Testimony
of
Mark P. Mills, Senior Fellow, Manhattan Institute
Before
Subcommittee on Environment, Manufacturing, and Critical Materials
U.S. House Committee on Energy and Commerce
Hearing on:
"*Exposing the Environmental, Human Rights, and National Security Risks of the Biden Administration's Rush to Green Policies***"**

April 26, 2026

Testimony Summary

Good afternoon. Thank you for the opportunity to testify. 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 my focus is on future manufacturing technologies. And, for the record, I'm a strategic partner in a venture fund focused on energy software, and I'm also a director of an oil-field services company.

Permit me to begin by observing two indisputable facts about our future. First, economic growth is the fundamental driver of energy demand. And second, while periods of slow growth and recessions are inevitable in all societies, those periods always end. But any subsequent growth can be stifled if energy supplies are either unavailable or too expensive.

Energy supply itself is not as much a matter of finding resources as it is one of building machines, regardless of the natural resource used, whether sun, wind, water, oil, gas, coal, or uranium. Thus realities around machine-building determine costs and all the associated environmental, social, and geopolitical impacts.

We know a lot about those impacts—both the good and the bad—associated with energy machines that use hydrocarbons because we've been using those technologies at scale for a long time, and because that's how 85 percent of U.S. and global energy is supplied. We've learned a lot less about impacts from wind, solar, and battery technologies because they're relatively new and, so far, supply only a few percent of society's overall energy.

The Biden Administration has a stated policy goal to see America powered increasingly, eventually entirely by renewable energy. I should like to stipulate that the future will doubtless see far greater use of wind and solar technologies, and electric cars, if for no other reason than the sheer scale of future energy needs, and because developed countries are wealthy enough to pay higher costs.

However, there are many misconceptions about the realities of renewable energy technologies at scale, especially if the goal is to replace rather than supplement hydrocarbons. It begins with the core reality that renewables aren't green. In fact, nor are renewable technologies inherently cheaper, nor more geopolitically secure.

That renewable energy isn't green is a consequence of an unavoidable feature of wind and solar resources; they have very low energy density. That means, compared to using hydrocarbons, one must build machines that occupy roughly ten-times more of the earth's surface to deliver the same amount of energy to society—whether it's an hour of heat, or light, or computing time, or a mile of driving.

Essentially all life occupies the thin, surface interface of our planet, whether it's land or water. One of humanity's greatest achievements has been the radical reduction in the amount of that interface we use to deliver increasing quantities of food and fuel.

The inherent low-energy-density of renewables also means that far more machinery must be fabricated to deliver the same energy as now supplied by hydrocarbon machines. That in turn translates into a radical increase in global mining and minerals processing to supply all the critical materials needed to build renewable machinery.

Renewable plans proposed or underway will require from 400 percent to 8,000 percent more mining for dozens of minerals, from copper and nickel, to aluminum, graphite, and lithium. The IEA says the world will need hundreds of new mines, soon. Given regulatory realities, those won't be here. Instead, most will be in emerging economies and most will be on or near the lands of indigenous people in areas that are culturally and ecologically valuable and fragile.

And given machine realities, the huge jump in mining required will increase energy use in that sector, thus offsetting a lot, in some cases all the CO2 emissions saved later by replacing hydrocarbons in powerplants and cars. Global mining today already accounts for 40 percent of worldwide industrial energy use, which is dominated by hydrocarbons, and will be for decades.

It bears noting that renewable-energy machines are like all machines; they wear out. This means the near future will see megatons of worn-out hardware, of trash, much at unprecedented scale because of the unprecedented quantities of energy machinery needed. Some of it cannot be recycled at all, some not easily, much of it expensively.

The huge land footprint and materials requirements of renewable machinery shows up in the economics too. Despite claims of cost parity, the fact is that in every state and nation, a rising share of wind and solar on grids has brought higher electricity costs. EVs, for similar reasons, are locked into inherently higher prices because of greater use of underlying resources.

Finally, the claim that renewables are geopolitically superior is exposed by one now well-known fact: China has a 40 to 80 percent market share in producing or refining energy minerals needed to build renewable machinery. That is a strategic dominance roughly double OPEC's market share in oil. Building assembly plants in the U.S. for EVs and solar panels doesn't change that fact.

There is, however, one common claim for renewables that's true: they create more jobs. That emerges directly from the excess land, materials and machinery needed to deliver the same energy. The problem is that much of that work isn't in America. And, to the extent it can be, any new jobs come at a time when our nation doesn't necessarily need more jobs, as much as it needs more people willing and able to fill the jobs we have, especially in the skilled trades.

<<>>

Full Testimony

For everything built or fabricated, including energy-producing machines from gas turbines to wind turbines, one can trace a straight line back upstream to where people use heavy equipment (in some countries, just shovels) to extract materials from the earth. Different forms of energy involve radically different types and quantities of energy-harvesting machines and therefore involve different kinds and quantities of materials, and of land used.

Whether it's liquids extracted from the earth to power an internal combustion engine or solids used to build batteries, any significant increase in materials used per mile will add up because Americans alone drive some 3 trillion road-miles a year. The same is true for delivering kilowatt-hours and all other energy uses. The upstream nature of the underlying minerals and materials needed for civilization has always been important. It is critical now that governments around the world are rushing to embrace if not force expansion of renewable energy.

All machines wear out, and there is nothing inherently renewable about green machines, since one must engage in continual extraction of materials to build new ones and replace those that wear out. All this requires mining, processing, transportation, and, ultimately, the disposing of millions of tons of materials, much of it functionally or economically unrecyclable.

Assuring access to the minerals that undergird society is a very old concern, one that is woven through history and has even precipitated wars. In the modern era, U.S. policies to address mineral dependencies date to 1922, when Congress, in the aftermath of World War I, developed a list of 42 "strategic and critical materials" for the technologies and machines important to the military at that time.[1] Next came the Strategic Materials Act of 1939, renewed and modified several times since, incorporating ideas to encourage domestic mining and create stockpiles of strategically critical minerals for military equipment.

Over the past century, there have been two significant developments. First, the U.S. has not expanded domestic mining, and, in most cases, the country's production of nearly all minerals has declined. Second, the demand for minerals has dramatically increased. These two intersecting trends have led to significant transformations in supply-chain dependencies. Imports today account for 100% of some 17 critical minerals, and, for 28 others, net imports account for more than half of demand.[2]

The Material Cost of "Clean Tech"

The materials extracted from the earth to fabricate wind turbines, solar panels, and batteries (to store grid electricity or power electric vehicles) are 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 environmental terms. Before considering the supply chain, it is important to understand the scale of the material demands. For green energy, it all begins with the fact that such sources are land-intensive and very diffuse.

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.[3] Building those wind

[1] National Research Council, "*Managing Materials for a Twenty-First Century Military*" (Washington, DC: National Academies Press, 2008).

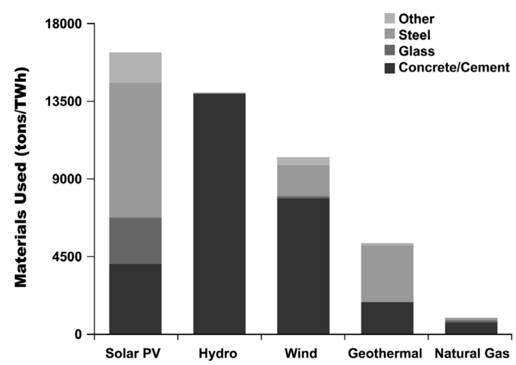
[2] U.S. Department of the Interior (DOI) and U.S. Geological Survey (USGS), "Mineral Commodity Summaries 2020," Feb. 6, 2020, p. 7.

[3] Landon Stevens, "The Footprint of Energy: Land Use of U.S. Electricity Production," Strata, June 2017. The calculation in this paper understates land usage; at least double the number of wind turbines, plus storage, is required if the goal is to replace the continuous availability of electricity from conventional generation.

machines consumes enormous quantities of conventional materials, including 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."[4]

All forms of green 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 hydro dams in material consumption, and solar farms outstrip both. In all three cases, the largest share of the tonnage is found in 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 (Figure 1).

Figure 1. Materials Requirements to Build Different Energy Machines



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

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.[5] With solar hardware, the tonnage in cement, steel, and glass is 150% greater than for wind, for the same energy output.[6]

[4] 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.

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

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

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, explored below. 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.[7] 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%.[8] Lithium production, used for electric cars (never mind the grid), will need to rise more than 2,000%.[9] 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%.[10]

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] renewable energy

---

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

[8] 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.

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

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

production capacity," the study noted, "is not possible with present-day technologies and annual metal production."[11]

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. That is because forecasts of future mineral demands focus on counting the quantity of refined, pure elements needed—but not the overall amount of 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.[12] 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 the 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.[13]

For a snapshot of what all this points to regarding the total materials footprint of the green energy path, consider the supply chain for an electric car battery. A single battery providing a useful driving range weighs about 1,000 pounds.[14] Taking into account various ore grades and typical overburdens, the math works out to providing the refined minerals needed to fabricate a single EV battery requires the mining, moving, and processing of more

[11] 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.

[12] 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.

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

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

than 500,000 pounds of materials somewhere on the planet (see sidebar).[15] That's 10 times more than the roughly 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."[16] 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.

Renewables: Hidden Costs of Materials

Today, the most dramatic factor driving the scale of future global mining is not the creation of products that require new uses of minerals (e.g., silicon for computers, aluminum for aircraft) but the push to use green machines to replace hydrocarbons to meet existing energy demands. Green machines mean mining more *materials per unit of energy* delivered to society. Since clean tech is about supplying energy in a more "sustainable" fashion, one needs to consider not just the physical mining realities but also the hidden energy costs of the underlying materials themselves, i.e., the "embodied" energy costs.

Embodied energy arises from the fuel used to dig up and move earth, grind and chemically separate minerals from the ores, refine the elements to purity, and fabricate the final product. Embodied energy costs can add up to surprising levels. For example, while an automobile weighs about 10,000 times more than a smartphone, the car requires only 400 times more energy to fabricate. And the world produces nearly 600,00 *tons* of consumer electronics annually.[17] Epitomizing this reality: the embodied energy to produce about 200 pounds of steel is the

---

[15] There is, over the life span of a conventional car, a total of about 50,000 pounds of cumulative upstream materials when both gasoline consumption (25,000 pounds) and the 25,000 pounds of coproduction of other associated liquids.

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

[17] Vaclav Smil, "Your Phone Costs Energy—Even Before You Turn It On," IEEE Spectrum, Apr. 26, 2016.

same as used to produce one pound of semiconductor-grade silicon.[18] The world also uses some 25,000 *tons* of (energy-intensive) pure semiconductor-grade silicon, a nonexistent material in the precomputer era.[19]

Embodied energy use starts with the fuel used by giant mining machines, such as the 0.3 mpg Caterpillar 797F, which can carry 400 tons of ore. There are also energy costs for electricity at the mine site (in remote areas, often diesel-powered) to run machines that crush rocks, as well as the energy costs in producing and using chemicals for refining. For minerals with very low ore grades, fuel can be a significant factor in the cost of the final product.

Rare earth elements, used in all manner of tech machines, including green ones, have rare properties but are much more abundant than gold. However, the physical chemistry of rare earths makes them difficult and energy-intensive to refine. It takes about twice as much energy to get access to and refine a pound of rare earth as a pound of lead, for example.[20]

For the mining industry, there is nothing new or surprising about the quantities of energy and chemicals used in the multistep processes needed to purify minerals locked up in rocks. While there are always ways (including, these days, with digital tools) to improve economic efficiency—and improve safety and environmental outcomes—research shows that, with regard to *energy efficiency*, the majority of the underlying mineral processes themselves already operate near technical or physics limits.[21]

This means that, for the usefully foreseeable future, increasing the production of green machines will unavoidably increase embodied energy. For example, analyses show that manufacturing a single battery, one capable of holding energy that is equivalent to one barrel of oil, entails processes that use the energy equivalent of 100 barrels of oil.[22] About half that energy is in the form of electricity and natural gas, and the other half oil. If the

[18] Timothy G. Gutowski et al., "The Energy Required to Produce Materials: Constraints on Energy-Intensity Improvements, Parameters of Demand," *Philosophical Transactions of the Royal Society A: Mathematical, Physical, and Engineering Sciences*, Mar. 13, 2013.

[19] Semiconductor Industry Association, "Rebooting the IT Revolution: A Call to Action," September 2015.

[20] Talens Peiró and Villalba Méndez, "Material and Energy Requirement for Rare Earth Production."

[21] Julian M. Allwood et al., "Material Efficiency: Providing Material Services with Less Material Production," *Philosophical Transactions of the Royal Society A*, Mar. 13, 2013.

[22] Jens F. Peters et al., "The Environmental Impact of Li-Ion Batteries and the Role of Key Parameters: A Review," *Renewable and Sustainable Energy Reviews* 67 (January 2017): 491–506; Qinyu Qiao et al., "Cradle-to-Gate Greenhouse Gas Emissions of Battery Electric and Internal Combustion Engine Vehicles in China," *Journal of Applied Energy* 204 (October 2017): 1399–1411.

batteries are manufactured in Asia (as 60% of the world's batteries are now), more than 60% of the electricity to do so is coal-fired.[23]

Embodied energy is also necessarily a part of building wind and solar machines, especially since large quantities of concrete, steel, and glass are required.[24] These commodity materials have relatively low embodied energy per pound, but the number of pounds involved is enormous.[25] Natural gas accounts for over 70% of the energy used to fabricate glass, for example.[26] Glass accounts for some 20% of the tonnage needed to build solar arrays. For wind turbines, oil and natural gas are used to fabricate fiberglass blades, and coal is used to make steel and concrete. Some perspective: if wind turbines were to supply half the world's electricity, nearly 2 billion tons of coal would have to be consumed to produce the concrete and steel, along with 1.5 billion barrels of oil to make the composite blades.[27]

One additional energy factor absent from analyses of the embodied energy of clean-tech machines is in how the materials are delivered. More than 75% of all oil and 100% of natural gas are transported to markets via pipelines.[28] (Most of the remaining ton-miles take place on ships.) Pipelines are the world's most energy-efficient means of moving a ton of material. However, nearly all the materials used to construct green machines are solids, and a very large share will be transported by truck. Using trucks instead of pipelines entails a 1,000% increase per ton-mile in the embodied transportation of energy materials.[29]

All the increases in upstream, embodied energy use for mining and mineral processing will collaterally increase the associated CO2 emissions which offsets a significant share, and in some cases all the CO2 emissions saved later by replacing hydrocarbons in powerplants and cars. Global mining today accounts for 40 percent of worldwide industrial energy use, which is dominated by hydrocarbons, and will be for decades.

---

[23] International Energy Agency (IEA), "Asia Is Set to Support Global Coal Demand for the Next Five Years," Dec. 17, 2019.

[24] Mia Romare and Lisbeth Dahllöf, "The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries: A Study with Focus on Current Technology and Batteries for Light-Duty Vehicles," IVL Swedish Environmental Research Institute, May 2017.

[25] Oil and natural gas have embodied energy costs, but one-tenth that of green tech per unit energy delivered.

[26] U.S. Energy Information Administration (EIA), "Glass Manufacturing Is an Energy-Intensive Industry Mainly Fueled by Natural Gas," Aug. 21, 2013.

[27] Smil, "To Get Wind Power You Need Oil."

[28] Jennifer B. Dunn et al., "Update to Transportation Parameters in GREET," Argonne National Laboratory, table 5, Oct. 7, 2013.

[29] Clark W. Gellings ed., *Efficient Use and Conservation of Energy* (Oxford: Eolss, 2009), p. 25.

Finally, in any full accounting of environmental realities, there is the disposal challenge inherent in the very large quantities of batteries, wind turbines, and solar cells after they wear out, a subject discussed below. For now, it bears noting that many wind turbines are already reaching their 20-year end of life; decommissioning and disposal realities are just beginning. The massive, reinforced fiberglass (plastic) blades are very expensive to cut up and handle, are composed of nonrecyclable materials and will end up in a landfill. As for solar farms, the International Renewable Energy Agency forecasts that by 2050, with current plans, solar garbage will constitute double the tonnage of all global plastic waste.[30]

For many green energy proponents, the solution to all these challenges with materials is found in a well-worn call for greater attention to "reduce, reuse, and recycle." Many people also take refuge in the belief that our future has room in it for more energy materials because technology is "dematerializing" the rest of society. In reality, neither dematerialization nor recycling offers a solution to the heavy costs of a green energy future.

The "Dematerialization" Trope

There is a popular claim in our digital times that the increasingly service-dominated economy means that "the need for resource-intensive manufacturing is not inevitable."[31] Or, as MIT scientist Andrew McAfee put it: "For just about all of human history our prosperity has been tightly coupled to our ability to take resources from the earth. . . . But not anymore."[32]

It is true that resource extraction—food, fuel, and minerals—accounts for only a minor share of America's overall GDP; that has been true for more than a century. However, the foundational requirement for any of those inputs has not decreased in absolute quantity, nor has there been a diminution of the importance of the reliability and security of the supply, and price, of those inputs.

---

[30] Stephanie Weckend, Andreas Wade, and Garvin Heath, "End-of-Life Management: Solar Photovoltaic Panels," International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems Programme (IRENA & IEA-PVPS), June 2016. Each year, 35 million tons of plastic pollution are produced around the earth. See, e.g., Seth Borenstein, "Science Says: Amount of Straws, Plastic Pollution Is Huge," phys.org, Apr. 21, 2018.

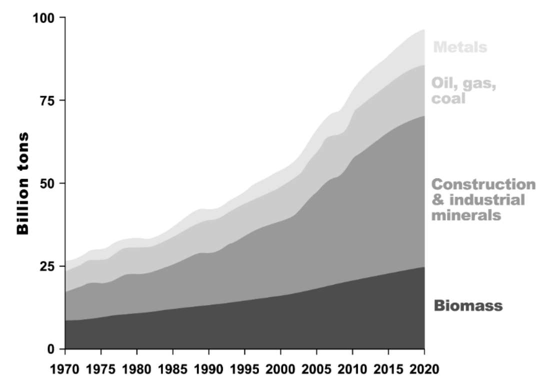
[31] Daniel Tenreiro, "Capitalism Will Save the World," *National Review*, Oct. 25, 2019.

[32] Andrew McAfee, *More from Less: The Surprising Story of How We Learned to Prosper Using Fewer Resources—and What Happens Next* (New York: Scribner, 2019), p. 1.

For evidence that society is not dematerializing in any fundamental way, we need only compare two iconic products of this and the past century: the smartphone and the automobile. These two products characterize a cultural shift and an apparent shift in material dependencies. As one analyst put it, teenagers have gone from driving cars to the mall to purchase music cassettes to streaming music digitally.[33] But the digital world has not eliminated the use of automobiles or the surprising quantities of minerals and materials used in the upstream production of all things digital. Forecasts for the next two decades see a 300% rise in global demand for common materials such as plastics, paper, iron, aluminum, silica (sand), and calcium (in limestone) for concrete.[34]

Wealthy economies have become more efficient, and the rate of economic growth has outpaced a slower rise in overall material use. But greater economic efficiency in material use *slows the growth rate*—it is not a fundamental decoupling of materials from growth. The world consumes over 100 billion tons each year in materials for construction, food, fuel, and metal parts (Figure 2).[35] That averages out to over 2 million pounds for each person's lifetime on the planet. More than 85% of that, so far, is for nonenergy purposes.

Figure 2. Global Use of Materials



Source: Gillian Foster et al., "Sustainable Consumption and Production," in Stephan Lutter, Fred Luks, and Sigrid Stagl, eds., *Towards a Socio-Ecological Transformation of the Economy*, Institute for Ecological Economics / Vienna University of Economics and Business (January 2019); Circle Economy, "Circularity Gap Report 2020"

Still, it is true that eventually—even if it is a century from now—there will be a slowing in demand for everyday materials as poorer nations approach a saturation level of per-capita use of food, homes, roads, and

[33] Lee Peterson, "The Dematerialization of Society in the Digital Age," *Fast Company*, Aug. 27, 2013.

[34] Gutowski et al., "The Energy Required to Produce Materials."

[35] OECD, *Material Resources, Productivity and the Environment*, Feb. 12, 2015; Circle Economy, "Circularity Gap Report 2020."

buildings.[36] We are a long way away from such saturation: wealthy nations have about 800 cars per 1,000 people, while in countries where billions of poorer people live, the ratio is closer to 800 people per single car.[37] To the extent that a rising share of those cars are electric, the demand for a wide variety of minerals will grow even faster.[38]

Reduce, Reuse, Recycle: No Exit from Renewables' Mineral Dependencies & Epic Waste Production

The mantra to "reduce, reuse, and recycle" ingrained in modern culture has become a feature in virtually all analyses and policy proposals directed at finding a way to reduce the materials demands of green energy. Reuse is generally irrelevant, since the vast majority of all products in society cannot be reused, and this includes green energy machines. The technical and environmental challenges, and thus the costs to reuse, more often than not are greater than those associated with using virgin material.

Reduce

Modern "reduce and recycle" policies and mandates were motivated in large measure by the goal to reduce the amount of trash going to landfills. So what will become of the rapidly increasing number of wind/solar/battery machines that are being produced? Answer: nearly all of them will eventually show up in waste dumps.

As we noted earlier, the International Renewable Energy Agency (IRENA) forecasts that by 2050, with current plans, solar garbage will constitute double the tonnage of all forms of global plastic waste. Similar scales are expected from end-of-life batteries used in electric cars and on power grids. China's annual battery trash alone is already estimated to reach 500,000 tons in 2020. It will exceed 2 million tons per year by 2030.[39] Currently, less than 5% of such batteries are recycled.[40]

When the 20 wind turbines wear out that constitute just one small 100-MW wind farm, decommissioning and trashing them will lead to fourfold more nonrecyclable plastic trash than all the world's (recyclable) plastic

[36] OECD, *Material Resources*.

[37] Oak Ridge National Laboratories, Transportation Energy Data Book, fig. 3.3.

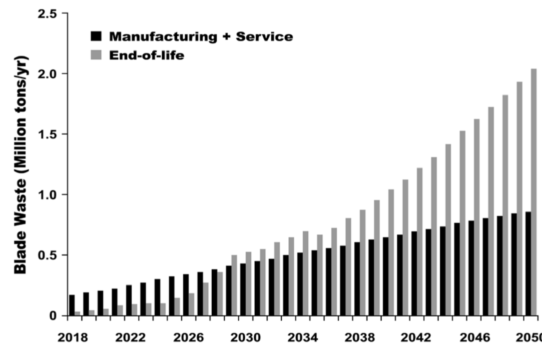
[38] Neil Hume and Henry Sanderson, "Investors Bet on Copper as Electric Car Race Hots Up," *Financial Times*, July 20, 2017.

[39] Mitch Jacoby, "It's Time to Get Serious About Recycling Lithium-Ion Batteries," *Chemical & Engineering News*, July 14, 2019.

[40] Ibid.

straws combined.[41] There are 1,000 times more wind turbines than that in the world today. If current International Energy Agency (IEA) forecasts are met, there will be over 3 million tons per year of unrecyclable plastic turbine blades by 2050 (Figure 3).

Figure 3. Annual Production of Waste from Global Wind Turbine Blades



Source: Pu Liu and Clare Y. Barlow, "Wind Turbine Blade Waste in 2050," Waste Management 62 (April 2017): 229–40

Recognizing the material intensity of clean energy technologies, some environmentalists suggest that what we need for a "real sustainable future is one that doesn't involve most people driving vehicles."[42] Proposals for encouraging or enforcing lifestyle changes are not new. They are no more likely to be effective in the future than they have been in the past.

Innovative engineering can lead to modest reductions in the use of some critical elements in electric motors and magnets. But that only slightly slows the rate of growth in demand. It doesn't eliminate the fact that building green machines is made possible by using the properties of many specific elements. For example: samarium enables smaller and more powerful magnets that are also far more stable at high temperatures. Lithium is, tautologically, the essential element in a lithium-ion battery; and copper remains the best option for electric conductors.

Recycle

[41] Borenstein, "Science Says: Amount of Straws, Plastic Pollution Is Huge."

[42] Paris Marx, "The Electric Vehicle Revolution Will Be Dirty and Unequal: Batteries for New Cars Will Require a Lot of New Mining," *Medium*, June 14, 2019.

For green energy advocates, the idealized vision for recycling encompasses deploying a "circular economy" as a number-one priority for dealing with the material implications of clean tech.[43] But the idea of a green energy circular economy based on the goal of 100% recycling is a pipe dream.[44]

Many materials, especially high-value metals, *can* be significantly recycled. But we can consider the implications and lessons for green waste by looking at the 50 million tons of so-called e-waste generated globally from worn-out or outmoded digital devices that are also built using many critical and rare minerals. The tonnage of global e-waste equals "the weight of all commercial aircraft ever built" and is forecast to double in the next several decades.[45]

The millions of tons of e-waste contain hundreds of tons of gold and thousands of tons of silver (generally the primary target of recyclers, for obvious reasons) as well as more than a dozen other elements.[46] In order to increase e-waste recycling from today's 20% level, the World Economic Forum (among others) proposes various measures to increase consumer "awareness," add new regulations and subsidies, and push to redesign the original devices. The Forum estimates that these efforts would reduce consumer costs by 14% over the next two decades.[47]

But as the scale of global recycling grows, many governments and some environmental organizations are beginning to focus on the serious health and safety issues that have been ignored.[48] So far, the majority of e-waste is recycled—as is much other waste—in poorer nations willing to undertake the labor-intensive, largely unregulated, and sometimes hazardous processes involved. Ghana, for example, is where Europe exports the largest quantity of its e-waste.[49] Meantime, the global recycling industry is still adjusting to a new reality: two years ago, China abruptly banned the importation of waste, asserting that much of it was "dirty" and "hazardous."[50]

The challenge with recycling trace minerals is essentially the same as in mining itself: much depends on concentrations. The concentration of useful minerals in e-waste and green waste is very low and often far lower than

---

[43] Frédéric Simon, "Circular Economy Erected as 'Number One Priority' of European Green Deal," EURACTIV.com, Nov. 13, 2019.

[44] Ellen MacArthur Foundation, "Completing the Picture: How the Circular Economy Tackles Climate Change," September 2019.

[45] World Economic Forum, "A New Circular Vision for Electronics: Time for a Global Reboot," Jan. 24, 2019.

[46] Vincent Magnenat, "A World Without Waste: How Gold Mining Is Going Green," *Eco-Business*, Dec. 16, 2019.

[47] World Economic Forum, "A New Circular Vision for Electronics."

[48] Hannah Beech and Ryn Jirenuwat, "The Price of Recycling Old Laptops," *New York Times*, Dec. 8, 2019.

[49] Magnenat, "A World Without Waste."

[50] Leslie Hook and John Reed, "Why the World's Recycling System Stopped Working," *Financial Times*, Oct. 25, 2018.

the ore grades of those minerals in rocks. In addition, the physical nature of trashed hardware is highly varied (again, unlike rocks), making it a challenge to find simple mechanisms to separate out the minerals. Recycling processes are often labor-intensive (hence the pursuit of cheap labor, sometimes child labor, overseas) and hazardous because techniques to burn away unwanted packaging can release toxic fumes.[51]

If "urban mining"—the oft-used locution for capturing minerals hidden in worn-out products—were easier, cheaper, and safer than mining new materials, there would be a lot more of it, and it would not require subsidies and mandates to put into effect. While technology, especially automation and robotics, will eventually bring more economically viable and cleaner ways to recycle, the challenges are daunting and progress has been slow. That's the reason that the overall global levels of net recycling and capture of most metals (for all purposes, not just e-waste and green waste) are below 20%, and much lower than those for all the rare earths.[52]

Even as Apple has championed recycling programs for its products—including inventing a robot to disassemble iPhones (it can only do iPhones)[53] and opening a new Material Recovery Lab in Austin, Texas—the company, along with many other tech companies, vigorously promotes green energy.[54] But there is as much cobalt in a single EV battery, for example, as there is in 1,000 iPhones, as much plastic in a single wind turbine as in 5 million iPhones, and as much glass in a solar array that could power a single data center as in 50 million iPhones.[55]

A recent Department of Energy vision for offshore wind turbines (not counting onshore wind) in the U.S. would lead to nearly 10 thousand tons of neodymium alone "buried" inside more than 4 million tons of machinery that will eventually head for waste dumps.[56] That sounds like a lot of material worth recovering, but it pencils out to a neodymium concentration in the trash that is one-tenth of the natural ore grade for that mineral at a mine site.[57] Such realities can lead to the surprising outcome that the energy required to recover a recycled mineral can be greater than expended to get it from nature's ore.[58] That doesn't mean that recycling won't continue to have a role,

---

[51] Ibid.

[52] Edmund Nickless et al., "Resourcing Future Generations White Paper: Mineral Resources and Future Supply," International Union of Geological Sciences, October 2014.

[53] Heather Clancy, "Meet Daisy, Apple's Latest Robot for Recovering and Reusing iPhone Components," *GreenBiz*, Apr. 19, 2018.

[54] Lauren Phipps, "Apple Dials Up Its Circular Materials Aspirations," *GreenBiz*, Apr. 18, 2019.

[55] "iPhone X Environmental Report," Apple.com, Sept. 12, 2017.

[56] DOE, Office of Energy Efficiency & Renewable Energy, "Wind Vision: A New Era for Wind Power in the United States," Mar. 12, 2015.

[57] Talens Peiró and Villalba Méndez, "Material and Energy Requirement for Rare Earth Production."

[58] Bradley S. Van Gosen et al., "Rare-Earth Elements," USGS, Professional Paper 1802-O, 2017.

even a greater one. But its limits are clear. The challenges in meeting the requirements for global minerals in the future will not be met with wishful thinking about "circular economies."

Renewables and Minerals: Ethics, Conflicts and Dependencies

One can trace a straight line from an electric car to Inner Mongolia's massive Bayan Obo mines (for rare earths), and from a smartphone to mines in the Democratic Republic of Congo (for cobalt in batteries), or from a medical MRI to giant trucks in the mines of Brazil (for niobium in superconducting magnets).[59] Each of those regions represents the world's largest supply of rare earths, cobalt, and niobium, respectively.[60]

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.[61]

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."[62] 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.[63]

Automakers building electric cars have joined smartphone makers in such pledges for "ethical sourcing" of minerals.[64] Car batteries use far more of "conflict" cobalt.[65] 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.[66] 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.

[59] Júlia Pontés, "I Dream … that One Day, We'll Also Have a Niobium Valley," *Bloomberg Businessweek*, 2019.

[60] 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."

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

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

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

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

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

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

Strategic Dependencies: Old Security Worries Reanimated

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.[67]

As recently as 1990, the U.S. was the world's number-one producer of minerals. It is in seventh place today.[68] 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.[69] 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.[70]

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.[71] In 2018, USGS identified a list of 35 minerals as critical to security of the nation.[72]

But decades of hand-wringing over rising mineral dependencies have yielded no significant changes in domestic policies. The truth 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

---

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

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

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

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

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

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

stockpiles. The options—other than eschewing more green energy—are to simply accept more strategic dependency, or to increase domestic mining.[73]

Renewable Energy's Radical Strategic Dependencies

The U.S. has in the past half-decade achieved strategic energy independence. This comes after decades of political, economic, and geopolitical anxieties over import dependencies for natural gas and oil, in particular. The nation now produces more gas than it consumes and is thus a net exporter; it also produces 90% of net petroleum needs and is thus essentially strategically independent. As with agricultural products, where the U.S. is also a net exporter, achieving net independence does not obviate a need for or value in imports as part of the overall complex structure of commodity exchanges. But strategic "insulation," as well as geopolitical "soft power," comes from a posture of "dominance" in commodities critical to national survival.[74] While it remains to be seen how much damage is inflicted on domestic energy production in the post-coronavirus recession, it is now clear that the nation has significant capabilities in strategic hydrocarbon production *and* exports. Given that 56% of all America's energy comes from oil and gas, this achievement has deep strategic implications.

On the other hand, as of today, just 4% of overall domestic energy needs are supplied by wind and solar machines, and batteries propel less than 0.5% of domestic road-miles. About 90% of solar panels are imported.[75] Even if the panels were assembled here, the U.S. fabricates only 10% of the global supply of the critical underlying silicon material. China produces half.[76] For wind turbines, the U.S. imports some 80% of the electrical components (i.e., excluding fiberglass and steel).[77] And while Tesla (accounting for nearly 80% of all domestic EV sales)[78] manufactures domestically, essentially all the critical minerals originate overseas.

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

[74] Mark P. Mills, "Expanding America's Petroleum Power: Geopolitics in the Third Oil Era," Manhattan Institute, 2016.

[75] EIA, "2018 Annual Solar Photovoltaic Module Shipments Report," July 2019.

[76] Debra Sandor et al., "System Dynamics of Polysilicon for Solar Photovoltaics," *Sustainability* 10, no. 1 (January 2018): 160–87.

[77] Ryan Wiser et al., "2018 Wind Technologies Market Report," DOE, Office of Energy Efficiency & Renewable Energy, August 2019.

[78] Zachary Shahan, "Tesla Gobbled Up 78% of U.S. Electric Vehicle Sales in 2019," CleanTechnica, Jan. 16, 2020.

Thus, any significant expansion in green machines' tiny share of domestic energy will radically increase imports of either those machines, or the green energy minerals, or both. The quantities of imports will be unprecedented.

The strategic implications of green energy materials have not escaped attention in Europe. An analysis from The Hague Centre for Strategic Studies summarized the "security dimension" of the world's rush to promote renewable energy. The analysis points to three obvious macro trends noting that "large unexploited mineral reserves" will gain strategic importance and drily observes that "import dependent countries may use military capabilities to secure mineral resources."[79]

It remains to be seen if Europe's newfound mining ambitions will be greeted by environmentalists and the continent's various green parties, given the hostility of both to extraction industries in general. Just prior to the global coronavirus pandemic, protests started to erupt over plans for new European mines,[80] in response to which industries were spooling up a PR campaign to try to manage "the unfavourable status of mineral extraction."[81]

Even without subsidies, mandates, and policies that favor green energy, the future for both America and the rest of the world will see many more wind and solar farms and many more electric cars. That will happen precisely because those technologies have matured enough to play significant roles. And given the magnitude of pent-up global demand for energy and energy-using machines and services—especially after the world struggles out of recession—it is a truth, not a slogan, that the world will need "all of the above" in energy supplies.

These realities, combined with the immutable reality that green machines require extraordinary quantities of energy minerals, can perhaps form a common intersection of interests that support an expansion of domestic mining. That would be, after all, of strategic and economic benefit to the United States, regardless of the debates over whether renewable energy can replace hydrocarbons, which it cannot, or whether it's a significant addition to energy supplies, which it most assuredly is. <><>

---

[79] Marjolein de Ridder, "The Geopolitics of Mineral Resources for Renewable Energy Technologies," The Hague Centre for Strategic Studies, August 2013.

[80] Peter Wise, " 'Lithium Fever' Grips Portugal as Mining Project Raises Hackles," *Financial Times*, Jan. 6, 2020.

[81] "A New Future for Mineral Exploration," INFACT, November 2019.