Testimony of
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Before
U.S. Senate Committee on Energy and Natural Resources
On
Establishing a Baseline of Global Climate Facts: Understanding the Scale and Source of Contributions

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Good morning. Thank you for the opportunity to testify before this Committee. I'm a Senior Fellow at the Manhattan Institute where I focus on science, technology, and energy issues. I am also a Faculty Fellow at the McCormick School of Engineering at Northwestern University where the focus is on future manufacturing technologies. And, for the record, I'm a strategic partner in a venture fund focused on software startups in energy.

Since the purpose of this hearing is to establish a baseline on the state of affairs regarding carbon dioxide emissions associated with supplying energy to society, permit me to note three basic realities, each with implications for the subject at hand. These are realities that help explain why, as this Committee's join staff memorandum notes, in the pre-pandemic trends, "the United Nations Environment Program has found that greenhouse gas emissions continued to increase" despite massive European and U.S. investments in non-hydrocarbon energy production.

First, it is indisputable, and it's a good thing, that the world will use more wind and solar machines, and more electric cars. The reason for that, aside from policies encouraging all three, is anchored in the fact those technologies are all profoundly better than they were a decade or two ago and, given the magnitude of future global energy needs, more options are always better.

Second, it is equally indisputable that all energy machines are, necessarily, built and operated using materials that must be first extracted from the earth. Replacing hydrocarbons with wind, solar and battery-powered machines constitutes a significant shift in both the nature and quantities of those "energy materials." It is a switch from using mainly liquids and gases to using solids. And it's a switch that, on average, results in a ten-fold increase in the quantity of materials mined and processed per unit of energy delivered.

Third, the United States is today, and will be for the foreseeable future, a net importer of, either wind, solar and battery machines, or key components for them, or for most of the critical "energy minerals" needed to build them.

All these realities have implications for the baseline accounting of carbon dioxide emissions trends. These realities also have economic, geopolitical, environmental and even human rights implications. While the U.S. is essentially self-sufficient today in net hydrocarbon use, it is an importer of alternative energy materials and machines. This means that replacing the former, which supply 80 percent of America's energy, with the latter would replace a large share of the GDP with imports.

And, given the world as it is, not as we'd wish it, increasing domestic use of wind, solar and batteries results in a *de facto* export of carbon dioxide emissions. That's because mining and processing of energy minerals, and the fabrication of energy machines, is inherently energy-intensive – and most of that energy use takes place offshore. Calculating the magnitude of that offshoring of emissions is complex. Some analyses have, for example, examined the processing of battery materials, or fabrication of battery components in China, where a major if not dominant share of such industries now resides. With China's 60 percent coal-fired grid, this leads to supply-chain carbon dioxide emissions that are a significant share, even the entire share, of emissions eliminated by replacing a combustion engine in many parts of America.

In general, it's worth noting that the aggregate use of oil by heavy machinery in global mining rivals oil use in global aviation, the latter of course before the Great Lockdowns. And it's as challenging to replace oil in mining as it is in aviation. Meanwhile, the energy path contemplated with the Paris Accord will lead to the greatest acceleration in demand for mining that the world has ever seen.

All this points to the need for realistic supply-chain emissions analyses, something largely lacking in the current global carbon accounting. It also points to an opportunity for the United States to revitalize our domestic mining and mineral processing industries, something that China has been focused on for years.

There is some irony in the fact that the world is coming full circle to revisit the importance of mining. It's humanity's oldest industrial activity. In fact, way back in 1934, speaking of baselines, the great American philosopher and technology historian, Lewis Mumford, observed in his seminal book on technology and civilization that the industrialization of mining was a major, indeed in his view, a primary driver in the creation of modern capital markets, the organization of labor, and our understanding of our relationship with the environment.

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EXPANDED TESTIMONY

The Material Cost of "Clean Tech"

The materials extracted from the earth to fabricate everything, including wind turbines, solar panels, and batteries (to store grid electricity or power electric vehicles) are typically out of sight, located at remote quarries, mine sites, and mineral-processing facilities around the world. Those locations matter in terms of geopolitics and supply-chain risks, as well as in general environmental terms, including accounting for carbon dioxide emissions. The scale of the material demands for "clean tech" machines is, for many, surprising.

For example, replacing the energy output from a single 100-MW natural gas-fired turbine, itself about the size of a residential house (producing enough electricity for 75,000 homes), requires at least 20 wind turbines, each one about the size of the Washington Monument, occupying some 10 square miles of land.[1] Building those wind machines consumes enormous quantities of conventional materials, such as concrete, steel, and fiberglass, along with less common materials, including "rare earth" elements such as dysprosium. A World Bank study noted what every mining engineer knows: "[T]echnologies assumed to populate the clean energy shift … are in fact significantly more material intensive in their composition than current traditional fossil-fuel-based energy supply systems."[2]

As it happens, all forms of renewable energy require roughly comparable quantities of materials in order to build machines that capture nature's flows: sun, wind, and water. Wind farms come close to matching

[1] Landon Stevens, "The Footprint of Energy: Land Use of U.S. Electricity Production," Strata, June 2017. This calculation understates land usage; at least double the number of wind turbines, plus storage, would be needed to replace the continuous availability of electricity from conventional generation.

[2] Daniele La Porta et al., *The Growing Role of Minerals and Metals for a Low Carbon Future* (Washington, DC: World Bank Group, 2017), p. xii.

hydro dams in material consumption, and solar farms outstrip both. In all three cases, the largest share of the tonnage is found in the use of conventional materials like concrete, steel, and glass. Compared with a natural gas power plant, all three require at least 10 times as many total tons mined, moved, and converted into machines to deliver the same quantity of energy.[3]

For example, building a *single* 100-MW wind farm—never mind thousands of them—requires some 30,000 tons of iron ore and 50,000 tons of concrete, as well as 900 tons of nonrecyclable plastics for the huge blades.[4] With solar hardware, the tonnage in cement, steel, and glass is 150% greater than for wind, for the same energy output.[5]

If episodic sources of energy (wind and solar) are to be used to supply power 24/7, even greater quantities of materials will be required. One needs to build additional machines, roughly two to three times as many, in order to produce and store energy when the sun and wind are available, for use at times when they are not. Then there are the additional materials required to build electricity storage. For context, a utility-scale storage system sufficient for the above-noted 100-MW wind farm would entail using at least 10,000 tons of Tesla-class batteries.

The handling and processing of such large quantities of materials entails its own energy costs as well as associated environmental implications. But first, the critical supply-chain issue is not so much the increase in the use of common (though energy-intensive) materials such as concrete and glass. The core challenges for the supply chain and the environment reside with the need for radical increases in the quantities of a wide variety of minerals.

The world currently mines about 7,000 tons per year of neodymium for example, one of numerous key elements used in fabricating the electrical systems for wind turbines. Current clean-energy scenarios imagined by the World Bank (and many others) will require a 1,000%–4,000% increase in neodymium supply in the coming several decades.[6] While there are differing underlying assumptions used in various analyses of mineral requirements for green energy, all reach the same range of conclusions. For example, the mining of indium, used in fabricating electricity-generating solar semiconductors, will need to increase as much as 8,000%. The mining of cobalt for batteries will need to grow 300%–800%.[7] Lithium production, used for electric cars (never mind the grid), will need to rise more than 2,000%.[8] The Institute for Sustainable Futures at the University of Technology Sydney last year analyzed 14 metals essential to building clean-tech machines, concluding that the supply of elements such as nickel, dysprosium, and tellurium will need to increase 200%–600%.[9]

The implications of such remarkable increases in the demand for energy minerals have not been entirely ignored, at least in Europe. A Dutch government–sponsored study concluded that the Netherlands' green ambitions alone would consume a major share of global minerals. "Exponential growth in [global]

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[3] U.S. Department of Energy (DOE), "Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities," September 2015, p. 390

[4] Vaclav Smil, "To Get Wind Power You Need Oil," *IEEE Spectrum*, Feb. 29, 2016.

[5] U.S. Department of Energy (DOE), "Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities," September 2015.

[6] La Porta et al., *The Growing Role of Minerals and Metals.*

[7] Matt Bohlsen, "Cobalt Miners News for the Month of November 2019," Seeking Alpha, Nov. 26, 2019; John Petersen, "The Cobalt Cliff Will Crush Tesla's Business and May Restore Some Sanity to the EV Industry," Seeking Alpha, Sept. 29, 2019.

[8] Jamie Smyth, "BHP Positions Itself at Centre of Electric-Car Battery Market," *Financial Times*, Aug. 9, 2017.

[9] Elsa Dominish, Sven Teske, and Nick Florin, "Responsible Minerals Sourcing for Renewable Energy," Institute for Sustainable Futures, University of Technology Sydney, 2019.

renewable energy production capacity," the study noted, "is not possible with present-day technologies and annual metal production."[10]

Behind the Scenes: Ore Grades and "Overburden"

The scale of these material demands understates the total tonnage of the earth that is necessarily moved and processed, all of which requires the use of energy-consuming machines and processes. Forecasts of future mineral demands focus on counting the quantity of refined, pure elements needed—but not the overall amount of the earth that must be dug up, moved, and processed.

For every ton of a purified element, a far greater tonnage of ore must be physically moved and processed. That is a reality for all elements, expressed by geologists as an ore grade: the percentage of the rock that contains the sought-after element. While ore grades vary widely, copper ores typically contain only about a half-percent, by weight, of the element itself: thus, roughly 200 tons of ore are dug up, moved, crushed, and processed to get to one ton of copper. For rare earths, some 20 to 160 tons of ore are mined per ton of element.[11] For cobalt, roughly 1,500 tons of ore are mined to get to one ton of the element.

In the calculus of economic and environmental costs, one must also include this so-called overburden—the tons of rocks and dirt that are first removed to get access to often deeply buried mineral-bearing ore. While overburden ratios also vary widely, it is common to see three to seven tons of earth moved to get access to one ton of ore.[12]

For a snapshot of what all this points to regarding the total materials footprint of the green energy path, consider the supply chain for a single electric car battery, which in final form weighs about 1,000 pounds.[13] Providing the refined minerals needed to fabricate a single EV battery requires the mining, moving, and processing of more than 500,000 pounds of materials somewhere on the planet.[14] That's 20 times more than the 25,000 pounds of petroleum that an internal combustion engine uses over the life of a car.

The core issue here for a green energy future is not whether there are enough elements in the earth's crust to meet demand; there are. Most elements are quite abundant, and nearly all are far more common than gold. Obtaining sufficient quantities of nature's elements, at a price that markets can tolerate, is fundamentally determined by technology and access to the land where they are buried. The latter is mainly about government permissions.

However, as the World Bank cautions, the materials implications of a "clean tech" future creates "a new suite of challenges for the sustainable development of minerals and resources."[15] Some minerals are difficult to obtain for technical reasons inherent in the geophysics. It is in the underlying physics of extraction and physical chemistry of refinement that we find the realities of unsustainable green energy at the scales that many propose.

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[10] Pieter van Exter et al., "Metal Demand for Renewable Electricity Generation in the Netherlands: Navigating a Complex Supply Chain," Metabolic, Universiteit Leiden, and Copper8, 2018.

[11] Laura Talens Peiró and Gara Villalba Méndez, "Material and Energy Requirement for Rare Earth Production," *Journal of the Minerals, Metals & Materials Society (JOM)* 65, no. 10 (August 2013): 1327–40.

[12] McArthur River Mine (Glencore), "Overburden," 2020.

[13] A Tesla 85-kWh battery pack weighs 1,200 lbs.: Neil Brooks, "Tesla Battery Weight Overview—All Models," enrg.io, Jan. 20, 2020.

[14] There is, over the life span of a conventional car, 50,000 pounds of cumulative gasoline consumption (counting upstream coproduction of associated liquids).

[15] La Porta et al., *The Growing Role of Minerals and Metals*.

Sources of Minerals: Conflicts and Dependencies

The critical, and even vital, roles of specific minerals have long been a concern of some analysts and various government commissions over the years. One can trace a straight line from an electric car to Inner Mongolia's massive Bayan Obo mines (for rare earths), and to mines in the Democratic Republic of Congo (for cobalt in batteries). Both of those regions represent the world's largest supply of rare earths and cobalt, respectively.[16]

Politically troubled Chile has the world's greatest lithium resources, although stable Australia is the world's biggest supplier. Elsewhere in the battery supply chain, Chinese cobalt refiners have quietly gained control over more than 90% of the battery industry's cobalt refining, without which the raw cobalt ore is useless.[17]

The Institute for Sustainable Futures in Sydney, Australia, cautions that a global gold rush for green minerals to meet ambitious plans could take miners into "some remote wilderness areas [that] have maintained high biodiversity because they haven't yet been disturbed."[18] And then there are the widely reportedly cases of abuse and child labor in mines in the Congo, where 70% of the world's raw cobalt originates.[19]

Late in 2019, Apple, Google, Tesla, Dell, and Microsoft found themselves accused in a lawsuit filed in a U.S. federal court of exploiting child labor in the Congo.[20] Similar connections can be made to labor abuses associated with copper, nickel, or niobium mines around the world.[21] While there is nothing new about such real or alleged abuses, what is new is the rapid growth and enormous prospective demand for tech's minerals and green energy minerals. The Dodd-Frank Act of 2010 includes reporting requirements on trade in "conflict minerals." A recent Government Accountability Office (GAO) report notes that more than a thousand companies filed conflict minerals disclosures with the Securities and Exchange Commission, per Dodd-Frank.[22]

Automakers building electric cars have joined smartphone makers in such pledges for "ethical sourcing" of minerals.[23] Car batteries are, however, create the biggest demand for "conflict" cobalt.[24] Companies can make pledges; but unfortunately, the facts suggest that there is little correlation between such pledges and the frequency of (claimed) abuses in foreign mines.[25] In addition to moral questions about exporting the environmental and labor challenges of mineral extraction, the strategic challenges of supply chains are a top security concern as well.

Strategic Dependencies: Old Security Worries Reanimated

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[16] Hong-Rui Fan et al., "The Giant Bayan Obo REE-Nb-Fe Deposit, China: Controversy and Ore Genesis," *Geoscience Frontiers* 7, no. 3 (May 2016): 335–44; DOI and USGS, "Mineral Commodity Summaries 2020."

[17] John Petersen, "The Cobalt Cliff Could Eradicate Non-Chinese EV Manufacturing Before 2030," Seeking Alpha, July 3, 2019.

[18] Ashley Stumvoll, "Are There Potential Downsides of Going to 100% Renewable Energy?" *Pacific Standard*, June 20, 2019.

[19] Douglas Broom, "The Dirty Secret of Electric Vehicles," World Economic Forum, Mar. 27, 2019.

[20] Jennifer Smith, "Apple, Google, Tesla, Microsoft and Dell Are Accused of Exploiting Child Labor in the Democratic Republic of Congo by African Families Whose Kids Have Been 'Maimed or Killed' Mining Cobalt to Be Used in Lithium Batteries," *Daily Mail*, Dec. 16, 2019.

[21] Kate Hodal, " 'Most Renewable Energy Companies' Linked with Claims of Abuses in Mines," *The Guardian*, Sept. 5, 2019.

[22] GAO, "Conflict Minerals: 2018 Company Reports on Mineral Sources Were Similar in Number and Content to Those Filed in the Prior 2 Years," September 2019.

[23] Andreas Cremer, "Automakers Pledge Ethical Minerals Sourcing for Electric Cars," Reuters, Nov. 29, 2017.

[24] Vivienne Walt and Sebastian Meyer, "Blood, Sweat, and Batteries," *Fortune*, Aug. 23, 2018.

[25] Hodal, "Most Renewable Energy Companies."

Supply-chain worries about critical minerals during World War I prompted Congress to establish, in 1922, the Army and Navy Munitions Board to plan for supply procurement, listing 42 strategic and critical materials. This was followed by the Strategic Materials Act of 1939. By World War II, some 15 critical materials had been stockpiled, six of which were released and used during that war. The 1939 act has been revised twice, in 1965 and 1979, and amended in 1993 to specify that the purpose of that act was for national defense only.[26]

As recently as 1990, the U.S. was the world's number-one producer of minerals. It is in seventh place today.[27] More relevant, as the United States Geological Survey (USGS) notes, are strategic dependencies on specific critical minerals. In 1954, the U.S. was 100% dependent on imports for eight minerals.[28] Today, the U.S. is 100% reliant on imports for 17 minerals and depends on imports for over 50% of 28 widely used minerals. China is a significant source for half of those 28 minerals.[29]

The Department of Defense and the Department of Energy (DOE) have issued reports on critical mineral dependencies many times over the decades. In 2010, DOE issued the Critical Materials Strategy; in 2013, DOE formed the Critical Materials Institute, the same year the National Science Foundation launched a critical-materials initiative.[30] In 2018, USGS identified a list of 35 minerals as critical to security of the nation.[31]

But decades of warnings about rising mineral dependencies have yielded no significant changes in domestic policies. The reality is that depending on imports for small quantities of minerals used in vital military technologies can be reasonably addressed by building domestic stockpiles, a solution as ancient as mining itself. However, today's massive domestic and global push for clean-tech energy cannot be addressed with small stockpiles. The options are to accept more strategic dependency, or to increase domestic mining.[32] And both those options have unaccounted for implications for total fuel-cycle carbon dioxide emissions.

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[26] National Research Council, *Managing Materials for a Twenty-First Century Military*.

[27] National Mining Association (NMA), "U.S. Mines to Markets," 2014.

[28] USGS, "Risk and Reliance: The U.S. Economy and Mineral Resources," Apr. 12, 2017.

[29] DOI and USGS, "Mineral Commodity Summaries 2020."

[30] GAO, "Strengthened Federal Approach Needed to Help Identify and Mitigate Supply Risks for Critical Raw Materials," September 2016.

[31] USGS, "Interior Releases 2018's Final List of 35 Minerals Deemed Critical to U.S. National Security and the Economy," May 18, 2018.

[32] Dave Keating, "Europe Waking Up to Raw Materials 'Criticality'," EURACTIV.com, Dec. 11, 2019.