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MEMORANDUM September 10, 2019

To: Senate Committee on Energy and Natural Resources
Attention: Tristan Abbey

From: [redacted]

Subject: **Projected Demand for Critical Minerals Used in Solar and Wind Energy Systems and Battery Storage Technology**

This memorandum is in response to your request for a list of critical minerals used in renewable energy technologies,[1] and for demand projections for those critical minerals needed for wind, solar, and battery storage technology. This memo provides the results of three global forecasting studies on the subject.[2] These were the only three forecasting studies CRS located in the time available. The three studies use a number of variables that impact mineral demand, including: market penetration of renewable energy technologies, global economic growth, demand for electricity, and public policy, among other variables.

This memo is organized to provide a discussion of critical minerals demand in general, a brief materials analysis of renewable energy systems, and demand projections for critical minerals used in wind, solar, and battery storage systems.

If you have additional research needs, please contact me at the extension above.

Background

Demand for Critical Minerals

The demand for mineral commodities is a derived demand which differs from consumer goods demand. Minerals are used as inputs for the production of goods and services. For example, the demand for rare earth elements (REEs) is derived from the production of their end-use products or use, such as flat panel displays, automobiles, or catalysts. As a result, the demand for critical minerals depends on the strength of the demand of the final products for which they are inputs. An increase in the demand for the final product will lead to an increase in demand for critical minerals (or their substitutes).

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[1] For a complete listing of minerals deemed to be critical by the Trump Administration, see *83 Federal Register, Final List of Critical Minerals*, 23295, May 18, 2018.

[2] U.S. Department of Energy, *Critical Materials Strategy*, 2011; World Bank Group, *The Growing Role of Minerals and Metals for a Low Carbon Future*, June 2017; and Kohmei Halada, et al., *Forecasting of the Consumption of Metals up to 2050*, Materials Transaction, Vol. 49, No. 3 pp. 402-410, 2008.

U.S. and Global Demand

Some of the demand drivers in recent decades for critical minerals include permanent magnets using REEs, batteries using cobalt and lithium, automobiles and electronics using tantalum and niobium, and vanadium for steel production.

Many critical minerals (e.g., manganese, tungsten, and vanadium) are used for steelmaking and infrastructure projects, such as roads, housing, rail lines, and electric power grids. Others (e.g., REEs, lithium, indium, tantalum, gallium, and germanium) are used in the manufacturing of high-value electronic products, such as laptops and batteries, renewable energy systems, and other consumer goods, such as automobiles and appliances.

Materials Analysis of Critical Minerals Content in Finished Products and Systems

Materials analysis can be a useful tool to better understand various aspects of mineral demand. For example, such analyses can provide information on how material inputs are used in component parts and how components are used in larger systems such as solar arrays, wind turbines, and automobiles. Below are simplified examples of material requirements for wind and solar systems and battery storage technology.

Materials for Wind Energy

Based on the Department of Energy (DOE) Report *20% Wind Energy by 2030*, wind power installations consist of four major parts: wind tower, rotor, electrical system, and drivetrain (e.g., generator, gearbox, and motor).[3] Most of the common large wind turbines have tower heights over 200 feet and rotor blades as long as 150 feet. The average rated capacity of an onshore wind turbine is between 2.5 megawatts (MW) and 3 MW.[4] DOE lists the following as the most important materials for large-scale manufacturing of wind turbines: steel, fiberglass, resins (for composites and adhesives), core materials, permanent magnets, and copper. Some aluminum and concrete is also required. DOE considers the raw materials for large-scale wind turbines to generally be in ample supply. Turbine manufacturing, however, would be 100% dependent on permanent magnet imports, primarily from China, as that country produces 75% of the world's permanent magnets which contain REEs (assuming certain drivetrains are used).

Recent analysis indicates that the offshore wind industry could be a major driver for increasing REE demand. There are indications that the larger turbines that are better suited for offshore locations, which also contain REEs, may be more reliable and require less maintenance than onshore turbines.[5]

Materials for Solar Energy

There are two major types of photovoltaic (PV) cells: crystalline silicon cells (most widely used) and thin film solar cells. The silicon based PV cells are combined into modules (containing about 40 cells) then

[3] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, *20% Wind Energy by 2030, Increasing Wind Energy's Contribution to U.S. Electricity Supply*, July 2008. (www.energy.gov/eere)

[4] Offshore wind farms are deploying much taller structures, with longer blades and greater MW capacity.

[5] T Fishman and T.E. Graedel, "Impact of the Establishment of U.S. Offshore Wind Power on Neodymium Flows," *Nature Sustainability*, vol. 2, April 2019; Dodd, Jan, "Rethinking the Use of Rare Earth Elements," *WindPower Monthly*, November 30, 2019, https://www.windpowermonthly.com/article/1519221/rethinkingtheuseofrare-earthelements.

mounted in an array of about 10 modules. Ethylene-vinyl acetate and glass sheets typically frame the PV module, with additional aluminum frames for added protection.[6] Thin-film solar cells use layers of ultra-thin semi-conductor materials that can serve directly in rooftop shingles, roof tiles, and building facades. Thin-film PV cells have been noted to use cadmium-telluride or copper-indium-gallium-diselenide. A separate category of solar technology is concentrating solar power; these systems use mirrors to convert the sun's energy into heat and then into electricity.

Permanent Magnets

The use of REEs in permanent magnets are another example of how materials analysis for end uses may inform an understanding of critical minerals vulnerability. For example, some of the pertinent questions that might be raised with respect to permanent magnets include: How much dysprosium, neodymium, terbium, and Praseodymium go into a neodymium-iron-boron (NdFeB) permanent magnet and what fraction of the total cost is each element? What are permanent magnet unit production costs and what portion of the total costs of a wind turbine do the permanent magnets represent? And what is the likelihood and the economics of substitution?

Lithium-Ion Batteries

The use of lithium-ion batteries for the rapidly growing electric vehicle market is expected to transform the material requirements for battery technology. Material analysis of lithium-ion batteries would bring to light useful insights on materials composition, cost, technologies, and supply chains. In the case of the lithium-ion (li-ion) battery[7] for electric vehicles, what is the material composition of the battery?[8] In other words, how much cobalt, lithium, nickel, and other materials are needed per battery, how much are the material costs for each battery, and what percent of the total battery manufacturing cost do the materials represent? Then, further, what is the battery cost per electric vehicle? Analysts would want to know the point at which material price increases would warrant a shift in the use of those materials. Other useful insights in materials analysis would be to understand the suite of battery technologies being developed, their manufacturing capacity, and the ownership structure of the supply chain for the materials and the batteries.

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[6] Vasilis M. Fthenakis, Hyung Chul Kim, and Erik Alsema, "Emissions from Photovoltaic Life Cycles," *Environment Science and Technology*, vol. 42, no. 6, 2008.

[7] Helbig, et al., "Supply Risks Associated with Lithium-ion Battery Materials," *Journal of Cleaner Production*, October 12, 2017 (hereinafter referred to as Helbig 2017).

[8] Material composition of a product (MCP) is a unit of measurement used to study the impact of metal/minerals on demand for a product. MCP measures the efficiency of converting raw materials into final end use products. The greater the efficiency, the less demand for the material per unit of output.

Critical Minerals Used in Renewable Energy Systems and Demand Projections

Selected Critical Minerals used for Wind Energy:

- Rare earth elements (neodymium, dysprosium, terbium and praseodymium) used in permanent magnets
- Aluminum

Selected Critical Minerals Used for Solar Photovoltaics and Concentrated Solar Power:

- Aluminum
- Indium
- Gallium
- Tellurium

Selected Critical Minerals Used in Battery Storage Technology:

- Aluminum
- Lithium
- Manganese
- Natural graphite (projected demand not available)
- Vanadium (projected demand not available)

DOE Critical Minerals Demand Projections

One study by DOE presents its results out to 2025 for some of the REEs used in permanent magnets for direct drive wind turbines and also used in general consumer goods. The DOE study also provides demand projections for critical minerals used in solar and battery storage systems. DOE's findings on projected demand for selected rare earths (neodymium, dysprosium, and terbium) show a more than doubling in demand for neodymium and dysprosium, and a 35% increase in demand for terbium from 2010 to 2025. All three rare earth minerals are used in permanent magnets for wind energy turbines, electric vehicles, and consumer electronics. The DOE study, based on a "high penetration" for renewable technology, illustrates an increase in demand for critical minerals used in solar energy systems; more than doubling for tellurium and gallium by 2025. DOE also projects mineral demand for battery storage technology such as manganese dioxide, cobalt, and lithium (all used in the lithium-ion battery storage technology). Graphite is also used widely in most battery storage technologies but projection data was not available at the time of this writing. **Table 1** below shows a four-fold increase in demand for lithium, and a 50% increase in demand for manganese dioxide and cobalt that are used in the lithiumi-ion battery.

Table 1. DOE Selected Critical Minerals Projections

Renewable Energy System	2010	2025
Wind Energy		
Neodymium oxide	~20 kilotons (kt) per year	~59 kt/year
Dysprosium oxide	~1,500 metric tons (mt) /year	~4,000 mt/year
Terbium oxide	~400 mt/year	~650 mt/year
Solar Energy		
Tellurium	~600 mt/year	~1,300 mt/year
Gallium	~230 mt/year	~550 mt /year.
Indium	~1,450 mt/year	~2,500 mt/year.
Battery Storage		
Manganese dioxide	~800 kt/year	~1,200 kt/year
Cobalt	~60 kt/year	~90 kt/year
Lithium	~100 kt/year	~400 kt/year

Source: DOE, *Critical Materials Strategy,* 2011.

Notes: ~ = approximately

World Bank Group Critical Minerals Demand Projections

The World Bank Group (WB) study projected several minerals used in wind, solar, and battery technology and describes the projections as the percentage of increased demand under a scenario that is based on the 2 degree Celsius (2DS) commitment under the Paris Climate Agreement. They also present projections under a 4 degree Celsius scenario (4DS); both scenarios show a greater increase in demand compared to an increase over a 6 degree Celsius (6DS) scenario. The 6DS scenario is described as an expansion of current policy and practices under the 2DS scenario. Compared to the 6DS scenario, the WB results show a more than doubling of demand from 2013 to 2050 for aluminum, neodymium, and manganese used in wind energy systems, and a 300% increase in aluminum and 325% rise in indium demand used in solar energy systems. WB results also show a 1,200% increase in demand for all four critical minerals used in battery storage technology discussed in the study (i.e., aluminum, cobalt, lithium, and manganese); see **Table 2** below.

Table 2. The World Bank Study — Selected Critical Minerals, Percentage Increases between 2013 to 2050 (under its 2 degrees Celsius (2DS) and 4 degrees Celsius (4DS) Scenarios)

(% Increase)

Renewable Energy Technology	2DS	4DS
Wind Energy		
Aluminum	250	160
Neodymium	240	150
Manganese	250	150
Solar Energy		

Renewable Energy Technology	2DS	4DS
Aluminum	300	160
Indium	325	170
Battery Storage Technology (lithium-ion)		
Aluminum	1,200	100
Cobalt	1,200	100
Lithium	1,200	100
Manganese	1,200	100

Source: World Bank Group, *The Growing Role of Minerals and Metals for a Low Carbon Future, June 2017.*

Halada, et al. Selected Critical Mineral Demand Projections

A third study, by Halada et al., highlights the following critical minerals: aluminum, manganese, lithium cobalt, indium, and gallium, among other non-critical minerals. The study bases its projections on global gross domestic product (GDP), population growth, and the relation between per capita metal consumption and per capita GDP, among other variables such as electricity demand. Their results predict a nearly fourfold increase (or higher) in demand for aluminum, lithium, cobalt, and gallium and a five-fold increase in indium and rare earth demand from 2010 to 2050. Manganese would increase by three-fold.

Table 3. Selected Critical Mineral Projections for 2010 and 2050 by Halada, et al., Study

Renewable Energy Technology	2010	2050
Wind Energy		
Rare Earth Elements	190 kilotons (kt) /year	800 kt/year
Solar Energy		
Aluminum	20,000 kt/year	75,000 kt/year
Indium	2 kt/year	10 kt/year
Gallium	1 kt/year	4.5 kt/year
Battery Storage		
Manganese	12,500 kt/year	40,000 kt/year
Lithium	100 kt/year	425 kt/year
Cobalt	90 kt/year	390 kt/year

Source: Kohmei Halada, et al., *Forecasting of the Consumption of Metals up to 2050*, 2008.