as lithium or even copper, that will be needed in high demand in order to see the desired disruptive growth in the clean energy sector. Materials criticality is a function of the technology and the market, and all scientists, technology developers, and investors need to understand the high demands for material in energy technologies, and build their R&D agenda or portfolio strategically.

There are a number of key questions explored in this report, but two provide the over-arching framework for the discussion that follows:

- What are techniques or processes that might shift some materials off the critical list?
- What are the best mechanisms for implementing these potential solutions?

In answer to these questions, the report summarizes the consensus reasons for the critical nature of some of these materials, and then attempts

to map out the solution space for increasing supply and reducing demand for materials.

The report highlights materials that demonstrate some of the constraints to expansion of renewable energy technologies. Of these, the heavy rare-earth element dysprosium is perhaps the most critical in the short term, as evidenced by the recent flurry of activity to keep up with demand for magnets in wind turbines and electric motors. However, the increasing demand for silver in photovoltaic panels and the demand for copper to build an energy infrastructure in the developing world are equally noteworthy, and could create similar “critical shortfalls” if not addressed through a balanced approach of increased supply and innovation to reduce demand.

The optimistic news is that for all materials and technologies there are R&D solutions. However, the significant effort required to realize these solutions may limit the deployment of new renewable energy sources in the near to mid-term. The report develops a framework for analysis of materials in the supply chain for a given technology. This framework plots the reduction in criticality as a function of the “technical effort” required to achieve it. When applied, the analysis framework maps R&D options such that multiple layers of data may be considered.

The final section of the report evaluates mechanisms for implementing R&D changes. In addition to expanding or modifying existing efforts by industry, governments and academia, there is room for the establishment of some new programs specifically tailored to address these challenges.

- First and foremost, research and development efforts in basic and applied energy science need to be evaluated from initial conception based on a holistic assessment of materials use. This approach to materials criticality needs to be incorporated into the mindset of all energy researchers from academia and industry, and into the assessment of all research and development programs.
- There is a need for improved basic and applied research into the properties of these critical materials, and how to develop more abundant substitutes. Combinatorial methods and numerical simulations in part-

nership with experiments could help to further this research. The cultivation of public/private partnerships and international collaborations could pay large dividends in translating this work from the university lab into commercial use.

- The creation of a central facility for the development of new processing techniques for extraction/separation of metals, or a network of collaborating universities and labs, could help promote innovative solutions without requiring companies to make substantial, risky capital investments. If new techniques can be demonstrated as cost-effective, they stand a good chance of being implemented. However, without government support, these investments might be deemed too risky to happen at a sufficient level. Such a central facility could also serve to address another major problem: the lack of trained scientists and engineers with the relevant expertise to find innovative solutions to critical materials supply problems.
- The USGS is still considered a leading source of information on global materials. Investment in this work should increase, as comprehensive, reliable and up-to-date information on all aspects of the lifecycle of materials enables researchers, developers and investors to plan for the needs of new technologies.
- A final concern is the need for improved public perception around critical materials. The importance of these materials, how they relate to sustainable energy, and how they can be recycled are a few factors which could be stressed. The public conversation has been dominated by the mining industry, and has led to an air of hype and paranoia. Transitioning towards a more integrated approach to critical materials, as proposed in this report, combined with education and outreach could have a positive impact.

Introduction: An Integrated Approach for Evaluating Critical Materials in Sustainable Energy Applications

Energy is a major challenge of the 21st century. Meeting the world's growing demand for new energy sources in a sustainable way will require the deployment of orders of magnitude more renewable energy systems than are in place currently. The world's energy economy is built upon a base of metals, and the sustainable energy economy is more critically dependent on a wider array of metals than the current one. It is imperative that the materials necessary to implement these potentially game-changing technologies are readily available to the diverse industries engaged in those markets.

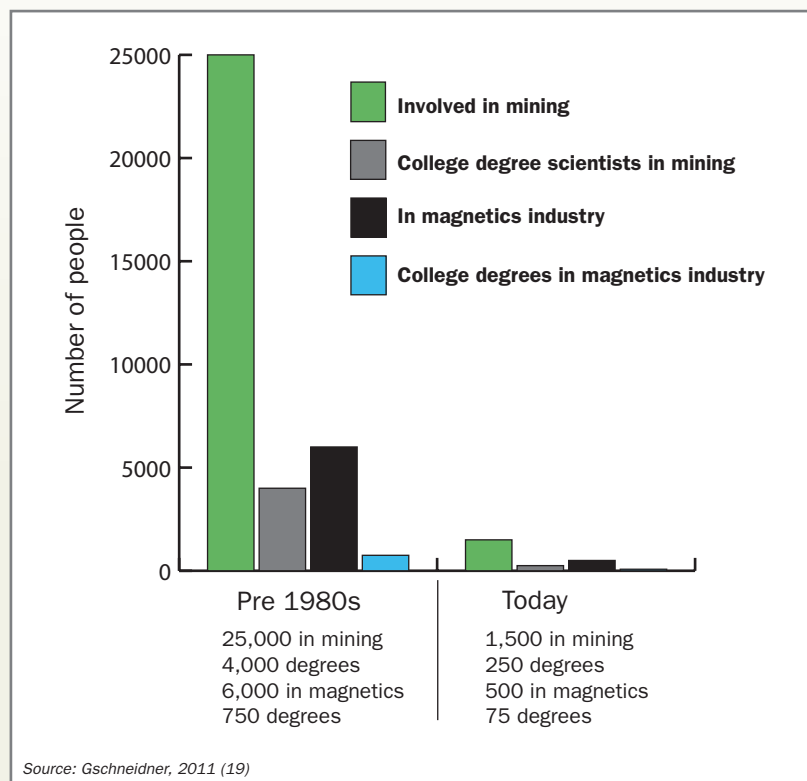
Over the last 2 years, there has been a constant and escalating discussion about the shortfall of so-called critical materials, including indium, lithium, gallium and tellurium, as well as the rare earth elements and precious metals such as platinum and silver. Although current industrial demand for these technology metals is small in terms of tonnage, they are essential in an ever-growing number of high-technology energy applications, ranging from permanent magnets for wind turbines and electric vehicle motors, metal alloys for batteries, to energy-efficient lighting, catalysts and separators for fuel cells, and photovoltaics. These materials are also used for consumer and military electronics in digital cameras, mobile phones, LCD/LED TVs, thermal barrier coatings for gas turbines and aircraft engines, and many other applications.

In addition to these less common metals, expansion of the clean energy sector will be tied to the availability of a number of additional materials, such as magnesium, nickel, molybdenum, cobalt and tungsten. Even the base metal copper, which is of clear importance as our primary conduit for electricity, will face pressure from rapidly increasing demand as China, India and other developing countries develop an energy economy based on renewable technology. Energy is a large-scale investment and material demands are very high. For instance, although only a fraction of a percent of world energy use comes from solar panels, many times more raw silicon (Si) is used for solar than for electronics.

Workforce Woes

As US mining (and manufacturing) moved overseas in the latter part of the last century, there has been a steady decrease in the number of US trained scientists qualified to work in rare earth mining and related industries, as shown in Figure 1: compared to 25,000 employees prior to 1980 (4,000 of them holding science degrees), the mining industry currently employs a mere 1,500 workers, only 250 of which hold college degrees in the sciences. The absence of a trained workforce has led to a slower than desired response in the US to the current global squeeze on rare-earth materials.

Figure 1: Decline in the U.S Rare Earth Industry



Clean energy technologies currently constitute about 20 percent of global consumption of technology metals; that is likely to increase significantly in the future. (1) (2) These considerable increases in demand for certain key elements will rapidly outstrip existing supplies, given the long lead times required to bring new production capability online.

A lack of diversification in supply sources could also put future availability of these elements at risk. For example, the United States relies on other countries for more than 90 percent of most of these elements, and China produces 95 percent of all rare earth elements. (3) China's recent decision to decrease its exports of rare earths has added to the concern over pending shortages and prompted calls for action.

To meet these challenges, it is necessary to adopt a holistic strategy around materials use in the energy sector. Future supply must be considered when evaluating a material for potential use in a new technology. Every technology and every innovation needs periodic materials audits, and focus should be placed on new technologies that are more robust relative to materials shortage issues. Industry leaders are beginning to conduct such reviews internally, and the governments of several countries have established oversight agencies to implement broad policies relating to the issue of materials critical to achieving a sustainable energy future.

Table 1:

Materials Policies In Other Nations Per U.S. DOE				
	Nation	Policy Goal	Oversight Body	Materials of Interest
Producers	Australia	Maintain mining investment while fairly taxing depletion of natural resources.	Department of Resources, Energy and Tourism	Ta, Mo, V, Li, REEs
	Canada	Promote sustainable development of mineral resources, protect environment, public health, and ensure attractive investment climate.	Natural Resource Canada/ Provincial jurisdiction	Al, Ag, Au, Fe, Ni, Cu, Pb, Mo
	China	Balance the domestic and international market, while promoting the healthy development of China's rare earth industry.***	Ministry of Commerce/ State Council/ Ministry of Land and Resources/ Enforcement varies by province	Sb, Sn, W, Fe, Hg, Al, Zn, V, Mo, REEs
Consumers	European Union	Limit impact of supply shortages on the European economy.	European Commission	Sb, Be, Co, Ga, Ge, In, Mg, Nb, REEs, Ta, W, Fluorspar, Graphite, **Pt, Pd, Rh, Ru
	Japan	Secure a stable supply of raw materials for industries.	Ministry of Economy, Trade and Industry/ The Japan Oil, Gas and Metals National Corporation/ The Japan Bank of International Cooperation	Ni, Mn, Co, W, Mo, V. *Li, Be, B, Ti, V, Cr, Mn, Co, Ni, Ga, Ge, Se, Rb, Sr, Zr, Nb, Mo, Pd, In, Sb, Te, Cs, Ba, Hf, Ta, W, Re, Pt, Tl, Bi, REEs
	Korea	Ensure a reliable supply of materials for industries.	Ministry of Knowledge Economy	As, Ti, Co, In, Mo, Mn, Ta, Ga, V, W, Li, REEs
	Netherlands	Reduce material consumption through "managed austerity".	M2i Institute: Collaboration between government, universities, industry, and research organizations	Ag, As, Au, Be, Bi, Cd, Co, Ga, Ge, Hg, In, Li, Mo, Nb, Nd, Ni, Pb, Pd, Pt, Pd, Rh, Ru, REEs, Re, Ru, Sb, Sc, Se, Sn, Sr, Ta, Te, Ti, V, W, Y, Zn, Zr

*Sources: Bauer, 2011 (20), U.S. DOE, 2010 (1), *Watanabe, 2011 (4), **European Commission, 2010 (9), ***Chen, 2011 (17)*

Summary of Recent Work

Several reports have been released in recent years on this issue. In 2008, the National Research Council (NRC) released a report on critical materials entitled *Minerals, Critical Minerals and the U.S. Economy*. (5) That report recommended the US government enhance its data collection, dissemination, and analysis of minerals and mineral products as they relate to essential elements that might be subject to supply restrictions. It also developed the concept of a criticality matrix, which has been adopted by future work for assessing which materials should be deemed critical.

The United States Geological Survey (USGS) continues to produce reports that provide an overview for understanding of current mineral resources, and this data is essential for governments and companies around the world (see for instance, refs (6), (7), (8)). The NRC study and the ones that followed all address the need to increase the scope and detail of these data, which form the backbone for any attempt to categorize the supply risk of mineral resources.

The European Commission on Enterprise and Industry issued a report in July 2010, *Critical Raw Materials for the European Union*. (9) That report made numerous recommendations to secure future access to and material efficiency of critical raw materials. Those recommendations included regular assessments of materials used and supply risks, emphasizing life-cycle analyses, and promoting exploration and research on materials efficiency and substitute materials.

In December 2010, the U.S. Department of Energy (DOE) released a preliminary report, *Critical Materials Strategy*. (1); This report was focused tightly in scope on vehicles, lighting, solar PV and wind turbine technologies. Based on a criticality matrix assessment, the DOE focused on nine critical or near critical elements over the next five-fifteen years (including seven rare earth elements plus tellurium and indium). The DOE report concluded that sound policies and strategic investments can reduce the risk of supply disruptions, especially in the medium and long term. These strategies again included diversifying global supply chains, developing substitute materials, improved data collection, and improving recycling and reuse of critical materials. An updated report should be available by the end of 2011.

In February 2011, the American Physical Society and the Materials Research Society released a joint report entitled, *Energy Critical Elements: Securing Materials for Emerging Technologies*. (2) To deal with the multifaceted issue of availability, the APS/MRS report made several recommendations, again focusing primarily on such areas as information collection and analysis, and research and development into possible substitutes and efficiency gains (including geological deposit modeling, mineral extraction and processing, material characterization and substitution, utilization, manufacturing, recycling and lifecycle analysis). The report cautioned against the government using such direct market interventions as non-defense-related stockpiling.

Table 2:

Critical Materials Literature Review Summary		
Publication	Materials Evaluated	Recommendations
European Commission: <i>Critical Raw Materials for the EU</i>	Sb, Be, Co, Ga, Ge, In, Mg, Nb, Pt, Pd, Rh, Ru, REEs, Ta, W, Flourspar and Graphite.	<ul style="list-style-type: none"> • Update list of critical raw materials every five years. • Improve availability of reliable data. • Conduct more research into life cycle analysis of raw materials and their products. • Create working group to analyze impact of emerging technology on raw materials. • Promote exploration. • Make recycling more efficient. • Promote research on substitute materials.
APS & MRS: <i>Energy Critical Elements: Securing Materials for Emerging Technologies</i>	La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Tb, Lu, Sc, Y, Ru, Rh, Pd, Os, Ir, Pt, Ga, Ge, Se, In, Te, Co, He, Li, Re, Ag	<ul style="list-style-type: none"> • Create subcommittee to oversee energy critical elements and coordinate federal response. • Improve data collection and analysis. • Promote R&D into substitute materials. • Improve post-consumer collection
US DOE: <i>Critical Materials Strategy</i>	Li, Y, Co, Ga, In, Te, La, Ce, Pr, Nd, Sm, Eu, Tb, Dy	<ul style="list-style-type: none"> • Develop sound policy and strategic investments. • Diversify global supply chains. • Develop substitute materials. • Improve recycling, reuse, and efficiency of use. • Improve data to accurately monitor supply and demand.

In addition to these public reports, leading corporations heavily invested in key energy-related industries have begun conducting their own internal studies. Particulars vary, but there is a strong consensus among all these analyses on the broader trends, and that it is time to take action to address likely future shortages of critical materials.

While these reports and studies have been very useful in bringing attention to the subject, they have mostly focused on identifying the problem, and on suggesting broad changes in policy. They all suggest that the US and other governments should gather, analyze and disseminate information on critical elements across the life-cycle. They also agree that it is necessary to fund research and development in new substitute materials for technology applications where appropriate.

Gains in new production and processing improvements (or even some form of stockpiling) can alleviate some issues by providing a larger supply base. However, demand for new energy technologies is expected to increase by orders of magnitude in the coming years in response to growing world energy needs. Therefore finding technology solutions that use orders of magnitude less of any critical materials is likely essential to enable this growth to happen in a sustainable fashion. Research and development efforts, whether funded by public or private sources, need to be assessed based on the materials they use and the supply risk associated with those materials, starting from the basic science and engineering efforts.

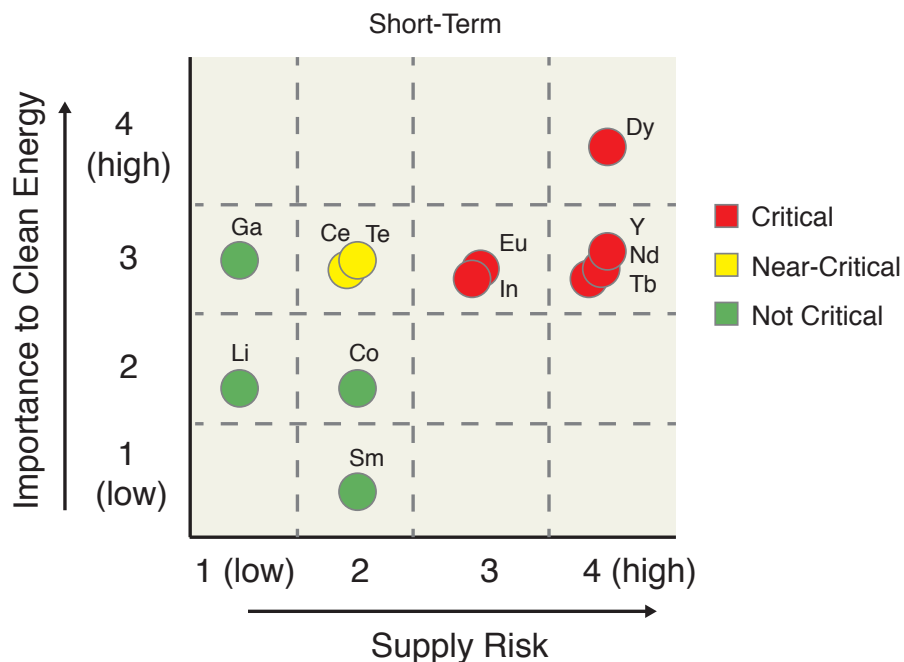
Defining Critical Materials

As discussed above, extensive work over the last several years has attempted to cover which materials should be deemed critical. Determining material criticality is very time dependent and hinges conceptually on the “eye of the beholder.” The fluid nature of the marketplace also intensifies the difficulty in assessing which materials should be deemed critical. The public conversation about critical materials has been dominated by the materials producers and speculators, and this has created an atmosphere of paranoia and hype regarding this issue that is counter-productive to finding viable solutions. This report aims to change the tone of the discussion, emphasizing collaboration and innovation as long-term solutions.

This report will follow the conventions of the previous studies and broadly define a “critical material” in terms of its importance to the clean energy economy and risk of supply disruption. Because every element has its own story, and every application has its own list of essential materials, a broad

interpretation is required. There is strong consensus on guidelines for determining criticality: namely, that the material has one or more properties that appear to be physically essential for the performance of the system, and that there is some uncertainty or risk in the supply of that material. A criticality assessment can be performed for any material or application, both to analyze the importance of the materials for the technology in question, and to analyze the supply risk for the material. Materials can then be rated based on this analysis, as has been done by the NRC, EU and DOE reports discussed above, and plotted in a “criticality matrix” as shown in Figure 2.

Figure 2: Typical Criticality Matrix



Source: Reprinted from DOE, 2010 (1)

Importance

Materials are deemed important or to have a high impact based on the particular properties that make them well suited for applications in which they are used. For photovoltaics, this might be the semiconductor bandgap. For magnetic materials it might be the magnetic flux density. The Table 3 shows some of the elements currently deemed critical for major clean energy applications.

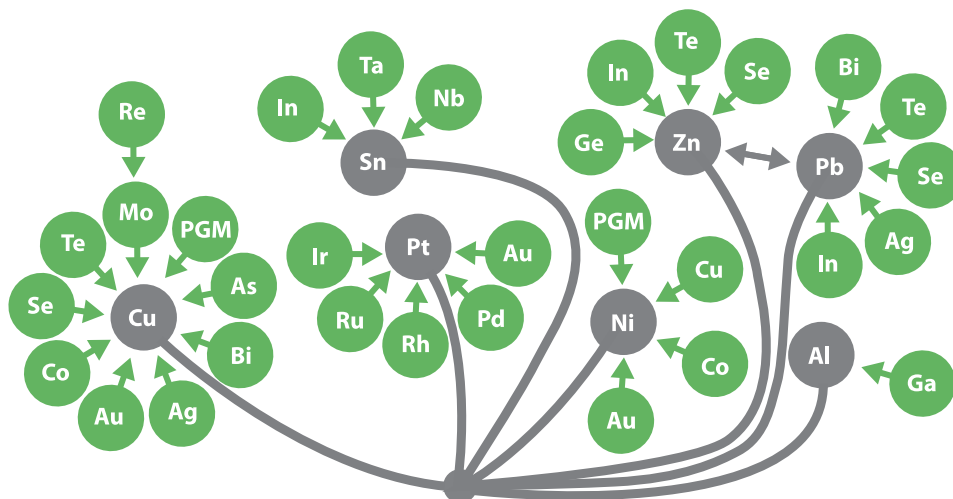
Table 3:

Critical Materials Found in Clean Technologies		
Technology	Component	Material
Wind	Generators	Neodymium
		Dysprosium
Vehicles	Motors	Neodymium
		Dysprosium
	Li-ion Batteries (PHEVs and EVs)	Lithium
		Cobalt
	NiMH Batteries (HEVs)	Rare Earths: Cerium, Lanthanum, Neodymium, Praseodymium
		Cobalt
PV Cells	Thin Film PV Panels General*	Tellurium
		Gallium
		Germanium
		Indium
		Selenium
		Silver
		Cadmium**
	CIGS Thin Films	Indium
		Gallium
	CdTe Thin Films	Tellurium
Lighting (Solid State and Fluorescent)	Phosphors	Rare Earths: Yttrium, Cerium, Lanthanum, Europium, Terbium
Fuel Cells*	Catalysts and Separators	Platinum, Palladium and other Platinum Group Metals, Yttrium
Sources: Table data extracted from Bauer, 2011 (20) and expanded upon with data from other sources per asterisks. *APS/MRS, 2011 (2). **Lifton, 2011 (10)		

Supply Risk

Some of the materials are simply rare in their overall abundance in the earth's crust, or do not commonly occur in single deposits with significant concentrations. Others are difficult to recover economically. An additional challenge arises from the fact that so many technology metals are byproducts of primary production metals such as copper, lead, and zinc (see Figure 3). Even if the process can be made more efficient, it is a risky capital investment to capture the byproduct stream, and the decision to do so will be based on economics. This is complicated by two factors. First, the technology metal is usually produced in such small quantities compared to the base metal that even astronomically high prices for the byproduct will not provide a strong financial incentive for producers. Second, the technology metals generally come with a larger uncertainty in demand and also in price. For example, while the copper market has traditionally been stable and fairly predictable (the rules of the copper market are currently changing, see sidebar), it has been much harder to predict what the long-term demand and pricing of tellurium will be, so investing in facilities to produce more tellurium was a riskier proposition for a producer.

Figure 3: Technology Metals Produced as Byproducts of Base Metals



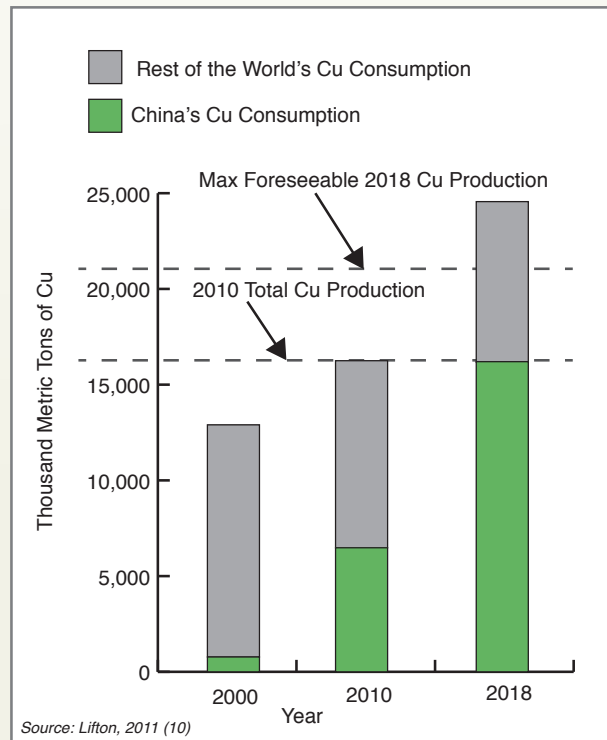
Source: Hagelucken and Meskers, 2010 (21)

The Copper Crunch

One need only look to the growth in demand for copper (Cu) for an example of the importance of long-term thinking when it comes to materials strategy. China now uses 40% of the world's Cu, compared to just 6% in 2000, an astounding increase over 10 years. If their current growth demand continues, they will require the equivalent of the worldwide 2010 Cu production by 2018. While ample resources exist, it may not be possible to increase Cu production to meet the worldwide demand (see Figure 4). This discrepancy could hamper the expansion of renewable energy activities throughout the world, as well as limit the growth of China's economy.

The increased volatility in the supply of copper will also likely lead to an even more jumbled picture for several technology metals that are co-produced with it, including tellurium, selenium, and rhenium. These materials are already deemed critical due to the unstable nature of this coproduction, which could be even more unstable if Cu production is squeezed.

Figure 4: Consumption of the World's Mine Production of Copper



It is worth exploring possible ways to build flexibility into these primary production chains, so that as demand for rarer byproducts change, it is easier to adapt the processes to extract different materials, depending on changing market conditions. This could be a useful role for governments, by offsetting capital risks through tax breaks or subsidies, or even through the establishment of a central research facility devoted to investigating issues relating to critical materials for clean energy technologies.

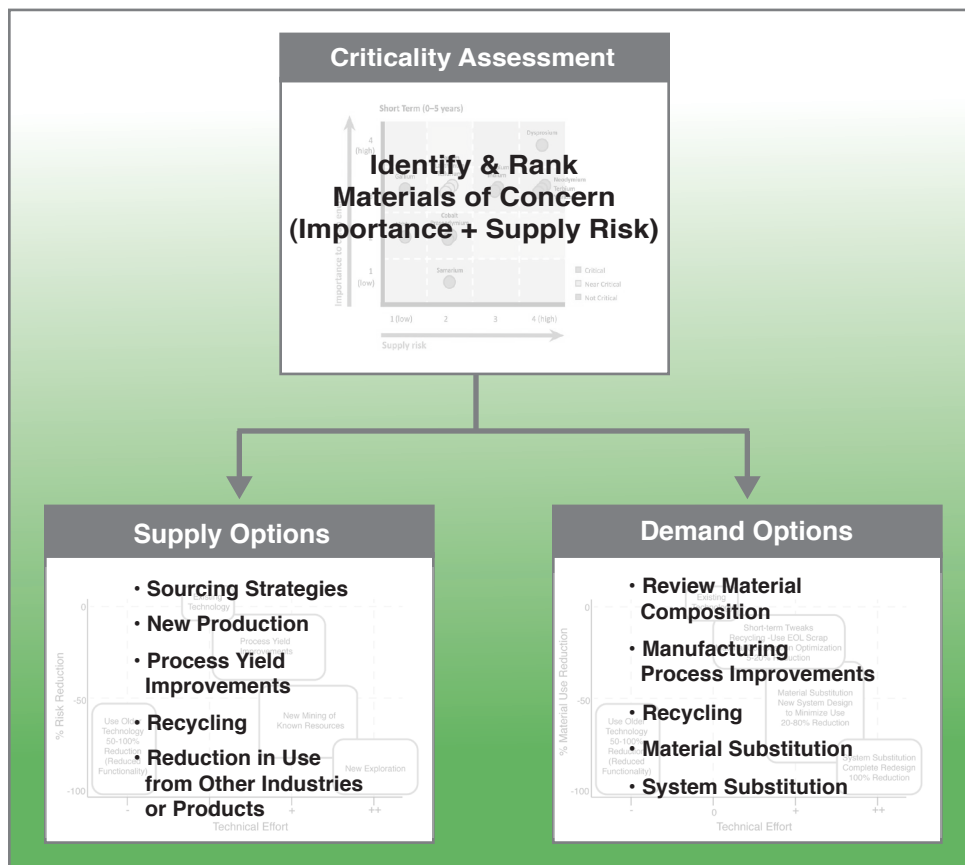
Environmental concerns may further complicate the supply issue. It is not a simple matter to boost supply or production. Not only does this require significant capital investment, but, mining and extraction can have adverse environmental impacts, and these added costs must also be taken into consideration.

China provides a cautionary example in this respect. At just one mining operation in Baotou, some 40 factories are involved in a complex process to pre-treat, separate, purify and process rare earths. But this process also produces a great deal of pollutants in the form of wastewater, waste gas and waste residue. In February 2011, the Chinese Ministry of Environmental Protection established stringent new emission standards for pollutants for the rare earth industry. When issued, none of the existing factories could meet these new standards, which could limit or halt their production of rare earths in the near term. China now has a strong focus on improving technologies used in extraction and processing, driven by environmental concerns, even though the country has abundant and diverse resources of many critical materials for renewable energy technologies.

R&D Strategy for Approaching Materials Issues

The criticality matrix assessment described above has been well documented by previous reports, and a thorough reading of those assessments is encouraged. The matrix can demonstrate the problem space quite clearly. However, to address critical materials problems, we also need to map out the solution space. It is important to evaluate each industry, dominating technology, and element individually, since there is no one-size-fits-all solution; the optimal combination of strategies for one element or technology will not be identical to what is required for another element or technology. The most effective solutions might not be more short-term approaches like stockpiling; they more likely lie in investing in technological development to achieve significant reductions in the use of critical materials.

Figure 5: Materials Criticality Solutions Assessment

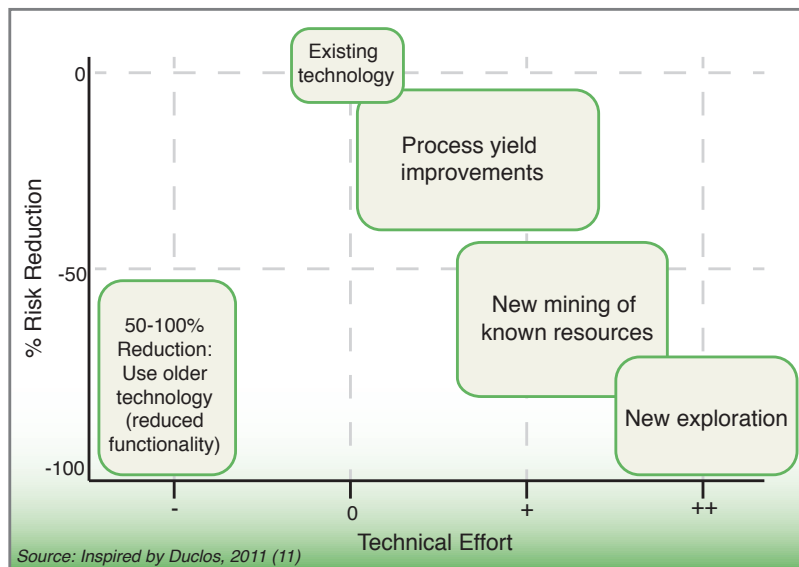


Because critical materials are defined based on a combination of impact in their application (demand) and risk of availability (supply), solutions can be found by addressing either or both of these factors. Supply option solutions include developing new sourcing strategies, end of life recycling, and increasing production of the material (through either new mining operations or processing yield improvements). Demand option solutions include materials and manufacturing optimization, material substitution and system substitution. In both cases, these different solutions will come with some expected benefit in material criticality (by either increasing supply or decreasing demand), and also some cost (time, money, or perhaps new technology development effort). It is therefore worthwhile to create new matrices to evaluate these options.

Supply-side Improvements

Strategic approaches to finding more material, improving process yields, and reducing waste are essential components in a multi-faceted approach to addressing the supply risk aspect of material criticality. Supply improvements may require incentives to hedge financial risk and improve cost effectiveness. Investigation of strategies, processes and economic concerns are first steps in the discussion of supply side R&D.

Figure 6: Option Space for Supply Side Criticality Reduction

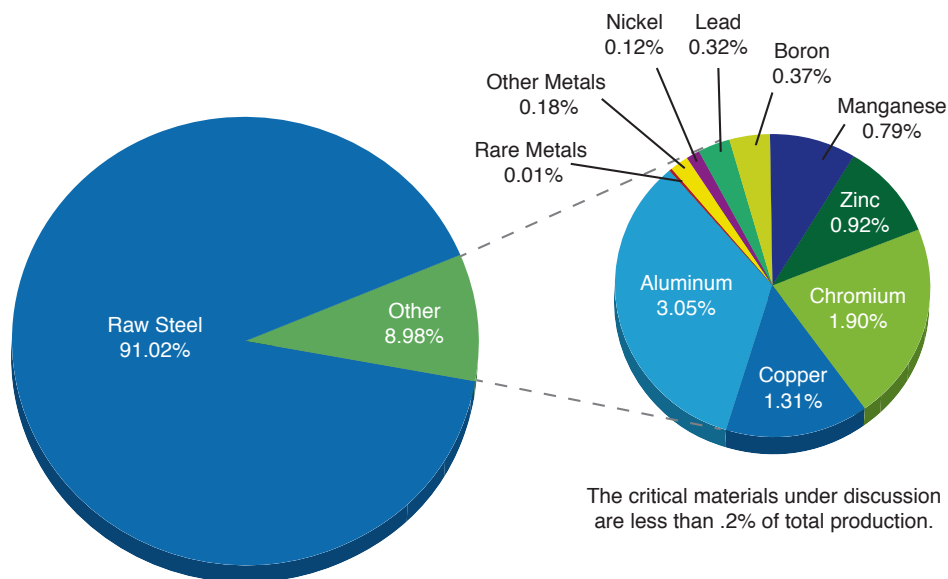


Sourcing Strategies

It may be possible to alleviate some supply issues simply by re-evaluating the supply chain. Sourcing strategies include diversification, hedging, strategic inventory reserves (stockpiling), and buying materials in volume. However, for most materials, this will not provide a long term solution to a critical material in an exponentially growing technology. Corporations with major investment in energy technologies may choose to engage in some stockpiling of critical materials to ensure a stable supply, as part of a broader strategy. In general, however, government stockpiling of these materials is a short-term, stop-gap measure, and one that will likely be insufficient to address the issue of critical materials in the longer term (As a special case, the APS report argues that helium should be stockpiled, since it cannot be recovered later).

Discover and Develop New Deposits

Figure 7: Breakdown of Metal Production in 2009



Source: Lifton, 2011 (10): US Geological Survey, Technology Metals Research

Around the world, government and industry are engaged in exploration to identify new deposits of critical elements to diversify sources of these materials. However, it is not sufficient, or sustainable, to merely increase production; the supply of critical materials, especially metals, is not infinite. Even when new deposits are located, it is very costly to extract these materials and increase production to meet constantly rising demand. Domestic production (mining and refining) of critical materials is in some sense equivalent to stockpiling or (virtual) hedging, and could be incentivized in the same way.

Instability exists in the marketplace because most of these materials are primarily produced as byproducts from mining other metals: indium is recovered during the processing of zinc ores, for example, while most tellurium is recovered by processing copper ores. For most co-produced metals, an increase in demand will not provide a strong enough economic incentive to increase the production of the base metal they are extracted with. An exception for this might be the rare earths. Approximately half of the mass of rare earths currently mined consists of the element cerium (Ce); but current demand for cerium is weak. Boosting demand for cerium would make it more cost effective to recover more rare earths. Potential demand drivers for Ce include UV absorbing glass for windshields, polishing of display glass for LCDs, three-way automotive exhaust emission control catalysts, ceramics, electrolytes and separators for solid oxide fuel cells, red pigment (cerium sulfide), and bioceramic materials such as teeth and bone implants.

Improve Process Yields

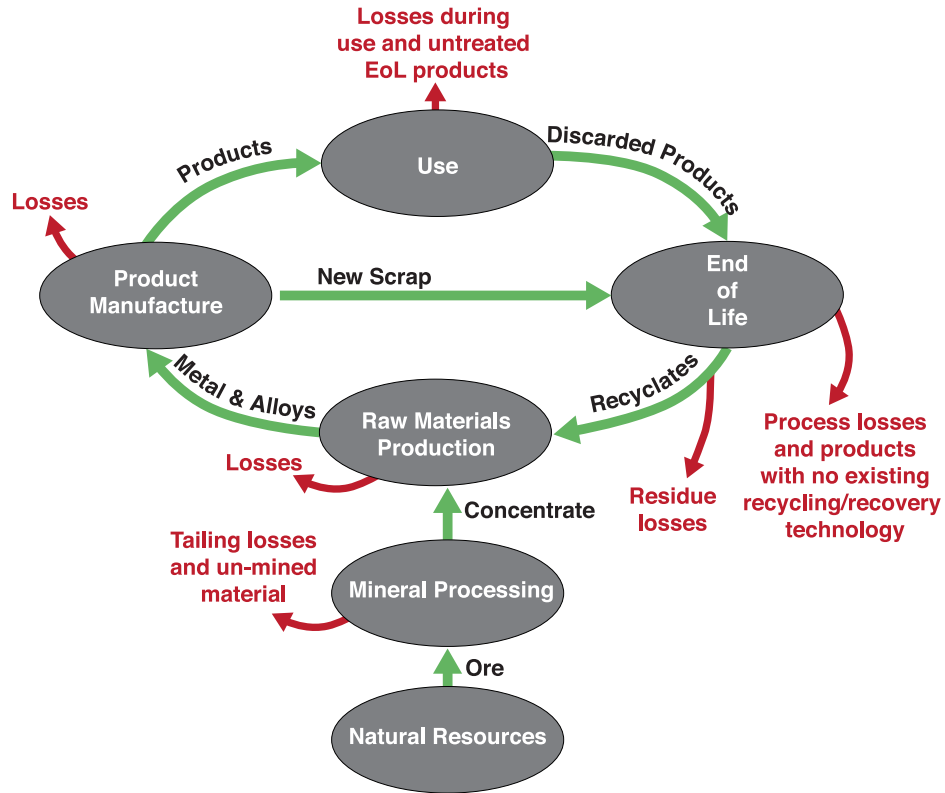
Another supply-side improvement strategy is to analyze the extraction and manufacturing processes, breaking them down into component steps to identify troublesome bottlenecks and improve efficiencies, thereby increasing yields. In a multistep extraction and purification process, improving four steps by 20% each will double the production. The biggest difficulty in improving process yield is the variability from material to material and even from ore-body to ore-body in composition, and therefore in refining steps. This is an example where the lack of a scientific workforce has slowed improvements. In some cases techniques could be borrowed from other industries, provided there was support to test these ideas without exposing producers to excessive risk to develop the technology.

A central lab for materials processing (perhaps a DOE national user facility) arguably would be a good use of federal dollars, although the scale of such a facility is yet to be determined. The scope of work for this facility would be large, as all materials require different techniques and chemistries. Even different ores of the same type may need tweaking of the process to optimize production. The biggest gains will be realized by identifying and improving upon the critical “pinch points” in the production flow. Currently China is working intensively on improving these processes for REEs, funding a national lab employing hundreds of researchers. Even so, many young scientists are reluctant to focus on these areas because they are not considered “hot topics” by the most prestigious research journals.

Reduce Waste/End of Life Recycling

Reduction of waste, improving manufacturing efficiency, and recycling of end-of-life products can have a significant impact on increasing the supply of critical materials. Japan is a major consumer of technology metals, particularly for electronics, hybrid car catalysts, magnets, rechargeable batteries and cemented carbide tools. Recycling is a major focus, due to Japan’s geological constraints. For example, since Japan consumes more than 50% of indium worldwide, it has invested heavily in increasing recycling rates for indium from scrap. Japan produced 218 tons of indium in 2002 and recycled 158 tons. By 2008 Japan was producing 740 tons of indium and recycling 680 tons. Japan hopes to reduce its consumption of new indium by 50% by 2013. (4) In addition to Japan, Europe has a strong recycling effort, and the US is ramping up its own recycling programs. While recycling of scrap production or process byproducts can have a 10% or greater improvement on material production, it requires capital investment and might not be cost effective. The complexity added by trying to recapture and re-separate the critical materials from finished goods adds to the challenge of compliance faced by end-of-life recycling programs.

Figure 8: Production Lifecycle with Losses



Adapted From Hageluken and Meskers, 2010 & Meskers 2008 per UNEP, 2011 (12).

Recycling efforts, especially end-of-life ones, have often faced difficulties with compliance even when mandated by the government. Japan loses money but recycles anyway, thanks to the Japanese concept of *mottainai*—“a strong sense of regret concerning waste.” There is a high economic incentive to recycle technology metals, but new business models are needed to encourage this practice, particularly in the consumer market sector. Many industrial applications feature “closed loop” lifecycles, with minimal losses and high recycling yields. This is in sharp contrast to consumer applications, which tend to have “open loop” lifecycles: once consumer products are sold into the marketplace, producers lose track of those items, leading to much lower recycling yields. Establishing new business models tailored to specific product segments would help the consumer market encourage recycling. For example, establishing a deposit system for old cell phones when users

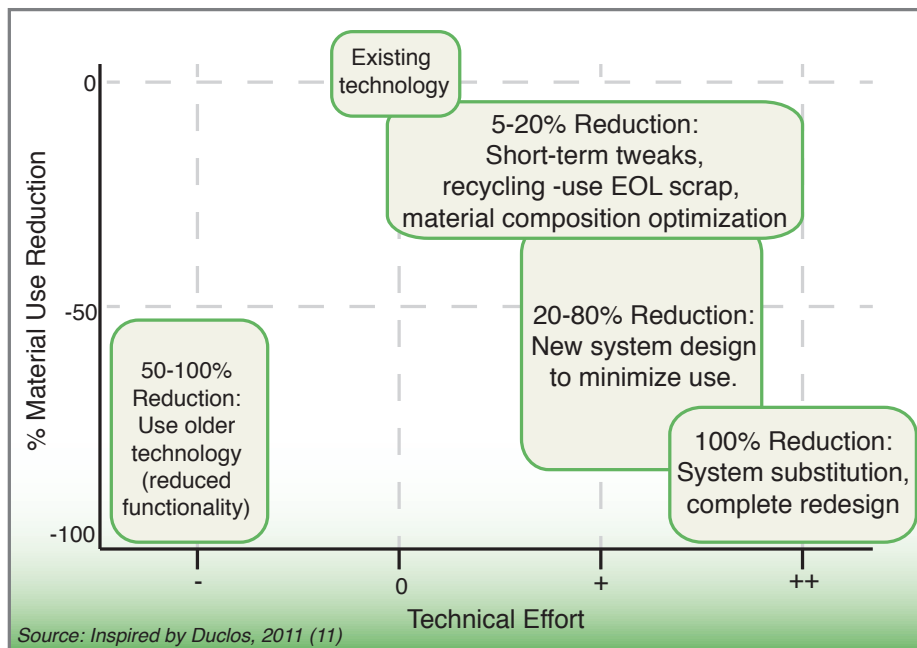
upgrade to newer models would make it easier to recapture those products and recycle the technology metals used in their manufacture.

The recent UNEP report on recycling rates for metals highlights the potential upside here. Of the 37 “specialty metals” considered in the report, only four have a recycling rate higher than 1%. (12) It is important to acknowledge, however, that it is not possible to satisfy an exponentially growing market, such as that for sustainable energy products, through recycling alone.

Demand Side Improvements

As demand for clean energy products grows over the next decade, the development of new technology that is less dependent on critical materials can have arguably the biggest impact on the marketplace. The greatest reduction in demand for critical materials is likely to come from investing heavily in R&D: designing products and materials for ease of recycling and reuse; designing new materials to minimize the use of at-risk elements; finding alternative material substitutions; and substituting entire systems where appropriate to reduce or eliminate reliance on critical materials.

Figure 9: Option Space for Demand Side Criticality Reduction



This is often easier said than done. By definition, these elements provide certain key benefits to the technology that are not easy to replace. In some cases, it is simply not possible to achieve significant reductions in use of critical materials. It also needs to be emphasized that this is a systems level problem and any changes to a material or process should be evaluated on the basis of the full system performance. In general, the more options that are available at the system level, the better. Designing systems that can be flexible and incorporate different materials solutions is a key means of safeguarding against fluctuating supply.

Improvements in manufacturing, waste reduction, and scrap recycling could produce savings of between 5% and 20% of critical materials usage. A similar level of savings might come from a detailed optimization of the material or component used. For example, it is possible to optimize the surface texture of a solar cell so that less material is needed to get the same level of absorption. Similarly, replacing platinum (Pt) nanoparticles in fuel cells or catalytic converters with other nanoparticles coated in Pt could significantly reduce Pt use in those applications.

Substituting less rare and costly materials in products could save from 20% up to 80% in critical materials usage. Computational methods and combinatorial screening techniques would be very useful in identifying replacement materials. In the case of catalysts, for example, calculations and initial measurements have shown that Ni-Mo hybrid materials might prove useful as a substitute for Pt catalysts for cars and other technologies.

Finally, a full-scale system substitution could reach 80%–100% reduction in some cases of critical materials usage. Consider the case of phosphors used in lighting applications. Light Emitting Diodes (LEDs) use much less phosphor than fluorescent lights, so focusing on improving efficiency and cost of LEDs will result in significant reduction in phosphor use—as much as a 90% reduction. As another example, we are undergoing a shift from Nickel-metal-hydride (NiMH) batteries to lithium (Li) batteries in hybrid and all-electric vehicles. This will reduce rare earth use, while increasing Li use. Of course, as EVs are expected to gain a significant market share, lithium is also considered a critical material, but with different challenges that need to be assessed. In some cases, these substitutions come at a loss

of functionality. There is still a big market in China for lead acid batteries, most notably for use in mining and construction sectors, because they are cheaper, even though they need to be recharged more frequently. With lead acid batteries, energy and power density are the tradeoffs for lower cost.

For nearly all materials, R&D directions can be identified that either reduce or eliminate the material constraint. Two specific case studies—solar/photovoltaics and permanent magnets—are outlined in detail below.

Case Study: Solar/Photovoltaics

The materials of concern for this sector are gallium (Ga), indium (In), silver (Ag), germanium (Ge), selenium (Se), tellurium (Te), and ruthenium (Ru). Here are the most common solar technologies and the critical materials used by each:

- Crystalline Si (Ag in contacts)
- Thin film: amorphous Si (Ge, Ag, and In in contacts)
- Thin film: cadmium telluride (Te, In, in contacts)
- Thin film: copper indium gallium diselenide or CIGS (In, Ga, Se)
- Multijunction III-V solar cells for concentrators/space (In, Ga, Ge Ag in contacts)
- Organic solar cells (Ru)

Currently by far the dominant technology is crystalline Si, which accounts for over 80% of the market. Thin film solar has grown steadily, and is forecast to account for 30% or more of the solar market by 2013. (13) The growth in thin film over the last several years has been fueled by installations of cadmium telluride (CdTe) modules from module manufacturer First Solar, although a number of CIGS module manufacturers are starting to ramp up to large scale production as well. The thin film solutions have generally provided cheaper modules, but at a lower efficiency.

Materials Reduction/Efficiency Strategies

Through improved manufacturing techniques and system design it seems possible to reduce further the thickness of the active layer of certain types of non-Si solar cells. For example, it should be possible to reduce the criti-

Spotlight on Silver

While crystalline Si dominates the solar market, silver (Ag), which is the material of choice for electrical contacts on the solar cells, is a material in the spotlight. The amount of Ag mined in 2010 was 23,000 metric tons, although overall Ag production (mined, recycled and sold from stockpiles) totaled 32,700 tons. A typical Si solar panel requires about 20 grams of Ag. Approximately 900 tons (or 4% of mined Ag) went into PV fabrication in 2009. However, that percentage more than doubled in 2010, when 1,984 tons, or 8.6% of the mined supply, went into PV fabrication. The price of Ag has skyrocketed in 2011, already adding as much as 6 cents/W to the cost of a panel, almost 5% of the total panel price. (22)

How might growth in the PV market impact the supply and demand balance for Ag? Current forecasts for future PV installations vary wildly for the next 5-10 years. The European PV industry association predicts the worldwide market could be 43 GW/year in 2015, roughly three times the 2010 market, at which point Ag use in PV will account for 25% of 2010 production. However, if the goals for renewable energy insertion into the grid are to be met in any degree by solar panels, the Ag content will be a major issue. To supply only 1% of 2010 world energy use from PV, we would need to deploy at least 800 GW of solar panels. Even if silver use per panel was cut in half, this would require twice the Ag mined in 2010. To supply 10% of the 2010 world energy use using solar would require nearly 100% of the worldwide Ag reserves, as estimated by the USGS in the 2011 commodity report. (14)

cal material used in CdTe systems by as much as two to four times using improved light trapping. For III-V cells, there is not much room for further reduction, as most III-V cells are used for concentrated PV and the materials use is already 500 to 1000 times less than for flat panel solar technology.

Improved recycling of production scrap materials in thin film systems (CdTe and CIGS) might save 10% of the material currently used. In general, the use of non-standard manufacturing and supply lines make it more challenging to standardize the technology and required certifications across the industry. However, if this could be achieved, it could further reduce the amount of critical materials required.

In the longer term, new work on meta-materials and advanced optical techniques could allow the reduction of semiconductor material by as much as 10–20x.

Materials Substitution

Ag is used in Si solar panels, most notably as a contact material. To date, no one has found a truly viable replacement for Ag back contacts; all the alternatives tested so far substantially reduce performance. Although technically challenging, the semiconductor industry has switched to Cu contacts, after the development of diffusion barriers using nitrides or tantalum, and a similar solution might also apply here. In addition, there might be the opportunity through smart use of alloys or buried/back contacts for Si panels to reduce Ag use by 10-20%, and perhaps as much as 50%.

It might be possible to completely replace the indium in the transparent conductive oxides (TCOs) with fluorine or cadmium (Cd). This is done to some extent in CdTe modules, although there is a small decrease in performance. Alternatively, it might be possible to replace the TCO altogether with carbon nanotubes (CNTs) or graphene embedded in polymers. CNT and graphene contacts have been under development for some time, and have not yet reached commercial viability.

Various semiconductors can be used for the active layers of thin film PV systems. Copper-Zinc-Tin-Sulfide/Selenide (CZTSS) has been demonstrated as an alternative to CIGS for solar cells. IBM researchers announced a breakthrough

9.6% efficiency solar cell in early 2010 using this new CZTSS material. (15) In addition, iron sulfide (FeS₂), copper oxide (Cu₂O), zinc phosphide (Zn₃P₂), and many other materials with appropriate bandgaps could be investigated as good materials for use in new devices. Some work has been done on materials R&D in the past, but there are many materials that haven't been explored. Recently, researchers at UC Berkeley compiled and analyzed a large list of potential active materials for solar cells. (16) Note that only CZTSS has been demonstrated to be a working solar cell at this point.

System Substitution

Focusing on Si and amorphous Si alleviates some materials use, although both still use Ag, and the latter system still requires the use of Ge in the bottom junction. It is possible that by focusing on high-concentration tracking PV instead of a flat panel approach, one can lower the use of active materials by 500 to 1000 times, along with an increase in the system complexity. It might also be possible to replace PV with solar thermal systems.

The same solar panel can generate 30-40% more energy in the desert in Arizona than in New Jersey, which translates into a materials savings as well. However, there would need to be significant investment in low-loss long distance transmission lines to take advantage of this savings, which has been difficult to do as well. Alternately, some investment in grid scale energy storage could have a similar effect.

Figure 10: Option Space for Material Reduction in PV Active Layers

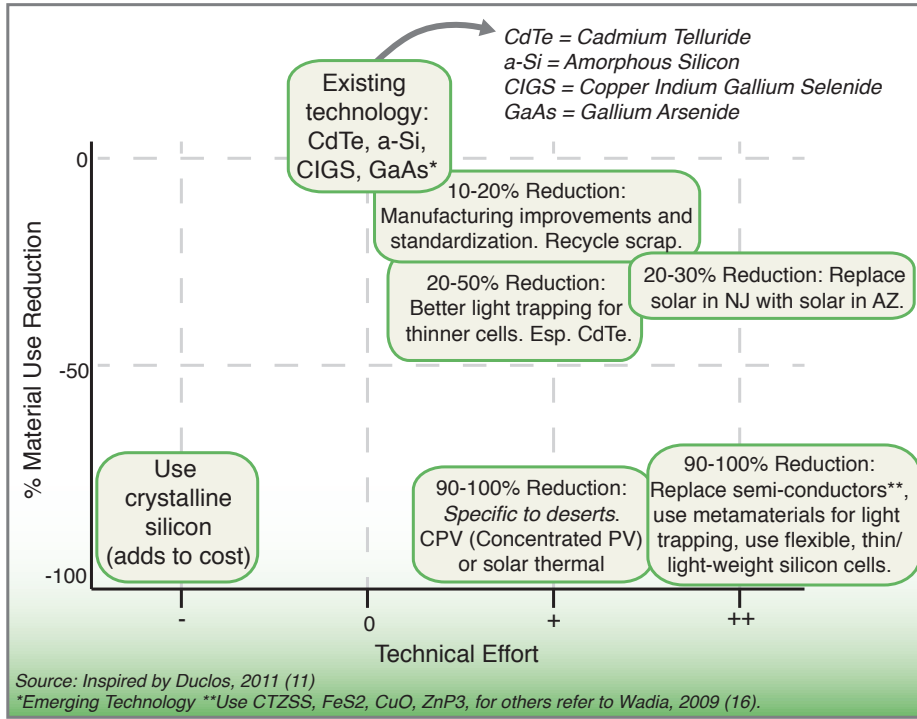
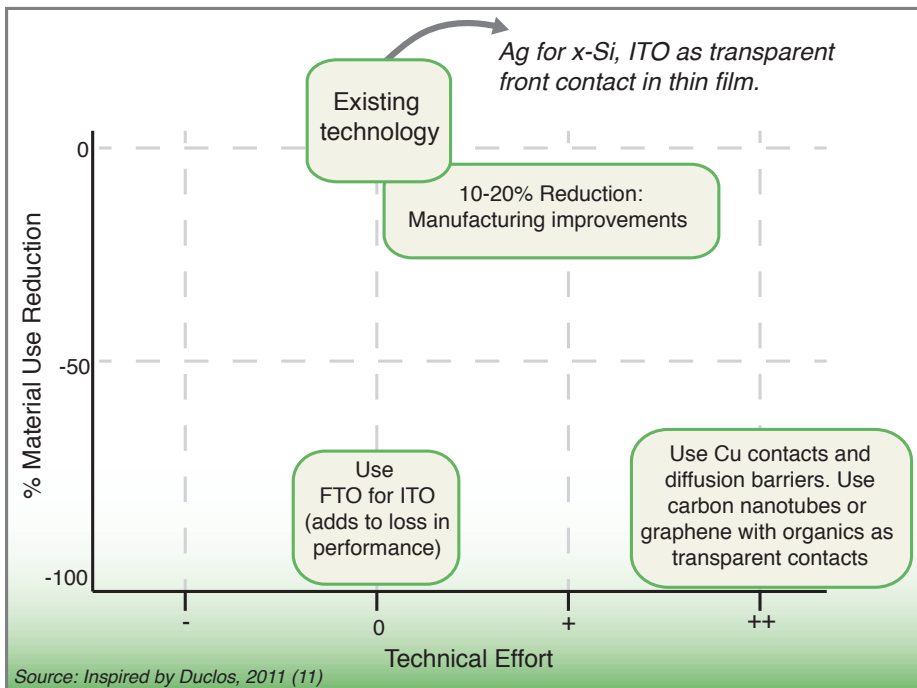


Figure 11: Option Space for Material Reduction in PV Contacts



Case Study: Permanent Magnets

The primary materials of interest for the permanent magnet sector are dysprosium (Dy), neodymium (Nd), and praseodymium (Pr), used in rare-earth permanent magnets (REPMs). Their most important end use is in the production of electrical machines such as motors (used to convert electricity into mechanical motion, for example in electric vehicles) and generators (used to convert mechanical motion into electricity, as in wind turbines). In Asia, REPMs are also used in electric motorcycles. The key issues are cost, power density, and weight; for example, an induction motor is generally cheaper, but also bigger and heavier than one using a REPM, and the power density is generally not as high. These concerns are driving the automotive industry to demand REPMs for the electric motors in hybrid and all-electric vehicles. These cars currently only account for 1% of vehicles on the market, but this could increase to 2%-5% by 2015, and to 10%-25% by 2020, as China and other growing economies provide incentives for EVs.

Materials Reduction/Efficiency Strategies

It is possible to reduce the grain size of REPM alloys, keeping the essential properties of residual flux density and coercive force while using less Dy. There are several new technologies in development for better characterization of materials, particularly grain boundaries at the atomic level, but as yet, no actual breakthroughs have been made in terms of composition.

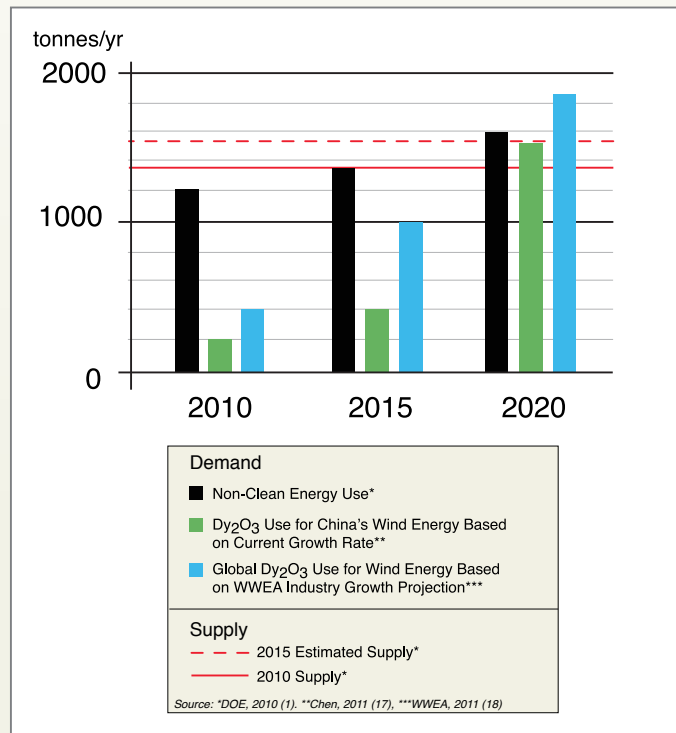
Another approach might be to lower the operating temperature of the assembly, by improving the cooling system. There could be useful insights to be gleaned from the electronics industry. For example, one Hong Kong company is developing new cooling techniques for electronics incorporating vapor chambers to carry excess heat away. If this could be applied in vehicle motors, heat could be removed at twice the efficiency of solid Cu, with significantly reduced amounts of Dy required.

There can be a fair amount of waste in the pressing of magnets, even though much of that waste material ultimately gets recycled. Currently customers provide suppliers with their specifications for magnet size and shape, and this is frequently cut from a large bulk material block. Designing products with simplified shapes whenever possible might be a good approach.

The Dysprosium Dilemma

The wind turbine industry is expected to increase demand for Dy and Nd in particular in the near future, because China and the rest of the world are investing heavily in wind turbine installations. In 2009 China accounted for 26 GW and 16.2% of global capacity produced by wind turbines; one year later that had increased to 41.8 GW and 20.9% of global capacity, a 60% growth rate. (17) This growth is expected to continue, resulting in a corresponding increased demand for magnets based on the neodymium-iron-boron (Nd-Fe-B) alloy system. Such systems require approximately one ton of Nd-Fe-B per 1.5 MW of generation, Dy is included at around 3% by weight to improve the performance of the magnets at high temperatures and to resist demagnetization. If Chinese wind installations continue to grow as they have over the last 5 years, by 2020 the Chinese wind installations alone will use nearly 100% of the estimated 2020 supply of Dy. The World Wind Energy Association predicts that total installed wind capacity could increase six-fold by 2020. (18) Under this scenario, demand for Dy could more than double in the next 10 years, vastly outpacing current production or even known resources. (1) (17)

Figure 12: Dysprosium Oxide Future Supply and Demand



More than 80% of REEs could be recycled, between better handling of manufacturing waste and recycling end of life products, such as the REPMs used in electric bicycles. Today all lead-acid car batteries must be returned to recycling centers to remove the lead, and it could be possible to use those same centers to recover other critical materials for recycling, including magnets from EV motors. The difficulty is the small size of some of these components, which makes it costly and time-consuming to recover them. Changes in product design, with an eye toward end-of-life recycling of energy critical components, might help address this issue. Products could be designed from the outset for easy removal of REPMs, NiMH batteries, and Cu, for example.

Materials Substitution

Certain iron oxide producers are investigating the possibility decreasing the particle size of iron nitride as a substitute for REPMs, although this is unlikely to be commercialized before 2025. Similarly, new research in exchange spring magnets, which incorporate both a hard and soft magnetic phase, have shown promise in reaching high energy product while using less of the critical materials. Both of these ideas are still in early research stages, but could have an impact in the medium term.

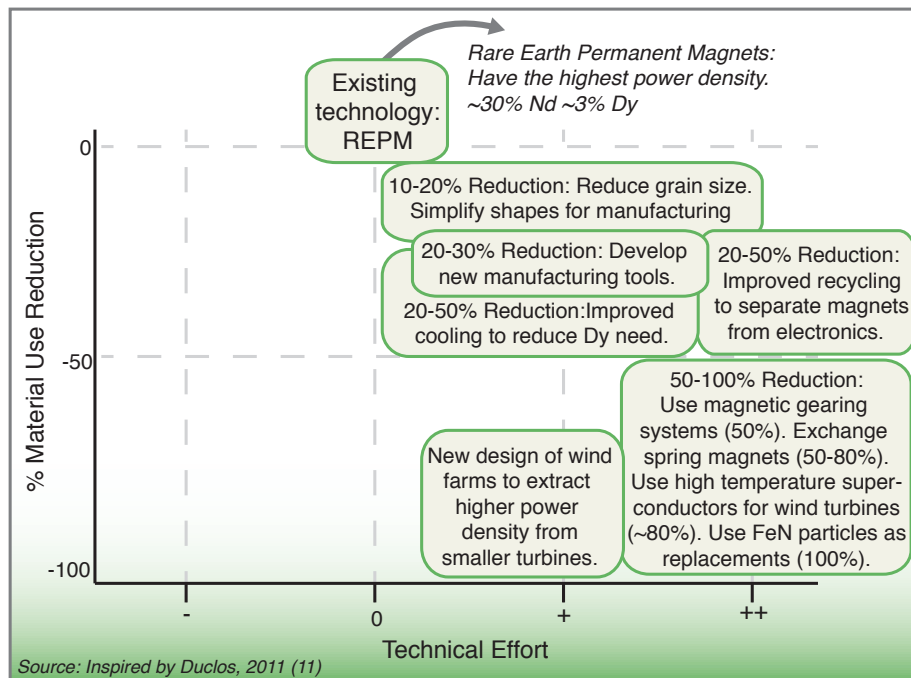
System Substitution

With respect to the use of REPMs in the automotive industry, a systems approach is desirable in order to maximize different tradeoffs. For example, weight affects fuel efficiency, but the extra weight of an induction motor might be compensated for by significantly reducing the weight of the batteries or other energy storage devices. A hybrid contains two or three motors, of which one or two could be induction motors, with the remainder being based on REPMs. There is a tradeoff in terms of motor efficiency but the advantage is lower manufacturing costs. Switched-reluctance motors, which do not use REPMs, could be used in these applications. There is also considerable interest in combining REPM electrical machines with magnetic gearing systems to get very high power density while using less overall magnet material, although at the moment such systems may be prohibitively

expensive. By combining the two into one system, one achieves a smaller motor, less energy losses, and smaller air gaps.

In the case of wind turbines, smaller might be better. Recent research has shown that more densely packed arrays of smaller vertical axis wind turbines can generate power at a much higher area density than large wind turbines. (23) These smaller turbines do not require such large magnetic fields, and can be manufactured with little or no rare earth content. For larger scale systems (e.g. offshore wind turbines), it may also be possible to use high-temperature superconductors for wind turbines by installing cryo-cooling systems. However, this approach may require another critical element, yttrium, which might limit large scale deployment as well.

Figure 13: Option Space for Material Reduction in Magnets



Agents of Change: Roles of Core Constituents

There are many different mechanisms for implementing these potential solutions, particularly in terms of public policy. Each element has its own story, so there is no one-size-fits-all solution. For rare earths, there might be some focus placed on relaxing the supply side constraints rather than on substituting other, less critical materials. It is a young industry, and such a small sector that relatively little work has been done (compared to other mineral resources) on geological models of ore occurrence and on mineral processing and extractive metallurgy. However, there is often more flexibility on the demand side of the equation, since almost all materials can be substituted at some cost. The focus should be on the best strategy for individual technologies; the more options we have available, the better we can employ the most effective strategies for reducing market demand for critical materials.

Industry, government and academia can play different roles in these varied strategic approaches and mechanisms. Markets are already responding to the potential rare earth crisis, even without any government intervention, so industry already plays a vital role with regard to addressing potential shortages of energy-critical materials. Industrial users, if they perceive supply risks, have every incentive to buy their own “insurance.” That said, there are appropriate roles for academia, particularly in the areas of basic research and workforce training. Government can play a vital role when it comes to correcting market failures or removing government failures, and in fostering innovative long-term solutions through the establishment of funding programs and interdisciplinary R&D centers.

It is in the interest of all stakeholders to work together to change the public tenor of the discussion. The largely negative perception of this issue in the public sphere, and how best to market the benefits of a sustainable approach to technology materials for clean energy, is a major concern. In the US and Canada, rational discussion has been overwhelmed by dire warnings from the materials producers and stock promoters. This has created both a credibility gap and an air of sensationalism that do not help educate the public. In Europe, the situation appears slightly better, but the issue still calls for honest and clear dissemination of information that helps orient both the next generation of scientists and the end users of this technology.

These actors all can benefit from a candid (as opposed to melodramatic) campaign of education on the constraints that materials availability place on technological development.

Industry

Materials Assessment: It should become standard industry practice to conduct materials assessments on all clean energy technologies on a regular basis, particularly when developing new products that could affect supply and demand.

Process Improvements: For rare earth elements, several new mines are slated to come online in the next five to ten years. However, not all rare earths are created equal in terms of abundance, and steps should be taken to balance the use of the more abundant versus the less abundant REEs. In the case of specialty metals, coproduction levels are more difficult to adjust, but in all cases, improvements in mineral processing and extractive metallurgy are possible. Investing in these improvements should be viewed as a virtual stockpile, which could help stabilize supply further. It is important, however, to develop techniques that are environmentally sustainable.

Recycling: Recycling of material can have an effect, both during production and at the end of a product's use cycle. It is easiest to recover scrap material from processing and production; once it gets into use, compliance issues often limit how effective recycling can be. Industry can make this cost effective by creating new business models to incentivize compliance.

Materials Reduction: Industry should look for the low hanging fruit when it comes to reducing the amounts of critical materials used in clean energy technologies, altering systems as necessary so that technologies can still perform adequately with less material. There is often an upfront capital cost, but the longer term savings could make such investment worthwhile to corporations.

Materials and Systems Substitution: Industry can invest in new materials R&D or new systems that generate the same effect without scarce minerals. Again, this is a longer-term investment, but the potential payoff is significant enough to make it worthwhile for corporations. In some cases this level of re-

search and development is best carried out by universities and national laboratories in partnership with industry. Public-private partnerships and private investment in basic R&D will pay dividends if the focus is on long term substitution of critical materials with abundant ones. Some countries have already begun building strong public/private partnerships to bridge the gap between the necessary fundamental R&D and their applications to the clean energy industry, and there are historical examples that could be emulated as well.

Government

International Collaborations: There is a useful role for international collaboration that will help introduce some stability in the supply of some materials. Continued focus on the renewable energy sector by Asian and European countries will mean that whether or not the US government—or the US power-consuming citizen—chooses to push for an increased adoption of these technologies will have a diminishing influence on their demand. This gives countries an opportunity to forge strong collaborative international relationships and work together to solve what are truly global issues.

Data Collection: Information gathering is a traditional role for government, as the private sector alone is likely to under-provide this necessary resource. There is still a lack of information relating to critical materials for energy technologies. The USGS is the de-facto lead investigator of mineral resources for the world and already tracks a great deal of information. With greater funding, this agency would be able to have a much greater impact as we develop new energy technologies, by providing, for example, pre-competitive geoscientific information, as well as data on reserves and subeconomic resources, coproduction, and stocks available for recycling throughout the material lifecycle. The US government has established a new inter-agency working group on materials issues. The initial focus is to prioritize critical minerals and develop early warning mechanisms for future shortages, and to help direct R&D efforts, develop global supply and coordinate information on markets and resources. The US remains behind the rest of the world in developing a coherent strategy, but the inter-agency group might hopefully be successful in raising awareness of materials availability issues throughout the government, from commerce and mining to basic energy science.

Stockpiling, Tax Incentives and Subsidies: Stockpiling, real or virtual, may help ensure further stability for certain critical materials. More direct government interventions in markets, such as loan guarantees, tax credits, and so forth, might influence private decisions in a way that alleviates demand for critical materials. For some critical minerals, more domestic mining would offset some of the supply risk problems. Better international trade policies could address the current distortions in this arena. However, these types of mechanisms should be viewed as short-term, stop-gap measures, and are not sufficient; long-term innovative solutions are still needed.

Research Funding and Facilities: When authorizing funding for research and promoting clean energy technologies, government programs should emphasize the materials issues, both in terms of current availability and the future sustainability of the supply base. This emphasis should come at all levels of research funding, from applied funding for companies and manufacturing facilities, all the way to basic energy science research. In addition, the US government could establish a national user facility for processing improvements. As discussed above, the US has a workforce “gap,” a shortage of trained scientists and engineers focused on mining, refining and mineral processing. Furthermore, the large variation in ore chemistries has made it difficult to apply lessons learned in different situations. A central facility related to processing technology could provide a training center and a knowledge base. Also, such a facility would provide leverage in the development and optimization of new processes that would be cost-prohibitive in more risk-averse private mining ventures.

Academia

Basic and Applied Research: Academic researchers should strive to focus fundamental research on understanding the properties of critical materials and how to engineer the same properties in abundant materials. Research should occur over the entire material lifecycle, from basic geosciences to recycling of materials. Federal, private and international research funding opportunities should incorporate these concepts as mentioned above to drive academic research to think more carefully about materials in basic research, through such techniques as simulation or combinatorial chemistry.

Future Workforce Training: It is important to teach students that sustainable energy means sustainable materials supplies, and to value processing of raw materials as a research endeavor. A lack of new workforce training in minerals processing and extraction is affecting potential research solutions, not just in the US but around the world. Resources alone aren't enough; we also need people to develop future mining projects. Each ore, and each deposit, is different, and requires unique processes. There are great leaps that could be made if we ever developed the resources and facilities to do this, but little research has been done in the last 30-40 years, at least in the US.

More money for scholarships and research projects could provide an incentive, but there is also a marketing element to the problem: namely, the need to create positive “buzz” about this area as a career. Young people are very interested in working in organic photovoltaics and advanced battery technologies, but extraction and flocculation are not on their radar (these topics are also less likely to be published in a high impact journal). Mining and extraction must engage in a reinvention of itself in terms of a sustainable energy future in order to draw talented young people into the field.

Conclusion

The first step in addressing the issue of critical materials for sustainable energy applications is to examine resource scarcity from the perspectives of both supply and demand. It is important to evaluate each industry, dominating technology, and element individually, since there is no one-size-fits-all solution. Increasing worldwide adoption of renewable energy technologies will require orders of magnitude more of the systems that generate, store, and distribute this energy; at this scale the solutions lie in investing in technological development to achieve similar reductions in the amount of critical materials used in any such system. Materials and systems level substitutions are the key to achieving these sorts of reductions in material usage.

One cannot separate critical materials from the development of new technologies, especially such materials intensive technologies as those related to the world's energy use. Specifically, when evaluating any new technology or concept, we must take into account an assessment of the materials used. This is true for private investment as well as academic research, and the mindset needs to be in place from the earliest stages, starting from basic energy science efforts.

Although reducing relative materials use will almost always have a large impact, there is a significant potential for expanding supplies of some of the technology metals. For many of these elements (including indium, tellurium, and the rare earths), we have historically devoted almost no effort in discovery and recovery (relative to other metals). It is also worth exploring possible ways to build flexibility into the production process, so that it is easier to adapt depending on changing market conditions. This might be a useful role for governments, by offsetting capital risks through tax breaks or subsidies, or even through the establishment of a central research facility or network of research centers devoted to investigating issues relating to critical materials for clean energy technologies.

It is important to remember that this is not just a US-centric concern; it is a global one, impacting many different geographical regions and cutting across many different industries. One must explore the issue in terms of international collaboration. It should not be viewed as a competition for scarce resources, but rather a search for the best solutions for the whole world.

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