MEETING SUMMARY

CRITICAL MATERIALS FOR ENERGY SUSTAINABILITY AND TECHNOLOGY
A Focus on Material Recovery

Science and Technology for Sustainability Program
Board on Energy and Environmental Systems
December 5, 2012

On December 5, 2012, the National Research Council's (NRC) Science and Technology for Sustainability Program (STS), in collaboration with the Division on Engineering and Physical Sciences' Board on Energy and Environmental Systems (BEES), convened a meeting of research leaders and technical experts in private industry as well as representatives from government and academia to discuss the criticality of materials used in energy sustainability related technologies.

Current and emerging clean energy technologies are dependent on a limited number of materials, such as rare earth and transition metals. Materials are derived from finite resources, and extensive use of these resources can pose challenges to societies for maintaining and improving their standard of living. The objectives of this meeting were to discuss the technical hurdles in recovering materials from waste streams, recycling, the potential for using recovered material in product development, and how best to implement sustainability strategies moving forward. Leaders from research and development programs in industry are faced with many complex challenges as they attempt to implement strategies and programs to address sustainability. This meeting provided an opportunity for these leaders to engage in dialogue with their counterparts.

Through the course of the meeting, participants discussed some of the challenges of recycling and reusing critical materials from waste streams:

- Supply concentration – The political, technical, and market risks for using any one material over another are challenging to fully understand, and often decisions are made under great uncertainty.
- Future demand growth scenarios – The potential for future demand can determine the material chosen for a given application, which will be especially important for the renewable energy sector moving forward.

- Substitution – There are intrinsic properties (i.e., conductivity, stability) unique to certain materials, and it is often difficult but necessary to find an alternative material.
- Integrity – It is important for consumers to believe they are receiving as valuable a product as a primary source, and for recyclers to ensure that sampling and evaluation of recycled materials is done regularly.
- The business case – There needs to be enough demand for a recycled material to incentivize companies to take a risk by entering the market.

MATERIAL CRITICALITY AND RECOVERY

Dr. Anthony Ku, senior engineer in the Manufacturing and Materials Technologies Organization at GE Global Research, discussed GE's approach to material criticality. Dr. Ku stated that GE uses at least 70 of the first 83 elements on the periodic table in their products. They use an internal corporate assessment to rank elements in terms of their criticality by developing a score based on impact factors (i.e., revenue, percentage of global use, and substitutability) and supply and price risk factors (i.e., global reserves, price volatility, and political factors).

First established in 2008, GE's criticality matrix enables GE to identify vulnerabilities within their array of products. Although Dr. Ku could not explicitly say which elements ranked highest in this matrix, many rare earth elements were highly ranked (Figure 1). GE tracks the criticality matrix with time to examine how it responds to fluctuations in the market. This type of analysis provides GE with information on their risk regarding certain elements and allows them to formulate the appropriate response, which might include finding new sources, manufacturing for efficiency (i.e., reducing waste), recycling, or redesigning to substitute alternative materials.

Two examples of GE responding to criticality issues include changing the use of rhenium in aircraft engines and phosphors in lighting. In 2008, prices of rhenium were increasing, which increased risk to GE's aircraft engine business. The sourcing department coordinated with manufacturing to recover scrap metals that contained rhenium and with a recycling vendor to recover turbine blades at the end of their life. They also redesigned materials to reduce the amount of rhenium needed to about half of what was originally being used.

The combination of product redesign and metal recycling is a success story in GE research and development, and although situations that arise are unique in the solution needed, this approach serves as a model for addressing concerns about criticality. GE's lighting business provides another example of this process in action. They are currently exploring the ability to recycle phosphors and alternatives to phosphor compositions by evaluating the trade offs in performance, cost, and availability. This includes a possible system redesign by evaluating phosphorus use in light emitting diodes (LEDs).

Figure 1 GE's Criticality Matrix.
Source: Anthony Ku, GE, Presentation December 5, 2012

Dr. Linda Wennerberg, in the Environmental Management Division, U.S. National Aeronautics and Space Administration (NASA), noted that availability and access to a material, along with the economic and political barriers that come with availability, are important elements of criticality issues for users. The time period is also important when assessing critical materials. For businesses, the timeframe for the supply of materials is generally only a few years, but for some agencies or larger companies, if there is a potential issue several years out, then that may be considered critical depending on the market or system that material feeds into.

PRICE AND SUPPLY AS FACTORS IN THE USE OF CRITICAL MATERIALS

Dr. Martin Green, leader of the Functional Properties Group of the Materials Science and Engineering Laboratory at the National Institute of Standards and Technology (NIST), indicated that price sensitivity of a material or metal is often more important than price itself. Dr. Ku commented that price is often an indication of its relative availability and that in a tight market, prices will rise when availability becomes restricted. In high profit margin products, that price can be absorbed; however, when there is a lower margin, price sensitivity is of greater concern.

Dr. Richard Teichman, development manager, Catalyst, Chemicals and Refining Division, Johnson Matthey North America, said that the price of precious metals affects their business. At the time a customer wants a particular metal, his company begins the process of moving that metal through their process promptly to ensure the customer has it when it is needed. They are not able to wait for the price of metals to be ideal to purchase them, but are very dependent on the price at the time they need to make their purchases.

Dr. James Stevens, corporate fellow in the Core Research and Development Department of the Dow Chemical Company, had a different perspective on the price of rare metals such as rhodium. Rhodium is used in a number of applications, including the production of rhodium-based catalysts to enable the production of aldehydes and other organic materials via the hydroformylation process. The price of rhodium started increasing in 2004, and increased 20 fold through the market collapse in 2008. Part of the cause in the increase in price had to do with demand, as newly established plants were requiring rhodium-based catalysts for their production. Although Dr. Stevens expected the hydroformylation business to seek alternatives to rhodium-based catalysts, he noted that Dow Chemical was content to continue their use. Rhodium-based catalysts stay in the process for long periods of time, and since they are considered as assets, the plant's asset value was increasing as the value of rhodium increased over time. Once the market crashed, however, the price went back down, as did the plant's assets. The asset balance sheet for a business using metal-based catalysts can thus vary greatly depending on the market for that metal, which can have major impacts depending on the size of the business.

Supply will continue to be a crucial component of criticality issues. Dr. Wennerberg stated that supply and how much information an organization knows about its supply chain will be key in making decisions about materials. She gave as example the Shuttle Environmental Assurance Program, which was an effort between engineers and environmental staff at NASA to determine if new regulations on materials would affect their program, what potential market issues needed to be addressed, and if possible substitutions existed for materials with a risk in supply. NASA also wants to evaluate systems instead of focusing on individual materials, and to also more fully understand their supply chain.

According to William Cassada, Director of Research and Emerging Technologies, Alcoa, having more control over the supply chain helps address some of these supply issues. Alcoa covers every stage of production (mining, refining, smelting, fabrication, and downstream products). Their products are used in transportation systems, building and construction, forgings and extrusions, and the power industry and include a variety of materials, including nickel, titanium, and rhenium.

Dr. Parikhit (Ricky) Sinha, director of environmental, health, and safety at First Solar, Inc., described First Solar's efforts in recycling metals from photovoltaic (PV) cells. First Solar started as a module manufacturing company, making cadmium telluride PVs, but has since moved to constructing the projects as well as making the modules. Instead of rooftop solar modules (panels), they focus on centralized energy and build PV-based power plants. Availability of raw materials is crucial to First Solar's products, which use cadmium telluride, a compound whose constituent elements are both byproducts of the mining industry: cadmium comes primarily as a byproduct of zinc mining and tellurium from copper mining. Tellurium is considered a critical material within the PV industry because its production is tied to the supply of copper and not mined directly.

Prior to its application in the PV industry, tellurium was primarily used as an additive to steel. The current world production is approximately 500 to 1,500 metric tons, and for every gigawatt of PV production, about 100 tonnes of tellurium is required.

Dr. Sinha explained that First Solar manufacturers about three gigawatts of electricity a year, requiring 200 tonnes of tellurium. In order for the PV industry to make a significant contribution to the world's electricity production, it needs to scale to terawatt, not gigawatt levels. Such a massive increase in scale would increase the global demand for tellurium beyond its current production capacity.

The Recovery and Recycling of Materials

Dr. Brajendra Mishra, professor and associate director of the Kroll Institute for Extractive Metallurgy in Metallurgical and Materials Engineering at the Colorado School of Mines described the Colorado School of Mines' new Industry and University Collaborative Research Center on Resource Recovery and Recycling that he co-directs with the Worcester Polytechnic Institute. They work with many companies to help move research in this field forward. Examples of the kind of research the center is conducting include photovoltaic metal separations, phosphor dust recovery, magnet recycling, catalyst recovery, and metal recovery from dust in iron and steel plants and zinc manufacturing.

Dr. Adam Powell, IV, chief technology officer and cofounder of Metal Oxygen Separation Technologies, Inc. (MOxST), described technology they developed that also focuses on magnet recycling. MOxST is a start-up business focused on molten salt electrolysis, mainly for reactive metals. In working with high temperature processes, molten salts, and reactive metals, they discovered a separation property of the molten salts that was first used to recycle magnesium, but is now being applied to rare earth magnets as well, such as those used in electric vehicles and wind turbines. The core idea is to go from metal oxide to metal. As a start-up, they are still at kilograms of product scale for magnesium and grams of product scale for neodymium, but are looking to scale up the process to produce larger amounts of pure metal.

Dr. Sinha stated that to address supply concerns, First Solar is using a lifecycle assessment approach to examine sourcing, recycling, and substitution options for tellurium (Figure 2). The recovery of tellurium from copper mining is about a 55 percent yield, but could possibly be increased to an 80 percent yield with enough economic demand. The largest yields for recovery will eventually be from recycling modules. Most of First Solar's modules are 5 to 10 years old, and will not be recovered for another 10 to 20 years. Once they start being returned for recycling, however, this will provide the largest source of tellurium. The process of recycling a module is straight forward, and first requires it to be shredded to reduce its size. This breaks a sealant that is applied to the glass to encapsulate the semiconductor. Once that is broken, the metals can be separated from the glass, resulting in two products that are recyclable – clean glass and semiconductor material. The semiconductor material is further refined and reused in new modules.

Dr. Cassada explained that there are 638 million metric tons of aluminum currently in use in products worldwide, which is approximately 75 to 80 percent of all the aluminum metal that has ever been produced. This demonstrates that aluminum has a high residual value owing to the amount of energy required to produce it, and that it only needs about 4 percent of that energy to be reconstituted into another product. Dr. Mishra indicated that this is also true for copper, lead, and zinc, and that for steel, there is a 75 percent decrease in the amount of energy needed for recycling.

For the year 2010, about 200 million metric tons of material was mined for aluminum production, which produced about 76 million metric tons of alumina - the raw material for the smelting process. From that, about 37 million metric tons of primary metal was produced. About the same amount of material, 38 million metric tons, was recycled and brought back into the material flow for a total of about 75 million metric tons of ingot.[1] This shows that aluminum has a high capacity for recycling, with the largest product recycled being the aluminum can. Once an aluminum can is consumed, it is back on the shelf as a can in less than 60 days. Alcoa takes back approximately 20 billion cans a year into their system, which is about 500,000 metric tons of aluminum. Alcoa would take more cans if they could; however, the recycling rate in the United States is only about 57 percent. This falls short of countries like Brazil and Sweden where recycling rates are closer to 90 percent or more. Approximately six million metric tons of aluminum is lost each year from people throwing cans and consumer products away.

Dr. Teichman's division at Johnson Matthey also has a significant recycling program. About half to two-thirds of the precious metals that move through his division are recovered materials from automobiles, jewelry, or catalysts from the pharmaceutical and chemical industries. They are recycled and worked into mostly automobile catalysts, heavy duty diesel catalysts, or stationary source abatement catalysts for electric generating rigs.

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[1] An ingot is a material, usually metal, that is cast into a shape suitable for further processing.

[2] Mischmetal is a term that describes an alloy of rare earth

Figure 2 The life cycle management of photovoltaics.
Source: Patrikhit Sinha, First Solar, Presentation December 5, 2012

INCENTIVES FOR AND IMPLEMENTATION OF SUSTAINABILITY STRATEGIES

Dr. Ku explained that ensuring that senior leadership understands critical material risks helps to implement different strategies for substitution or recycling of critical materials. For example, if there is a mining capacity issue, in that a certain material may be in short supply and will likely require a longer timeframe to bring into the market, then evaluating the exposure over several years becomes important. In the case of rhenium in 2008, senior management understood the issue of critical material exposure and that action was needed. The sense of urgency around the issue prompted activity and created the type of buy-in needed to examine other business operations for additional exposure issues. This buy-in from senior management was necessary and there was more cooperation within the company with gathering information and starting to mitigate some of the risks that were identified.

In addition to buy-in from senior leadership, there need to be incentives as well. Dr. Cassada gave price as the motivator for aluminum recycling. Initially, when the aluminum can was developed for the consumer, it was understood that in order for recycling it to be economically viable, a collection system had to be set up with price as the motivation. Deposit legislation has also served a role in motivating consumers to recycle. Dr. Wennerberg explained that with deposit laws, the deposit is paid when the can is purchased, and then when it is returned, you are returned that deposit. Dr. Wennerberg also explained that deposit laws vary from state to state, and inconsistency results in individuals being unfamiliar with another state's deposit law. There is also a strong behavioral and cultural aspect to convincing individuals to return the can for the deposit or recycling that also poses challenges.

Dr. Mishra stated that recycling becomes more favorable when demand outpaces supply, but that there are several key elements to ensuring that critical materials are recycled:

- Energy demand has to be lower for recycling than for primary production
- Efficient collection and separation is key, and as such, having the best technology will be a challenge but important to address
- There needs to be a market for recycled products
- People will need to be further educated to view recycled products as equivalent to primary production and change habits so that recyclable goods are sent to recyclers
- Profitability from the recycled product is crucial

An example of making recycling profitable was given by Shane Thompson, vice president of Kinsbursky-Toxco, whose business model addresses small, post-consumer batteries as well as large-format, industrial batteries. Large-format, industrial batteries are almost exclusively lead acid batteries; however, post-consumer batteries are often nickel-cadmium batteries. The nickel provides financial incentive for recycling, but the cadmium requires attention to regulatory compliance. Furnace technology allows for the separation of the two metals—the recovered cadmium can go back into batteries, and the nickel, recovered as ferronickel (an alloy of iron and nickel) is sold to the stainless steel industry.

Currently, Kinsbursky-Toxco is building a nickel-metal hydride battery recycling plant adjacent to their existing operations. This was feasible due to funding from the 2009 stimulus bill that authorized the Department of Energy to provide $25 million to build an advanced lithium ion recycling plant as part of a larger effort to stimulate the hybrid vehicle market in North America. Recyclers are not as concerned with what is currently being produced, but with what was produced 10 years ago and is now going to be available for collection and recycling. This is true with nickel-metal hydride batteries. Those that came on the market in 1999 are now becoming available for collection and recycling, and with the advent and proliferation of large format nickel metal hydride batteries in hybrid electric vehicles, there will be a long-term, continual supply of these types of batteries for recycling. Dr. Linda Gaines, systems analyst at the Center for Transportation Research at Argonne National Laboratory, cautioned that when there is a constant demand for a material from batteries, then recycled batteries can provide a constant supply; however, if the demand for that material increases, then the supply will only be however much was produced in the previous 10 years.

Mr. Thompson reiterated the issue with perception of recycled products. In battery recycling, the general principle is that cathode materials are separated from anode materials so that the cathode materials can be sold back into the value stream for the businesses producing batteries. Unfortunately, companies producing the cathode material are hesitant to purchase recycled materials, because of concerns with not meeting performance specifications. The perception is that the recycled material is of lower quality than the original material.

THE ROLE OF PUBLIC AND PRIVATE INITIATIVES MOVING FORWARD

Dr. Kurtis Haro, science assistant at the Directorate for Engineering at the National Science Foundation (NSF) presented findings from a recently held symposium at the American Chemical Society titled “Ensuring the Sustainability of Critical Materials and Alternatives: Addressing the Fundamental Challenges in Separation Science and Engineering”. One of the main themes from this symposium was the need for more robust separations that enable materials to be handled and maintained under the corrosive, high heat, and high acidity conditions needed for separating materials. The use of liquid extraction reagents is an area that needs more development to allow for the recovery of metals or hydrocarbons from waste streams.

Reductive refining of rare earth metals is another area where technological advances are needed for capturing critical materials. This process would require far less energy than what is currently needed for conventional oxidative processing of rare earth metals. Dr. Powell explained that one barrier to recycling rare earth magnets is that the metals in them are very hard to separate from one another. In order to recycle a magnet stream, MOxST will extract all of the rare earth metals as mischmetal[2], which makes the post-consumer aspect of re-use more limited.

Dr. Haro also addressed the need for chemists and chemical engineers to better integrate their work to enable new technologies and to build the capacity for scaling up from bench top to a systems level. Research is often done in isolation, and an innovation ecosystem that connects researchers and entrepreneurs, similarly to Silicon Valley, would help better connect creative ideas among researchers and lead to the development of technologies that enable more efficient refining, use, and reuse of critical materials.

Dr. Green described NIST’s efforts in trying to further the understanding of critical materials. There is ongoing research on tools for composite materials, and high throughput methods so that a wide variety of materials can be screened in the search for substitutes. There are also models for thermodynamic and thermochemical properties of metal ores and recycled materials containing critical elements. One activity that would be useful to industry is establishing standard reference materials—artifacts that one could use to calibrate tools and materials so that there is a more consistent understanding and use of materials. In regards to recycled materials, enabling more efficient sorting would prove useful because it would create a purer recycling stream or provide greater knowledge about the content of the material of interest. One effort that would help in better characterizing waste streams are instruments and methods for material fingerprinting. For example, many wheel manufactures use different alloys for different wheels, and it would be useful if recyclers were able to better identify the alloys so that they could make a purer, and thus more valuable, melt of recycled wheels.

Designing for recycling was also raised as a key consideration. Making a product easier to disassemble would help facilitate its being recycled. Dr. Cassada stressed that manufacturers are incentivized to design for performance, and the complexity inherent in a product’s design stems from this drive for greater performance. Dr. Wennerberg

[2] Mischmetal is a term that describes an alloy of rare earth elements in various naturally occurring proportions.

explained that at NASA, they have been trying to design for both performance and maintenance. Performance has not included issues around long-term disposal; however, maintenance can be included as a performance issue and may lead to more industries designing for recycling. There was discussion among the participants regarding the need to regulate designing for recycling. Some participants stated that if there is profit in returning the product back to the value stream, then that should serve as the incentive for businesses to invest in the recycling process. However, others felt that regulations can help to create markets where that value does not yet exist.

Dr. Sinha stated that regulations in Europe require electronics, including PV modules, to be recycled at the end of their life. This mandate requires the industry to collect modules and helps drive recycling technology to collect them at no additional cost to the customer. Although this type of regulation might also help drive recycling in the United States, it does not currently exist. Under certain construction permits, however, recycling modules at the end of their life is required. First Solar as a prefunded program so that when the customer buys the module, they pay a fee embedded in the cost that pays for collection and recycling. Ultimately, Dr. Sinha said, First Solar would prefer to see the market sizeable enough so that third-party recyclers are available, which would allow them to buy back recyclable material.

Dr. Mishra explained that there two aspects to how critical materials are related to energy sustainability—the materials required for energy production and the energy required for the production of critical materials. There are metals, such as tellurium, that are necessary for photovoltaic (PV) modules and thus may be key to enabling more sustainable energy production, and then there are metals, such as indium or aluminum, that require large amounts of energy for production and may become critical when the energy demand required for production and growth of that industry becomes too costly. This meeting focused mostly on the materials needed for energy production, and a common theme that emerged was creating economic incentives to move manufacturers toward designing for recycling and encourage recyclers to take risks that would ultimately create more profitable markets. There was also discussion about the need for more research into how to best create these incentives, and also in identifying strategies to motivate manufacturers toward zero waste operations.

Participants: William Cassada, Alcoa; Linda Gaines, Argonne National Laboratory; Martin Green, NIST; Kurtis Haro, NSF; Anthony Ku, GE Global Research; Brajendra Mishra, Colorado School of Mines; Adam Powell, Metal Oxygen Separation Technologies, Inc; Parikhit Sinha, First Solar, Inc; James Stevens, Dow Chemical Company; Richard Teichman, Johnson Matthey North America; Shane Thompson, Kinsbursky-Toxco; Linda Wennerberg, NASA. **Planning Committee:** Anthony Ku, GE Global Research (chair); Linda Gaines, Argonne National Laboratory; Martin Green, NIST. **NRC Staff:** Marina Moses, Director, Science and Technology for Sustainability Program (STS); James Zucchetto, Director, Board on Energy and Environmental Systems (BEES); Dominic Brose, Program Officer, STS; David Cooke, Associate Program Officer, BEES; Dylan Richmond, Research Assistant, STS.

DISCLAIMER: This meeting summary has been prepared by Dominic Brose as a factual summary of what occurred at the meeting. The committee's role was limited to planning the meeting. The statements made are those of the author or individual meeting participants and do not necessarily represent the views of all meeting participants, the planning committee, STS, or the National Academies.

The summary was reviewed in draft form by Carl Shapiro, United States Geological Survey, to ensure that it meets institutional standards for quality and objectivity. The review comments and draft manuscript remain confidential to protect the integrity of the process.

ABOUT SCIENCE AND TECHNOLOGY FOR SUSTAINABILITY (STS) PROGRAM

The National Academies' Science and Technology for Sustainability Program (STS) in the division of Policy and Global Affairs was established to encourage the use of science and technology to achieve long-term sustainable development. The goal of the STS program is to contribute to sustainable improvements in human well-being by creating and strengthening the strategic connections between scientific research, technological development, and decision-making. The program concentrates on activities that are cross-cutting in nature and require expertise from multiple disciplines; important both in the United States and internationally; and effectively addressed via cooperation among multiple sectors, including academia, government, industry, and non-governmental organizations (NGOs).

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