Shattered Green Dreams

The environmental costs of wind and solar

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Executive Summary

Wind turbines, solar panels, battery storage, and other "green energy" technologies are too often hailed as unqualified goods for the environment. However, there are no solutions, only tradeoffs, and the same is true for energy production and its environmental impact. All human activities have an impact on the environment.

Debates about the U.S.' energy mix almost entirely overlook or minimize the negative environmental impacts of wind, solar, and batteries while diminishing the positive impacts of oil and gas, coal, and nuclear. Policymakers must consider the costs of wind and solar and the benefits of oil and gas, coal, and nuclear when determining the desirability and feasibility of ambitious energy transition goals. Further, communities ought to be fully informed of the costs of wind and solar when debating the merits of proposed projects in their areas.

This executive summary is offered based on the findings of this report.

- **Every form of energy generation comes with its own set of challenges and benefits.** All renewable and hydrocarbon energy sources — wind and solar, hydropower, coal, natural gas, and nuclear — have environmental impacts. The mining of raw materials, manufacturing, and construction, the landscape footprints and ecological impacts of utility-scale wind and solar projects, and repowering and recycling costs must be considered.
- **The negative impacts of wind and solar on the environment are too often overlooked**. A wide variety and large quantity of minerals are used in solar panels, wind turbines, battery storage, transmission lines, and more. The U.S. currently sources most of its minerals from foreign countries that do not adhere to modern environmental or worker health and safety standards, which exacerbates environmental impacts that could be managed with domestic mining.
- **The positive impacts of nuclear, natural gas, oil, and coal are rarely discussed.** These sources of energy are highly reliable, 24/7 power sources that provide baseload and peaking power to the grid. They are scalable, affordable, and have small landscape footprints.
- **Existing estimates of material intensity of net-zero carbon emissions, both U.S. and global, reflect the enormity of this industrial undertaking.** Some methodologies may be significant underestimates due to optimistic capacity factors for wind and solar, high uptake of recycling, and other model assumptions.
- **Every form of energy production requires real estate.** The low electricity density of wind and solar generation means that they require at least 10 times as much land per unit of power produced as coal- or natural gas-fired power plants. If the U.S. were powered entirely by wind turbines, the land area necessary would exceed two Californias.
- **The ecological impacts of wind and solar cannot be discounted**. Evidence is growing that offshore wind turbines are disruptive to whale populations and wind turbines strike bird and bat populations. Habitat fragmentation disrupts nesting, migration, and wintering activities of some species. Large land use footprints exacerbate habitat loss and disruption to wildlife, endanger prime agricultural lands, and lead to zoning conflicts with residents.
- **Decommissioning and repowering wind and solar energy is required more often than other forms of electricity generation, compounding costs.** The operating lifespan of wind turbines and solar panels is between 20 and 25 years at maximum, while natural gas plants may operate for 40 years, and nuclear plants operate between 40 and 80 years. Repowering often occurs well before expected lifespans, which further exacerbates the environmental impacts of wind and solar.
- **Some components in wind turbines and solar panels are hazardous, with few commercial recycling pathways.** Current recycling pathways are uneconomic and underutilized, which means that decommissioned wind turbines and solar panels often end up in landfills.
- **Recycling and technological advances may help reduce mineral needs, but they will not entirely mitigate the need for new materials**. Technological advances may eventually change the types and

quantities of minerals needed for wind and solar power but are unlikely to radically change system-wide material intensity, as it is not possible to recycle materials that have not been manufactured.

- **Debates about the feasibility and desirability of an "energy transition" should include the negative impacts of wind and solar.** If voters and policymakers decide the benefits outweigh the costs, it should only be done with a clear accounting of both.

Introduction

This report describes the significant environmental drawbacks of wind, solar, and battery storage and compares them to the environmental impacts of other sources of electricity generation. Mining, manufacturing, and land use have tangible impacts on the environment and the surrounding communities.

Federal and state governments are mandating ever-stricter requirements for wind and solar electricity generation — but an honest accounting of their advantages and disadvantages should remind policymakers that there is no such thing as a free lunch. Ambitious energy transition goals may no longer seem as desirable when the environmental costs of wind, solar, and battery storage are factored in.

There is a growing understanding that our modern lives and our electric grids require an exorbitant amount and variety of new materials. As American Experiment illustrated in its October 2024 report "Mission Impossible: Mineral Shortages and the Broken Permitting Process Put Net Zero Goals Out of Reach," the mineral demands needed to meet net-zero by 2050 deadlines cast doubt on the feasibility of the entire endeavor.[1]

Maximizing the reliability and affordability of the country's electricity supply while minimizing environmental impacts should be the goal of energy policy. Wind, solar, and battery storage fail to meet reliability and affordability criteria. This report shows that they also fail to adequately protect the environment.

Section I will explain the conceptual basis for how wind turbines, solar panels, and battery storage can have a negative impact on the environment. Several reasons include the mining and manufacturing of raw materials in foreign countries, large land use footprints, impacts on wildlife, hazardous waste disposal, and increased local surface temperatures.

Section II examines existing estimates of material requirements of U.S. and global net-zero carbon emission scenarios as well as calculates simple estimates of the materials needed for individual technologies like wind turbines, solar panels, and battery storage. This section also calculates a simple estimate of the carbon dioxide emissions generated by cement production for wind turbines to meet a U.S. net-zero scenario.

Section III demonstrates that it matters where materials are mined and manufactured. Foreign countries have weaker regulatory protections for the environment and worker health and safety, which has devastating consequences for environmental stewardship and human health.

Section IV examines the scientific literature surrounding wind turbines and solar panels' impacts on wildlife populations, including species of birds, bats, and whales.

Section V discusses the important issue of decommissioning and waste management. The "life cycle" of wind turbines, solar panels, and battery storage is much shorter than other power generators and entails disposal of hazardous waste.

Section VI describes existing estimates of the land use requirements of grids with different power generation mixes.

Section VII directly addresses the assumption that advances in technology and upticks in recycling will drastically reduce material requirements. While some recycling and technological advances may help meet material demands, some materials are less recyclable than others and, more importantly, commercial recycling pathways are not yet well-developed.

Section I: How Can "Renewables" Be Bad for the Environment?

Sunshine and the breeze are nonpolluting. But building wind turbines, solar panels, and batteries to harvest and store wind and solar resources entail environmental costs in the mining of raw material. Emissions also occur during mineral processing, manufacturing, and construction, as well as repowering and decommissioning at the end of a facility's useful life.

Where minerals, metals, and materials are mined and produced matters for their environmental impact. The U.S. and other developed countries with modern mining regulations and technologies, such as the U.K. and Australia, can adequately manage the environmental impacts of mining. Procuring minerals from developing countries with lax environmental and labor protections poses greater harm to the environment, worker health and safety, and national security. The same is true for refining raw materials and constructing final products.

All forms of energy entail a land footprint. Coal, natural gas, and nuclear power plants can generate vast quantities of energy on small footprints, while wind and solar are dilute energy sources that require much more land to produce the same amount of electricity. Larger land use disrupts the habitats of birds, bats, whales, and other species, and many are killed through collisions with infrastructure.

Wind turbines and solar panels, like all machines, eventually wear out and need replacement. The International Energy Agency (IEA) expects that disposal of waste from worn-out wind turbines, solar panels, and batteries will become a major environmental challenge as these machines reach the end of their useful lifetimes. Construction of solar panels, wind turbines, battery storage, and electric vehicle batteries also release emissions.

Peer-reviewed scientific literature shows that wind turbines and solar panels have significant impacts on local surface temperatures, even though these technologies do not emit carbon dioxide or other "greenhouse gases" while generating electricity.

Section II: Material Requirements for Renewables Technologies

Section II.1: General estimates for key materials in the U.S. and global net-zero scenario

American Experiment's October 2024 report, "Mission Impossible: Mineral Shortages and the Broken Permitting Process Put Net Zero Goals Out of Reach," describes the importance of minerals to the U.S. economy and the mineral intensity of global net-zero carbon emissions goals, as defined by the IEA.[2] Notably, the IEA does not account for steel or aluminum demands in its estimates.

Under a global net-zero scenario, the IEA estimates that total mineral demand from clean energy technologies will at least quadruple from 2020 levels. Electric vehicles (EVs) and battery storage account for almost half of total mineral demand growth, growing 10 times over 2020 levels to reach global net zero emissions by 2070. Electricity networks create the second-highest mineral demand, with wind, solar, and other low-carbon energy sources comprising the rest of the mineral demand. The IEA forecasts demand doubling for copper, nickel, cobalt, and rare earth elements, graphite demand quadrupling, and lithium demand increasing by a factor of 10. The geographic concentration of these minerals is expected to come primarily from China, as they do today.

The IEA estimates that globally, 50 more lithium mines, 60 more nickel mines, and 17 more cobalt mines would need to be constructed by 2030 — which is likely impossible given long permitting timelines and high capital costs. The United Nations Conference on Trade and Development suggests that new total mine investment would need to range between $360 and $450 billion, with significant investment gaps.

U.S. government policies like the Inflation Reduction Act of 2022 juiced demand for lithium (up 15 percent), nickel (up 14 percent), cobalt (up 13 percent), and copper (up 12 percent) compared to projections prior to the IRA. Compounding mineral demands are electricity needs for data centers, which are driving electricity demand growth and therefore construction materials like copper and aluminum.

Global copper demand will likely double, and mines will only be able to meet 70 percent of the forecasted demand. Another study for the International Energy Forum suggests that just business-as-usual needs will require 115 percent more copper to be mined over the next 30 years than has been mined in human history through 2018. Full vehicle electrification will require 55 percent more copper mines than would otherwise be needed under that baseline.

The U.S. government acknowledges about 50 minerals as "critical minerals" that are essential to the economy and national security but have supply chains vulnerable to disruption.[3] Copper, the electrification metal, also plays a significant role. However, most existing estimates of materials demand for clean energy transition goals don't attempt to account for construction materials like steel, concrete, and aluminum, which are less vulnerable to disruptions of global supply chains.

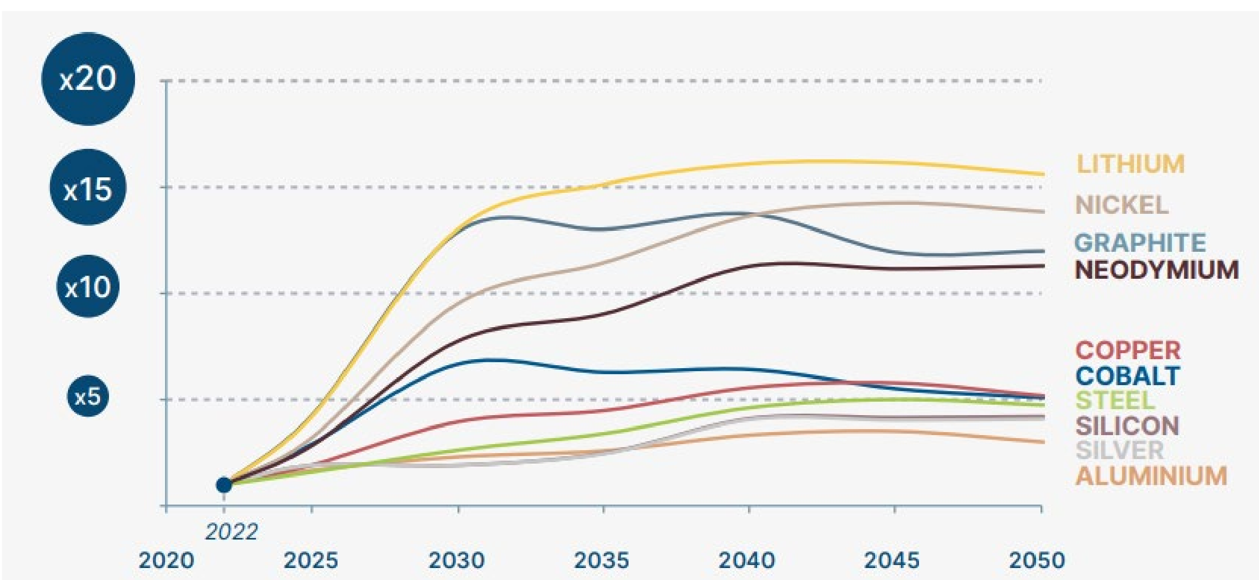
A 2023 report by the Energy Transitions Commission predicts that global steel demand will increase by five times its 2022 level by 2050 under a global net-zero emissions scenario.[4] While steel will also be driven by the construction of new buildings and other industrial applications, it is also used in technologies like wind, solar, and battery storage. The report states that demand for steel, aluminum, and copper account for 95 percent of total end-use material requirements for global net-zero.[5] The assumptions of the report are likely optimistic, especially its high end-of-life recycling rates of solar, wind, and batteries, which would exacerbate material demands.

Figure 1, reproduced from the 2023 Energy Transitions Commission report, shows that demand for steel from clean energy technologies will increase by a factor of five.[6] The report estimates that global annual requirements between 2022 and 2050 would be 170 million metric tons, or about twice the U.S.' domestic raw steel production in 2024 (81 million metric tons).[7]

The report also estimates that aluminum global average annual requirements would be around 30 million metric tons for clean energy, or 45 times the U.S.' 670,000 metric tons of primary aluminum production in 2024 and 42 percent of the world's 72 million metric tons of production in 2024.[8] These figures would render a global net-zero scenario untenable by themselves, were it not for aluminum's high recyclability, which enabled the U.S. to produce 3.3 million metric tons of secondary supply in 2024.[9] However, both steel and aluminum are in demand for other uses like construction, automobiles and transportation, machinery, appliances, food packaging, electronics, and more, which will drive up prices significantly if more iron and aluminum are not produced.

The 2023 Energy Transitions Commission report is most concerned about copper, with an average annual requirement between 2022 and 2050 of 20 million metric tons. The U.S. Geological Survey (USGS) estimates that the U.S. produced 1.1 million metric tons of copper in 2024 and another 870,000 metric tons from scrap.[10] However, the world only produced 23 million metric tons of copper from mines in 2024, so almost all of the world's copper would

Figure 1
Required Scale-Up in Materials Demand by 2050
Relative increase in demand for key materials from clean energy technologies, from 2022



Source: Energy Transitions Commission Report, "Material and Resource Requirements for the Energy Transition."

need to go to the technology needed for net-zero each year — which is simply not tenable when copper has other uses like electronics, plumbing, construction, automobiles, and other industries.

Concrete demand is not estimated in the 2023 Energy Transitions Commission report because "overall demand from the energy transition would be trivial when compared to demand from construction."[11] However, that does not mean that the absolute quantity of concrete demanded for net-zero emissions (not in comparison with global concrete use in construction) is insignificant.

Section II.2: Material demands of wind turbines

The U.S. Department of Energy (DOE) expects domestic demand for concrete to double by 2050 thanks largely to construction.[12] Over 90 percent of total material requirements for a wind turbine are steel and concrete, but turbines use many other materials less intensively. The National Renewable Energy Laboratory (NREL) released a 2023 technical paper that assumes that a U.S. net-zero economy would require "at least a threefold increase in wind energy deployment."[13]

Even under "business-as-usual" levels of wind energy development, U.S. demand for nickel could reach 317 percent of 2020 U.S. production annually through 2028 . From 2030 to 2045, annual U.S. wind energy demand for nickel could reach 1,200 percent of 2020 levels of U.S. production under the high levels of wind deployment necessary for a U.S. net-zero scenario. Annual U.S. demand for balsa, a lightweight hardwood used in turbine blades, would reach 520 percent of *global* production for the wind turbines necessary for a net-zero U.S. economy. Carbon fiber, used in wind turbine blades, would reach 440 percent of U.S. production and 120 percent of global production annually. Copper demand for wind turbines alone would reach 30 percent of 2020 U.S. production. The U.S. doesn't have any primary production of chromium, gallium, graphite, lithium, manganese, niobium, tin, titanium, and balsa, which would all need to be procured from overseas for wind turbines in the U.S.

According to the NREL report, onshore wind power plants currently require 1,200 metric tons of material per megawatt, comprised by mass of 53 percent road aggregate (636 metric tons), 34 percent concrete (408 metric tons), nine percent steel (108 metric tons), two percent composites and polymers (24 metric tons), one percent cast iron (12 metric tons), one percent other metals and alloys (12 metric tons), and one percent other materials (12 metric tons). The report suggests that future onshore turbines will be more concrete intensive due to bigger foundations required for larger and taller turbines.

While no aggregate estimates of concrete production needed for a U.S. net-zero economy were found in the literature review, a "back of the napkin" calculation demonstrates the scale of the concrete production necessary for wind turbine construction. For wind power *only*, the U.S. has a total capacity around 150 GW.[14] Assuming 408 metric tons of concrete per megawatt (and assuming that all turbines are onshore, the dominant market share in the U.S.), there is already 61.2 million metric tons of concrete used in U.S. wind turbines. In 2023, there was 6.5 GW of capacity added, or 6,500 megawatts, which suggests 2.65 million metric tons of concrete demand in 2023 can be attributed specifically to wind turbines.

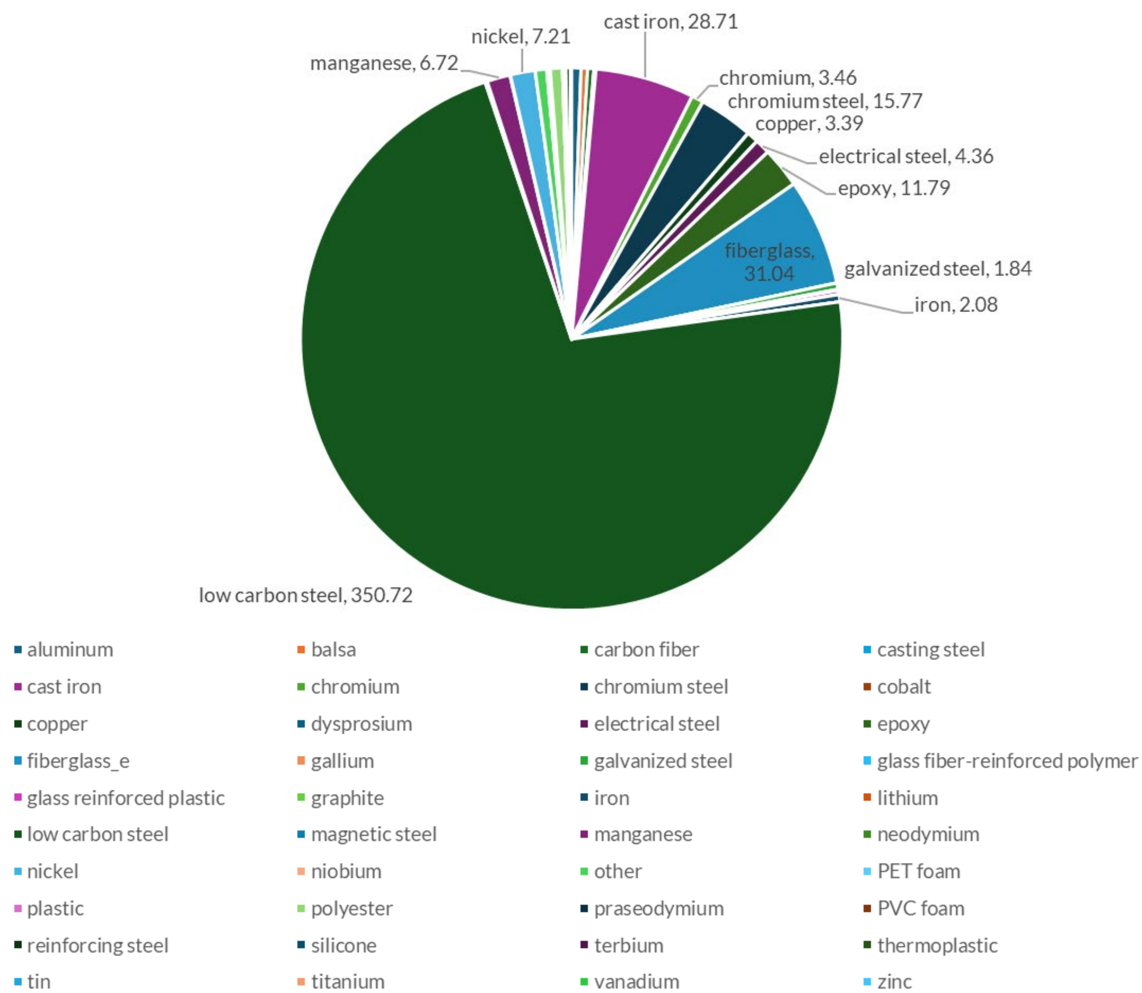
NREL expects that the U.S. will need a cumulative 1,000 GW of installed wind capacity by 2035 and nearly twice that by 2050, in concert with other renewables technology.[15] Therefore, total concrete used to build an additional 1,850 GW of wind capacity (assuming, for simplicity, onshore turbines only) would reach almost 347 million metric tons by 2035 and 755 million metric tons by 2050, or 34.7 million metric tons annually between 2025 and 2035 and 27.2 million metric tons annually between 2036 and 2050.

For context, the U.S. produced 84 million metric tons of cement in 2024, a key binding ingredient in concrete, which comprises only 10 to 15 percent of the concrete mix by volume, with sand, gravel, and water making up the bulk of the mix.[16] While the U.S. would likely be able to produce the amount of concrete necessary for the wind turbines to meet U.S. net-zero carbon emissions scenarios (in concert with other renewables technology), the USGS warns that domestic cement industry "continued to be constrained by closed or idle plants, underutilized capacity at others, production disruptions from plant upgrades, and relatively inexpensive imports."[17] Additional pressures on concrete from massive renewables buildout may lead to surging prices, and the USGS indicates that the price for cement has grown from $125 per metric ton in 2020 to $160 per metric ton in 2024.[18]

The concrete industry is also under pressure to reduce its emissions intensity due to the use of cement. Cement manufacturing releases carbon dioxide through the chemical conversion of calcium carbonate to lime and CO_2 and through burning fuel. That is estimated at 0.5-0.6 tons of CO_2 per ton of cement produced.[19]

As an illustrative example, assuming that the annual concrete demand for wind turbines *only* is 34.7 million metric tons, and cement comprises only 10 percent of the mix (3.47 million metric tons), then the CO_2 emissions released by concrete for wind turbines would be 1.735 million metric tons annually. The Environmental Protection Agency's Greenhouse Gas Equivalency Calculator estimates this to be equivalent to the annual emissions from 404,698 gas-powered passenger vehicles, 1.5 million EVs, or 1.9 billion pounds of coal. However, EPA's calculator also suggests that annual concrete demands for wind turbines would be offset by 518 wind turbines running for a year.[20] (This estimate assumes negligible carbon emissions through other portions of the manufacturing and transportation process, which is not the case, and assumes lower-bound estimates).

Figure 2
Metric Tons of Material Per 3.4 MW Onshore Wind Turbine



An average individual onshore wind turbine of 3.4 MW capacity, not including concrete foundations, is 72 percent low-carbon steel, or 350 metric tons.[21] Fiberglass (31 metric tons) and cast iron (28 metric tons) are about six percent of an average individual onshore turbine each. Copper, nickel, and manganese are about one percent each.

While the components of electrical steel may not see demand stressors, the NREL report highlights that "the manufacturing pathway for electrical steels is metallurgically specialized and the technical expertise for manufacturing electrical steels is highly guarded in industry"[22] Wind turbines need electrical steel for power generators and transformers, and broad-scale wind turbine deployment for net-zero could require 94 percent of 2020 U.S. production, and both material substitutions and recycling may not be viable options.

Section II.3: Material demands of solar

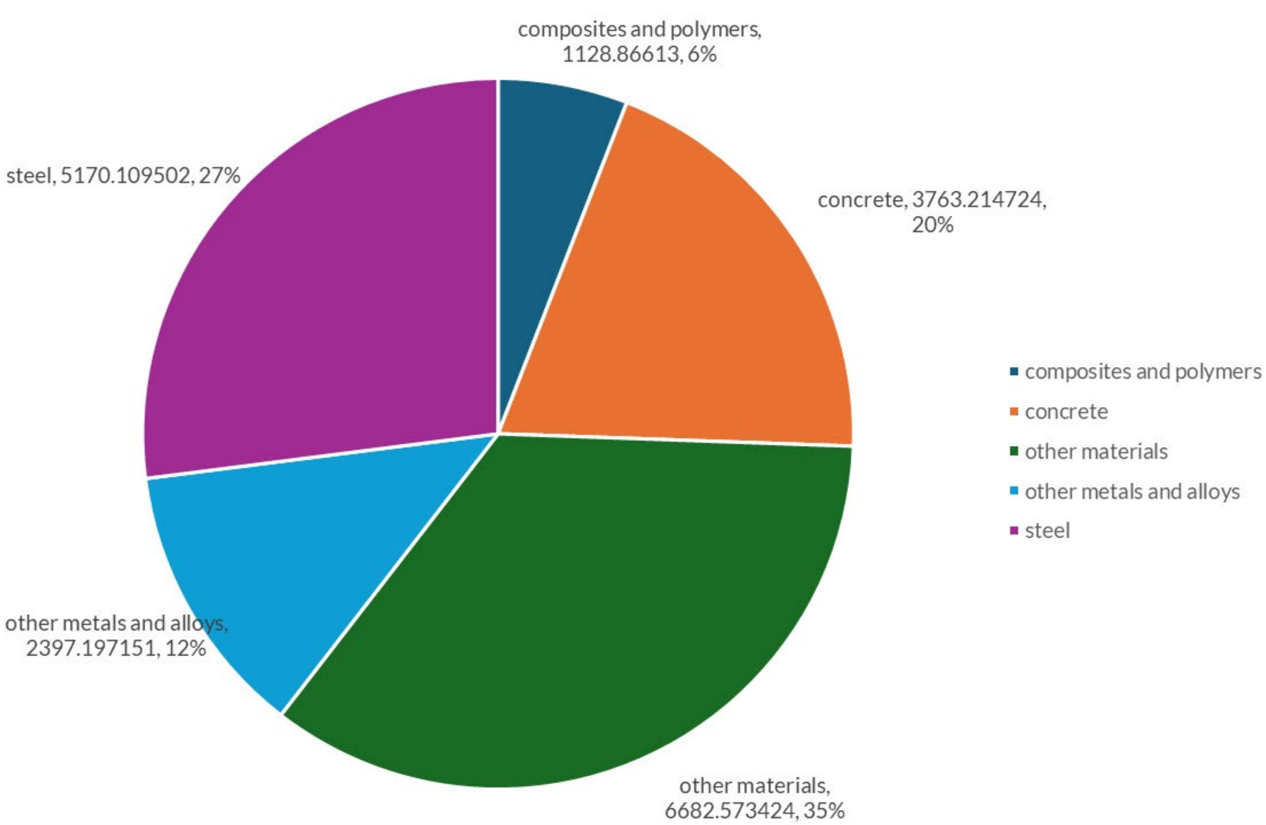
The Renewable Energy Materials Properties Database (REMPD) by NREL breaks down material quantities for four types of solar plants.[23] The types that comprise the most market share in the U.S. are utility photovoltaic crystalline silicon (c-Si) modules, followed by utility PV cadmium telluride modules, and residential and commercial rooftop solar.

A 100 MW capacity c-Si utility PV plant (which could be hundreds of thousands of individual panels) uses 3,763 metric tons of concrete (20 percent) and 5,170 metric tons of steel (27 percent). Other materials sum up to 6,682 metric tons of concrete (35 percent) and other metals and alloys sum up to 2,397 metric tons (12 percent).

Because PV modules produce direct current (DC), they must use an inverter to convert DC to alternating current (AC),

Figure 3

Metric Tons of Material for 100 MW c-Si UPV Solar Plant



which is used in homes and businesses. A 100 MW capacity c-Si utility PV plant uses 338 metric tons of materials for inverters, 440 metric tons for cabling, and 3,393 metric tons for transformers, compared with 7,765 metric tons for the PV modules themselves. Inverters last only about 10 to 12 years before requiring replacement but typically are only under warranty for five years, and inverters are the components of PV modules most likely to fail and require repair or replacement.[24]

The DOE estimates that the U.S. would need at least 1,600 GW of solar for a decarbonized grid by 2050 (alongside other sources like wind and nuclear), and 3,000 GW if this were accompanied by strong electrification.[25] Assuming that 1,600 GW of solar buildout by 2050 was met entirely by plants of the same material composition as NREL's model 100 MW c-Si utility PV plants, and subtracting the 235 GW of capacity already installed nationwide, that buildout would require 82.7 million metric tons of steel, 60.2 million metric tons of concrete, 38.3 million metric tons of other metals and alloys, 18 million metric tons of composites and polymers, and a staggering 106.9 million metric tons of other materials.[26] Over the 25 years remaining until 2050, these translate to annual demands of 3.3 million metric tons of steel, 2.41 million metric tons of concrete, 1.5 million metric tons of other metals and alloys, 722,364 metric tons of composites and polymers, and 4.3 million metric tons of other materials.

Section II.4: Material demands of nuclear

Nuclear power has, by far, the lowest material requirements per GW of capacity, especially for steel, concrete, and copper.[27] The energy density of uranium means that a typical one GW reactor produces the same amount of power as 431 utility-scale wind turbines or 3.125 million PV panels.[28]

The 2023 Energy Transitions Commission report assumes that concrete comprises about 640 metric tons per MW of nuclear power plant capacity.[29] Copper, steel, and uranium are assumed to entail 1.5 metric tons and 90 metric tons of steel per MW of capacity, and 24 tons of uranium per terawatt hour of energy production.[30]

Powering a one GW nuclear plant for one year requires mining 20 to 40 kilotons of ore, which is processed into about 27.6 metric tons of uranium fuel.[31] Only about 0.8 metric tons, or three percent, of that is high-level waste that requires cooling and shielding. The water usage of nuclear power plants ranges from 270 to 670 gallons per megawatt-hour (MWh).[32]

Consider that the U.S. experienced peak electricity demand of 745 gigawatt-hours (GWh) on July 15, 2024.[33] The EIA expects that U.S. electricity generation will reach 4,450 terawatt-hours in 2026.[34] Subtracting the 93 operational plants in the U.S. and assuming an average capacity factor of 92 percent, a hypothetical net-zero U.S. grid of 100 percent nuclear would need about 722 1-GW plants to meet peak demand. Alternatively, 464 1-GW plants could meet an average demand of 508 GW, alongside natural gas peaking plants to meet peak demand.

Uranium requirements to fuel the hypothetical nuclear-only fleet of 464 GWs would require 12,811 metric tons of fuel annually, of which approximately three percent (371 metric tons) is high-level waste. Even the grid that would be able to meet peak demand on nuclear alone (which is less flexible for ramping up and peaking than using natural gas to meet peak demand) would use 19,927 metric tons of fuel annually and produce 577.6 metric tons of high-level waste.

Material requirements may also decline as small modular reactors (SMRs) and microreactors are constructed within the next decade and grow as a proportion of market share. They are expected to use less steel and concrete for construction, have a smaller land footprint, and may use different fuel mixes that improve fuel efficiency and utilize recycled fuels.[35] Some SMRs are being designed for single time fueling and longer fuel cycles. However, SMR and microreactor designs will need to receive design certifications from the Nuclear Regulatory Commission (NRC) before being commercialized; only the NuScale Power Module has been approved.[36]

While these estimates are merely illustrative, it becomes clear that renewables grids will entail substantial system-wide materials costs to reliably deliver the same amount of electricity on an hourly basis compared with coal, natural gas, and nuclear-heavy grids. Section III describes some of the environmental costs of producing and manufacturing the materials that would be necessary for a net-zero carbon emissions U.S. economy.

Section III: Where We Mine Matters

All sources of energy require the extraction of raw materials, whether it is coal or natural gas for traditional energy generation, uranium for nuclear generators, or copper, nickel, and cobalt for renewable energy technology. The U.S. has some of the cleanest and safest mines in the world, and other developed nations like Australia and Canada also have robust regulations to protect workers and the environment during and after mining. Environmental effects of mining, processing, and manufacturing are best managed in developed nations.

Environmental destruction and worker health and safety violations are greatest in the developing world, where oversight and enforcement of protections are weak or nonexistent. The materials used in wind turbines, solar panels, and battery storage are overwhelmingly mined and manufactured in developing countries.

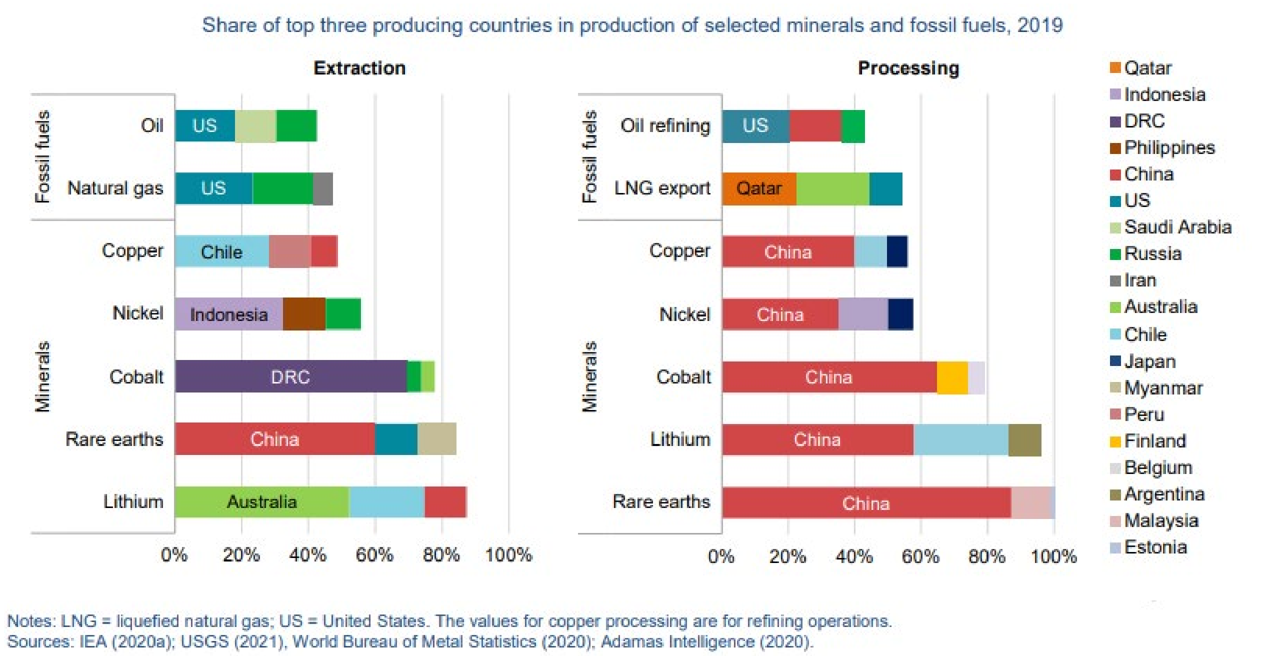
Procuring materials, metals, and minerals from foreign countries, including potential adversaries, may compromise the power grid's security and reliability, as well as the economy, national defense, and technological applications. The IEA's report "The Role of Critical Minerals in Clean Energy Transitions" shows the share of top producing countries in total processing of selected minerals and hydrocarbon energy sources in 2019.[37]

Figure 4 demonstrates that while the U.S. controls a significant share of oil and natural gas extraction as well as oil refining, China dominates rare earths extraction and processing, as well as copper, nickel, cobalt, and lithium processing. In fact, China's overseas mining investment hit another peak in 2024 at $21.4 billion.[38]

It wasn't always this way. Between 1910 and 1950, the U.S. produced between 30 and 40 percent of the world's mineral production. In 1916, the U.S. Secretary of the Interior, Franklin K. Lane, wrote: "We can build a battleship, or an automobile (excepting the tires), a railroad or a factory, entirely from the products of American mines and forests…"[39]

Further, mines located in Chile, Indonesia, and Democrat-

Figure 4
Share of Top Three Producing Countries in Production of Selected Minerals and Fossil Fuels



ic Republic of the Congo are usually owned by Chinese companies, which further concentrate geopolitical risks. The U.S. relies on a potential geopolitical adversary every day for minerals critical to U.S. national security, economic prosperity, energy transition ambitions, the electric grid, and more.

As documented in American Experiment's 2024 report "Mission Impossible: Mineral Shortages and the Broken Permitting Process Put Net Zero Goals Out of Reach," China does not hesitate to throttle supplies of critical minerals when it finds it advantageous.[40] In fact, in December 2024, China implemented full bans of gallium, germanium, and antimony exports to the U.S., strengthening enforcement of existing limits.[41]

The U.S. and other developed countries use modern mining methods due to stringent environmental protection criteria and monitoring requirements. American Experiment's 2018 report, "Unearthing Prosperity: How Environmentally Responsible Mining Will Boost Minnesota's Economy," describes Minnesota's mining regulations and the techniques used to manage tailings, dispose of waste, and ensure high water quality.[42] These include liners, covers and caps, water treatment, air emissions controls, and environmental monitoring systems.

Mining, processing, and construction greenhouse gas emissions are better managed in the U.S. and other developed nations not only due to strict environmental regulations, but because the electricity used in mining is often from cleaner sources than in developing countries. Mines in China, Indonesia, and elsewhere use electricity from grids predominantly burning coal (comprising 60 percent or more of the generation mix), rather than natural gas, which the U.S. used for 43 percent of its electricity generation in 2023.[43]

Further, Figure 4 demonstrates that extraction of many important minerals is dominated by countries like Indonesia, the Democratic Republic of the Congo, and Zambia, which have abysmal human rights and worker health and safety records.

In 2020, Indonesia accounted for 30 percent of global nickel mine production. The 2023 NREL material intensity report suggests that future U.S. deployment of *only wind energy* for net-zero could require 97 percent to 1,600 percent of current U.S. nickel production, and a U.S. net-zero scenario would require at least 11 percent of 2020 global production.[44] While ramping up domestic mining would be necessary, achieving massive wind turbine buildout (let alone additional demands from solar and battery storage) would require foreign sources of nickel.

Yet Indonesia is not a responsible steward of the environment nor a protector of mining workers' health. Reports from Indonesia allege a "production first, safety later" culture with lax safety protocols and 101 deaths between 2015 and the first half of 2024.[45]

On March 16, 2025, multiple tailings storage facilities were breached, flooding the facilities at the Indonesia Morowali Industrial Park and the village of Labota, "putting the health of workers and 341 families at risk through exposure to heavy metals."[46] Another tailings facility collapsed on March 22, 2025 and killed one worker with another two missing.[47] Photos taken at the site, sourced from Earthworks.org, are reproduced in Figure 5. Companies operating in the industrial park originally planned to dump tailings directly into the ocean — hardly an indication of responsible stewardship.

Figure 5

"Clockwise: (1) Tailings released from the collapsed filtered tailings storage facility of PT Huayue Nickel Cobalt (HNC) on March 16, 2025, flow down the Bahodopi River. (2) Liquefied tailings breach the facility, as seen in a still from a video. (3) Google Earth imagery from January 3, 2025, reveals an earlier landslide from the same facility." Source: Earthworks.org

A 2024 Department of Labor analysis of Democratic Republic of the Congo's cobalt workers found 44 percent could not refuse to do hazardous work, 85 percent reported restrictions on their movement, and 52 percent of workers reported children working at their mine site, especially artisanal mines (63 percent).[48] The report finds that "labor conditions for cobalt mine workers are abominable" and that many experience forced labor and most suffer illness or injury

Figure 6

Image courtesy of Afrewatch/Iled, (CC BY-NC-ND 4.0)

"Many artisanal miners are forced to work illegally on mine sites allocated to formal enterprises. This has left them in precarious financial and social situations." Source: Afrewatch.

On February 18, 2025, a tailings dam holding acidic waste from a Chinese-owned copper mine contaminated the Kafue River in Zambia, an important waterway that supplies drinking water for about five million people.[49] The *Associated Press* reported signs of pollution as far away as 60 miles downstream.[50] An AP reporter described dead fish washing up on the banks downstream "from the mine run by Sino-Metals Leach Zambia, which is majority owned by the state-run China Nonferrous Metals Industry Group." The article notes that another Chinese-owned mine suffered a leak mere days after this spill and the owners have been accused of attempting to hide it, with two mine managers arrested and one mine worker dead.

Sean Cornelius, living near the Kafue River, told the *Associated Press:* "Now everything is dead, it's like a totally dead river. Unbelievable. Overnight, this river died."[51]

The U.S. makes a value judgment every time it decides it would rather offshore a mining project than do it domestically under high environmental and worker health and safety standards. For more details on the foreign sources of energy minerals, consult Section III of American Experiment's report "Mission Impossible: Mineral Shortages and the Broken Permitting Process Put Net Zero Goals Out of Reach."[52]

In *Undermining Power: How to Overthrow Mineral, Energy, Economic & National Security Disinformation*, the authors write that, "No one would dispute that a highly automated, environmentally sound facility in Wyoming or Texas is vastly preferable to un-regulated, environmentally disastrous mines in remote countries."[53] These examples (from 2024 and 2025 alone!) show why a failure to promote U.S. mining is complicit in human rights abuses and environmental disasters.

Section IV: Ecological Impacts of Wind and Solar

Wind turbines and solar panels pose risks to wildlife through noise, habitat destruction, and impacts associated with land development. Peer-reviewed research is beginning to acknowledge the hazards that wind and solar create for wildlife and attempt to quantify the effects — although too many questions remain unanswered. An ounce of prevention may be worth a pound of cure for species that are harmed by wind turbines and solar panels.

Section IV.1: Whales and offshore wind

Offshore wind turbine construction may impact the North Atlantic right whale (NARW), a baleen whale only found in the North Atlantic. The whale was listed as endangered in 1970 under the U.S. Endangered Species Act and has additional protection under the Marine Mammal Protection Act.[54] There are only about 360 individuals left in the world. Almost all recorded NARW deaths are attributable to ship strikes and fishing gear entanglement. However, high noise levels have been associated with chronic physiological stress responses in NAWR, which influences reproduction patterns and has deleterious effects on the species' health.[55]

The construction of offshore wind farms is noisy, which jeopardizes the health of the right whale and other large whales that rely on echolocation. The National Oceanographic and Atmospheric Administration (NOAA) Fisheries division asserts that "there are no known links between large whale deaths and ongoing offshore wind activities."[56] However, this statement does not address *sublethal* effects that may still reduce whale populations through influencing reproduction and migration patterns. Further, while the increased ship traffic associated with construction and the noise associated with pile driving might not be *ongoing*, they pose considerable, acknowledged challenges to whales.

NOAA and the Bureau of Ocean Energy Management released a strategy to protect the NARW alongside offshore wind development in January 2024, though no part of the report is legally binding.[57] The report describes four main stressors on NARWs from offshore wind:

1. Exposure to noise may result in "hearing impairment, masking of NARW vocal communication, physiological impacts (e.g., stress), and/or behavioral disturbance, as well as mortality and injury that may result from exposure to detonations of unexploded ordnance."
2. Strikes from vessels, including those associated with offshore wind activities, as well as shifting species and/or vessel distribution around the wind project that make strikes more likely.
3. Entanglement, since offshore wind "may produce marine debris or involve appurtenances (e.g., from floating wind)."
4. Changes to habitat, since offshore wind "will result in habitat changes that may affect the abundance, quality, or availability of NARW prey (e.g., changes in ocean circulation and mixing from in-water structures, including turbines and foundations, and impingement or entrainment of prey in cooling water intakes associated with High Voltage Direct Current cable systems) or attract predators (e.g., predators with an affinity for a new 'reef structure' in the environment)."

The joint strategy continues by noting that deleterious effects on NARWs may be compounded "by exposure to multiple projects," a likely scenario for whales migrating along the U.S. Atlantic Coast.[58] Ultimately, BOEM will "attempt to avoid issuing new leasing in areas that may impact potential high-value habitat and/or high-use areas for important life history functions."[59]

A study by Quintana-Rizzo et al. finds that "although the effects of offshore wind energy development on right whales are unknown, it has been reported that baleen whales avoid impulsive sounds with noise levels similar to those of pile-driving activities."[60] Right whales appear to demonstrate stress responses due to the noise from large commercial vessels and "work is also needed to determine if wind farms alter the habitat's physical and oceanographic characteristics."[61]

The NARW may also be influenced by upstream effects on its food supply — small crustaceans called copepods — that are disturbed by turbines.[62] Research from the American Clean Power Association suggests that turbines may either increase turbulent mixing, therefore increasing nutrient mixing and copepod populations, or kick up sediments that reduce sunlight and therefore reduce copepod populations.[63]

Concerns about the health of whale species have only grown since 2023 after two decomposing humpback whales washed up near Martha's Vineyard in Massachusetts.[64] The U.S.' first utility-scale wind farm, Vineyard Wind, began construction nearby only one week before the deceased whales surfaced. NOAA autopsied one right whale after the incident (identified as #5120), which was discovered in January 2024, and determined the cause of death to be chronic entanglement.[65]

Figure 7

Credit: NOAA Fisheries. NOAA Fisheries Permit #24539.[66]

Necropsy (animal autopsy) of North Atlantic right whale #5120.

A precautionary approach to offshore wind development is favored across partisan lines. The Natural Resources Defense Council praised BOEM for "smart siting" decisions in the Gulf of Maine but argued in the same article that "the most effective ways to reduce the risk to right whales is to simply avoid developing offshore wind in habitat areas of importance to the species."[67]

Section IV.2: Birds, bats, and onshore wind

Onshore wind turbines present a different risk for bats and birds. Many bat and bird species are susceptible to collisions, especially at low wind speeds, and suffer habitat loss, fragmentation, and displacement. Many bats, including the hoary bat, eastern red bat, silver-haired bat, and Mexican free-tailed bats are particularly vulnerable during late summer and fall when these species are migrating and mating.[68]

Tens of thousands to hundreds of thousands of bats die at wind turbines in North America alone.[69] Bats may also suffer from barotrauma, injuries caused by sudden and extreme changes in atmospheric pressure, although the proportion of bat deaths at wind turbines attributable to barotrauma is still under debate.[70]

Mexican free-tailed bats are among the bat species most frequently killed by wind turbines in the southwestern U.S., in part because their suitable habitat overlaps strongly with areas of high wind potential during many times of year.[71,72] Research indicates that an ounce of prevention is (once again) worth a pound of cure, since "the best way to keep bats safe from wind turbines is to avoid building turbines in areas with high bat activity."[73]

Figure 8

USFWS/Ann Froschauer

Mexican free-tailed bat.

Some migratory bat species may eventually be driven to extinction by wind turbines. A 2017 study of the hoary bat (*Lasiurus cinereus*) suggests that their population could "decline by as much as 90% in the next 50 years."[74] The authors go so far as to say that "conservation measures to reduce mortality from turbine collisions likely need to be initiated soon."

Keeping bats safe after construction of wind turbines involves curtailment, where operators slow down or stop the rotation of the blades, which predictably means a "loss of power generation."[75] This is another way wind turbines are an intermittent, unreliable source of electricity generation for the electric grid.

Other strategies include deterring bats from approaching wind turbine sites. This involves emitting high-frequency sounds designed to encourage bats to move to other areas, which "can interfere with bats' ability to perceive echoes and therefore their ability to navigate and find food."[76] It is hard to imagine that these efforts are not disorienting and distressing to most bat species.

Wind turbines strike many birds every year — the American Bird Conservancy suggests between half a million and one million birds annually.[77] The midpoint estimate of several studies from 2013 and 2014 suggests average annual bird fatalities of 366,000 birds. The Conservancy extrapolates that this is likely an underestimate as of 2021, since in 2012, there were only 44,577 U.S. wind turbines in operation. The U.S. Wind Turbine Database reports data on 75,633 turbines in its February 2025 release, which is a 70 percent increase from 2012.[78] Half a million to one million birds is most likely an underestimate in 2025.

There is also substantial evidence that humans significantly undercount bird and bat fatalities in studies when compared with dog searchers, and most early studies rely exclusively on human counting. One study found that "dog searches resulted in fatality estimates up to 6.4 and 2.7 times higher for bats and small birds, respectively, along with higher relative precision and >90% lower cost per fatality detection."[79] Other searches are performed by humans from automobiles, which is even more likely to miss bird and bat fatalities than human searchers on foot.

Other studies suggest the U.S. median annual fatality is about 1.8 birds per MW of wind capacity, while in South Africa and Canada, the annual fatality is around 4.6 and 8.2 birds per turbine per year, respectively.[80]

In October 2008, the Spanish Ornithological Society in Madrid estimated that Spain's 18,000 wind turbines "may be killing 6 million to 18 million birds and bats annually."[81] A researcher hired to help birds, specifically the griffon vulture, navigate the "treacherous airspace" around some Spanish turbines said that "a blade will cut a griffon vulture in half. I've seen them just decapitated."[82]

It's important to note that numerous anthropogenic sources contribute to bird deaths. Domestic and feral cat predation (median estimate at 2.4 billion birds annually), building collisions (599 million), power line collisions (22.8 million), and communication towers (6.5 million) are strong contributors to bird mortality.[83] Mortality rates due to wind turbines increase with height, as with communication towers, and mortality from wind turbines is more broadly dispersed across rural areas than urban areas.[84] However, when many bird populations are declining already, "any cause of mortality needs to be tackled," including those at wind turbines.[85]

What matters more than sheer quantity is that certain species of birds are disproportionately susceptible to turbine strikes. A 2017 study by Thaxter et al. found that birds of prey like eagles, vultures, hawks, and kites, as well as hornbills and herons, and shorebirds like waders, gulls, and auks, are at a much higher risk of collisions.[86] This is in part because sites with high wind potential are often on ridgetops, which larger species use to gain lift, and because these birds are often migratory and wind farms may be sited within their migratory routes. These species also, unfortunately, tend to reproduce infrequently, with few offspring. With a long period of time before sexual maturity, premature deaths are much harder for a population to bounce back from.

In a 2012 interview with the scientific journal *Nature*, an ecologist lays bare the stakes:

> "There are species of birds that are getting killed by wind turbines that do not get killed by autos, windows or buildings," says Shawn Smallwood, an ecologist who has worked extensively in Altamont Pass, California, notorious for its expansive wind farms and raptor deaths. Smallwood has found that Altamont blades slay an average of 65 golden eagles a year. "We could lose eagles in this country if we keep on doing this," he says.[87]

The large land footprints of wind turbines also fragment habitats and displace wildlife. In Portugal, wind turbine installation "resulted in black kites (*Milvus migrans*) avoiding 3%-14% of their previously used habitat in the area."[88] Obstacles blocking the flight paths of migratory birds may force diversions into new routes that exhaust them and contribute to premature deaths. It also matters what native habitat is destroyed to make room for turbines: clearing a forest obviously destroys roosting and foresting habitat for tree-dwelling bats.

In the U.S. Southwest, greater sage grouse seem to abandon their leks — a gathering place for mating — more frequently near wind turbines, which may be because male vocalizations to attract females to the leks are drowned out by the turbines' noise.[89]

The transmission lines carrying electricity from projects can sometimes cause electrocutions, though this is not as significant at high-voltage transmission lines. For instance: "Electrocution of Egyptian vulture over a 31-km stretch of powerline in Sudan is thought to have resulted in sufficient deaths to partially explain their population decline."[90] A 2014 study suggests that between 12 and 64 million birds are killed each year at U.S. power lines.[91] It stands to reason that adding more transmission lines to connect wind and solar facilities to the grid will cause more fatalities.

While bird and bat species are largely the most impacted by onshore wind turbines, evidence from Europe suggests that large mammal species such as the European roe deer and wolves avoid wind farms, with wolves avoiding denning behaviors at distances up to 6.4 kilometers.[92] California ground squirrels showed "increased anti-predator behavior near turbines."[93] A 2021 study of female pronghorn deer in Wyoming found a "trend toward increased displacement" and that pronghorn avoided turbines when migrating.[94]

Section IV.3: Solar panels aren't much better for birds

Solar panels have their own impact on wildlife, though some impacts are not yet well understood. Collisions with solar panel equipment and transmission lines, as well as electrocutions, are the primary risks to birds and bats.

A 2022 study suggests that bird and bat mortality for solar panels is consistently underestimated for the same reasons that mortality is undercounted for wind projects.[95] Many studies have searchers operating from cars rather than on foot, compounding human inaccuracies. Reported estimates suggest fatalities of 37,546 birds and 207 bats annually *in California alone*, but one study by Shawn Smallwood estimates fatalities of 267,732 birds and 11,418 bats annually. The author also estimates that construction grading for solar in California eliminates the habitat of nearly 300,000 birds per year. The author recommends "that utility scale solar energy development be slowed" to more fully consider these effects.

Utility-scale photovoltaic solar panels are also theorized to create a "lake effect," in which birds are attracted to and collide with solar panels because their reflectiveness mimics bodies of water. This may cause fatalities from collision and strand water-obligate bird species that cannot take off from land, only from water. A 2024 study from Diehl et al, sponsored by the California Energy Commission, found that "animals in flight show strong evidence of descent" toward solar facilities "consistent with attraction from a solar cue."[96] Water-seeking insects may be attracted to panels in the same way.

Detailed pre-construction surveys may not provide enough information to predict high-traffic areas and choose to site projects elsewhere, which fails to prevent excess bird deaths through siting alone. A metanalysis of 87 solar and wind facilities finds only a "weak relationship between risk assessment pre-construction and actual fatalities" in both wind facilities and solar facilities.[97] The same study also finds "few waterbirds but many raptors were reported dead at wind facilities, but the opposite pattern was noted at solar facilities (many waterbirds, few raptors)," suggesting that the lake effect may be drawing more waterbirds than raptors to solar panels.

The solar glare that results in the lake effect disorients birds and insects and can cause severe burns and incineration if too close. The Association of Avian Veterinarians reports that the Ivanpah Solar Plant in California's Mojave Desert, which uses concentrated solar technology and massive mirrors, is responsible for at least 6,000 bird deaths per year due to burns and incineration:

> These numbers are likely an underestimation, as the sight of birds and insects rapidly immolated as they soar too close to the towers, which can reach temperatures of 1000 degrees Fahrenheit, is so common that staff at the plant have a name for them; "streamers". Road runners also frequently become trapped along perimeter fencing and fall victim to predators.[98]

A 2014 *Associated Press* article notes that federal wildlife investigators reported an average of one "streamer" every two minutes and told the publication that the plant might act as a "mega-trap" for wildlife.[99] The same source notes that the "sun rays sent up by the field of mirrors are bright enough to dazzle pilots flying in and out of Las Vegas and Los Angeles." The Association of Avian Veterinarians describes the mitigation efforts of the solar plant owners:

> Efforts have been made to reduce the impact of these solar plants on birds, with unknown efficacy. Ivanpah has fitted each tower with machines that emit a non-lethal respiratory irritant derived from grape juice, attached anti-perching spikes to tower frames, and emits recording of high-pitched noises. Other mitigation strategies to reduce the impact of these facilities include choosing appropriate locations for solar farms, such as already disturbed lands, using non-reflective materials and patterns on solar panels and rearranging mirrors to reduce birds' window of exposure, and integrating native vegetation and creating wildlife-friendly buffer zones around solar farms to mitigate habitat loss.

Solar panels lead to the loss and fragmentation of habitat as well as disrupt migration patterns. Construction activities also lead to soil erosion and degradation, which can increase sediment runoff to aquatic ecosystems and impact species, like mussels, that are sensitive to water quality changes.[100]

Desert tortoises have been a focal point for critics of solar panels in the Mojave Desert for years. The Mojave desert tortoise was designated as a “threatened” species under the Endangered Species Act in 1990, and it lives between 50 and 80 years and reproduces infrequently. The Basin and Range Watch implored the Biden administration’s Department of the Interior in March 2024 to cancel the Rough Hat Clark County Solar Project due to its impacts on the Mojave desert tortoise.[101]

The Ivanpah Solar project in the Mojave Desert, which was constructed in 2014, is reported to be heading for closure in 2026 — far earlier than the expected end of contract in 2039.[102] The Bureau of Land Management reportedly concluded when it was built that the project would lead to the loss or degradation of 3,520 acres of tortoise habitat, with the harm or death of 57 to 274 adult tortoises, 608 juveniles, and 236 eggs within the work area and 203 adults and 1,541 juveniles outside of the work area.[103]

It’s worth asking whether it’s reasonable to sacrifice concrete environmental goals, like protecting threatened species, biodiversity, and habitats, in exchange for energy generation from low-density, intermittent sources that kill and disturb birds, bats, and tortoises. Proponents of massive wind turbines and solar panel buildout claim that wildlife will benefit due to reductions in greenhouse gas emissions and global temperatures. Yet in a Request for Information solicited by the DOE, some conservation groups told the agency that “they have not observed any direct benefits to species from solar development” and “expressed concern about over-emphasizing benefits that solar may provide to species and habitats.”[104]

The tangible ways in which Americans interact with and enjoy the natural environment are what most matter to most people. Many Americans care in the abstract about climate change, but care most when their local songbirds stop coming to visit their bird feeder.

Section V: Decommissioning, Repowering, and Waste

What happens when wind and solar facilities reach the end of their useful lives? While all power plants eventually wear out and require replacement, wind turbines only last for 20 years, and most solar panels are warrantied for only 25 years. Coal and natural gas plants have operational lifespans of up to 60 years, and nuclear power plants may last for 80 years. Wind turbines and solar panels will need to be decommissioned and disposed of more frequently than natural gas, coal, and nuclear power plants. Managing discarded components and manufacturing new components more often exacerbates the environmental drawbacks of wind and solar.

Section V.1: The life cycle of wind turbines

According to the IEA and NREL, wind turbines last about 20 years, but some components degrade faster, including blades, gearboxes, and generators.[105] Decommissioning and repowering occur more often for wind turbines than for other types of generators.

Repowering, either partial or full, often occurs well before expected end-of-life because wind turbines’ generating output degrades over time. The DOE found that in 2021, turbines involved in partial repowers ranged from nine to 16 years old, with a median age of 10 years.[106] In 2023, according to the 2024 Land Based Wind Market Report, seven wind projects (totaling 630 MW) were partially repowered in 2023, with a median age of 13 years.[107] The report continues that “The primary motivations for partial repowering have been to re-qualify for the [Production Tax Credit].”

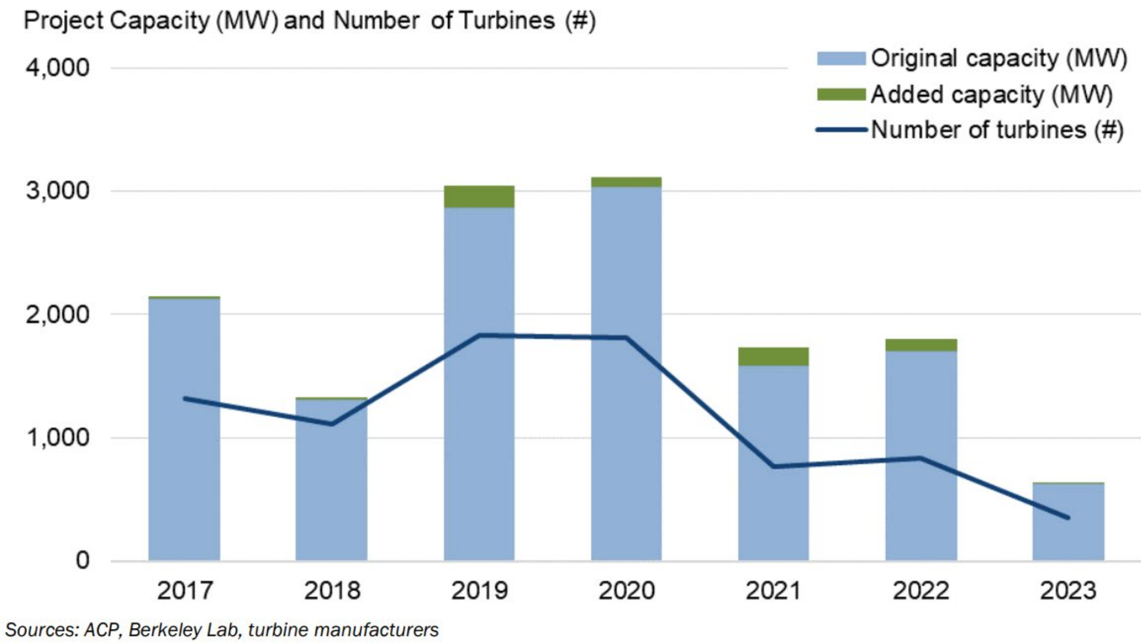
Figure 9 excerpts from the 2024 Land Based Wind Market Report, showing that partial repowering has declined significantly in 2023 compared with the three GW/year repowered in 2019-2020.[108]

Full repowering is less common but offers more opportunities to increase nameplate capacity substantially through new design. Repowering comes with impacts on communities, including temporary jobs in the deconstruction, “increased noise and road wear,” and “significant amounts of land” for component staging.[109]

A 2014 estimate found onshore wind farm output falls 1.6±0.2 percent per year, or about 16 percent per decade.[110] However, a 2020 Lawrence Berkeley National Laboratory study found that wind turbines degraded little over the first

Figure 9

Partially Repowered Wind Power Capacity, 2017-2023



10 years of generation and maintain 87 percent of peak performance after 17 years.[111] The authors hypothesize that "the ten-year duration of the [Production Tax Credit] impacts the performance degradation rate of US wind plants," suggesting that operators spend less on maintenance after PTC credits expire. It's no secret that "repowers may be motivated by securing continued access to the Production Tax Credit prior to the incentive's expiration."[112]

Decommissioning entails disassembly, demolishing, and removing wind turbine components and project infrastructure. The process can take anywhere from six months to two years, with associated deconstruction impacts on the community.[113] Per-turbine decommissioning costs for projects proposed in 2019-2021 ranged from $114,000 to $195,000.[114]

Concrete foundations, the largest fraction of material and the longest-lived component of wind turbines, may be reused or be disposed of "in place." Full removal of foundations and associated cables may, according to DOE, result in further environmental and community impacts that make it more desirable to keep foundations in place.[115]

Blades are composite materials of fiberglass or carbon-fiber, both of which are challenging and uneconomic to recycle on a commercial scale. A 2021 research paper expects 2.2 million tons of U.S. wind turbine blades to be retired by 2050, assuming 20-year turbine lifetimes, which amounts to one percent of remaining U.S. landfill space by volume.[116]

Wind turbine blades are also vulnerable to breakage on rare occasions, which have environmental impacts, though turbines are designed to shut off at high wind speeds. On July 13, 2024, a blade from the Vineyard Wind offshore wind turbine project fractured and fell into the Atlantic Ocean.[117] Thousands of shards of fiberglass and foam littered the beaches of Nantucket — an unfortunate incident for the first large-scale offshore wind farm to be federally approved. The first turbine on the project had only begun delivering power in January 2024, a mere seven months before the July failure.[118]

Maintenance costs should also be considered, though these costs are difficult to quantify. For instance, turbine blades in cold climates may need to be fitted with anti-icing and de-icing technology, including forced-air heaters or electrical heating. Frost buildup on blades considerably reduces generating efficiency and may harm the turbine. Wind turbines also require oil lubrication in their gearboxes, with a five-megawatt wind turbine requiring 700 gallons of lubricant, and oil changes scheduled from nine to 16 months.[119]

Section V.2: The life cycle of solar panels

Solar panels are expected to last for about 25 years.[120] However, solar panels degrade over time at a rate estimated to be between 1.4 percent per year[121] and two percent per year.[122]

A 2016 report by the IEA and International Renewable Energy Agency (IRENA) estimates that there could be up to eight million metric tons of total solar panel waste by 2030, and 78 million metric tons by 2050.[123] The U.S. is estimated to reach between seven million and 10 million tons of waste by 2050 alone.

Utility-scale panels may also be replaced well before their 25-year lifespan to take advantage of U.S. investment or production tax credits, which incentivizes projects to repower within 10 years. Residential solar customers may make individual decisions to "trade up" their panels based on installation prices, compensation rate, and module efficiency.[124]

Only about 10 percent of solar panels are recycled today.[125] Even though more than 85 percent of solar photovoltaic modules are recyclable materials like glass and plastic, recycling solar panels remains cost ineffective. The cost of module recycling ranges from $15 to $45 per module.[126] Disposal costs around $5 per panel at hazardous waste landfills but only $1 to $2 per panel at a solid waste landfill if hazardous disposal is not required or is ignored.[127] Minerals such as silver and crystallized silicon are valuable to recyclers, but their resale value is often not enough to be economical.

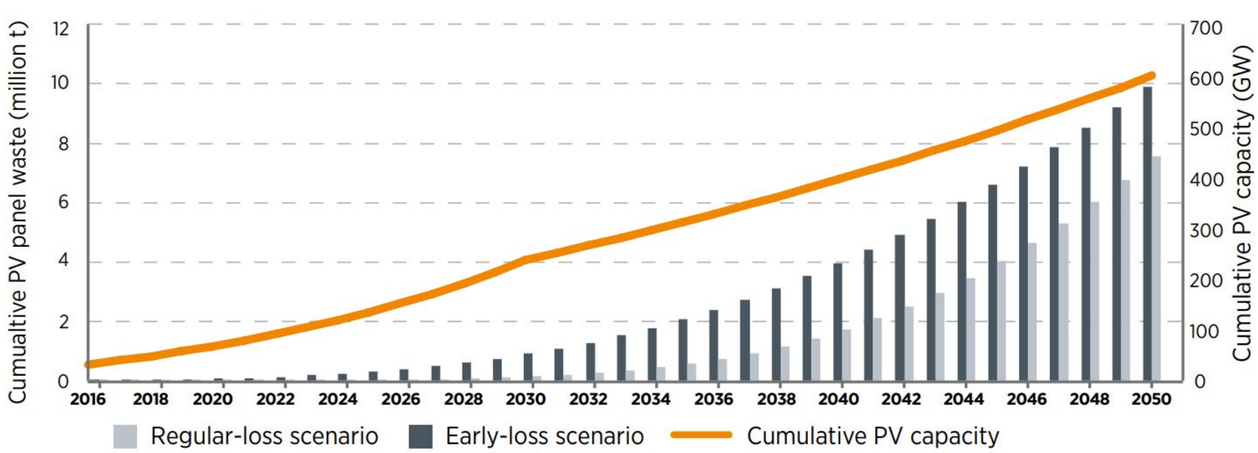
The inverters on solar panels, which convert DC into AC, are the most likely solar components to fail and require repair and replacement, with an optimal expected lifespan of only 10 and 15 years. Some manufacturers are no longer in business, causing difficulty in inverter maintenance, repair, and replacement.[128]

Solar panels may still function at their end-of-life, albeit at a degraded efficiency of around 60 percent. Degraded solar panels are often exported to developing countries at reduced prices where they continue to generate power and electrify households that may not otherwise have electricity. However, exporting end-of-life solar panels also exports later disposal hazards to foreign countries.

The minerals used in solar panels include silicon tetrafluoride, selenium, sulfur hexafluoride, lead, cadmium, and other toxic chemicals that cause environmental and human health harm. Disposing of these materials safely is a significant cost associated with building solar panels.

Figure 10

End-of-Life PV Panel Waste Volumes for the U.S. to 2050



Source: IEA and IRENA

Section V.3: The life cycle of battery storage

Battery energy storage lifespans vary depending on their thermal environment and how often the battery discharges, but typically last between eight and 15 years.[129] Lithium-ion battery storage in 2015 accounted for 51 percent of new capacity and 86 percent of deployed capacity, can run for between 2,000 and 4,000 charge/discharge cycles, and have a lifespan of about 10 to 20 years.[130]

Battery energy storage requires a power conversion system to invert direct current output to the alternating current used on the grid, which adds about 15 percent to the basic battery cost.[131] Batteries are most economic when used to smooth the variability of power from wind and solar systems over minutes or hours, not for long-duration backups.

Battery energy storage systems must be disposed of correctly to avoid toxic chemicals leaching into the environment and face many of the same disposal challenges as consumer electronics and electric vehicle batteries. Lead-acid and nickel-cadmium batteries, which are being rapidly displaced by lithium-ion batteries, are already recycled at rates between 96 and 98 percent.[132] A 2017 Electric Power Research Institute report finds that enhanced strategies for removal, disposal, and recycling of energy storage batteries "is needed by 2025 when the batteries begin to reach end-of-life."[133] Lithium-ion batteries must be disposed of as hazardous waste or recycled. Lithium-ion recycling is high volume due to consumer electronics, but many recyclers do not have the capabilities to handle the module-sized batteries found in grid-scale or electric vehicle batteries.

There have been high-profile reports of battery storage system fires, though incidents are rare. Unfortunately, the chemicals in lithium-ion batteries are flammable and susceptible to a process called "thermal runaway," which is an uncontrolled self-heating chemical reaction. The batteries in EVs and electric bicycles are susceptible to fires as well, especially when battery packs are damaged in a collision. Once a fire begins due to thermal runaway, it is difficult to extinguish: a typical EV fire burns at about 5,000 degrees Fahrenheit, while a standard internal combustion engine vehicle burns at only 1,500 Fahrenheit. Battery fires also release toxic chemicals.

A fire began on the afternoon of January 16, 2025, at the Moss Landing Energy Storage Facility in Monterey County, California.[134] The fire destroyed 300 megawatts of energy storage (a full two percent of California's energy storage capacity) and forced 1,200 residents to evacuate. Firefighters responding to the blaze "let this type of blaze burn itself out" due to the high temperatures of the blaze and emissions of toxic substances like hydrogen fluoride. Smoke fumes from the fire "are likely to have contained heavy metals and PFAS," forever chemicals.

Figure 11

@picklevisionz Via Instagram

"Vistra Corp's power plant in Moss Landing, California goes up in flames on January 16, 2025. Screen grab obtained from a social media video."

After the Moss Landing fire, "nearby residents reported feeling ill in the days after the blaze," and a lawsuit filed in February "cited possible soil contamination."[135] Scientists found "high concentrations of heavy-metal nanoparticles" nearby that were deposited recently.[136] Angie Roeder, living eight miles from the Moss Landing facility, told *Inside Climate News* that she "has had headaches, shortness of breath and a metallic taste in her mouth," and reports neighbors having the same symptoms.[137]

While Moss Landing may have been more prone to fires due to battery chemistry and indoor housing, "communities nationwide are expressing concerns about hosting similar plants."[138] Nick Warner, a cofounder of the Energy Safety Response Group, told *NPR* in an interview that "ultimately the incident has tremendous potential to derail the industry, not just within California but across all of North America."[139]

At a January 17 press conference, Monterey County Supervisor Glenn Church said, "This is really a Three Mile Island event for this industry."[140] In the same way that Three Mile

Island spurred nuclear power plant owners to revamp safety operations, let's hope that battery storage owners think hard about how to avoid a future Moss Landing.

Section VI: Estimates of Land Use Requirements

The low energy density of wind and solar power means that more land area must be dedicated to the production of electricity than energy-dense sources like coal, natural gas, and nuclear. This has predictable consequences for other uses of land like productive agriculture and grazing and encounters resistance from residents near wind and solar projects. The opportunity cost of land used for wind and solar is an important consideration for policymakers and communities.

Wind turbines and solar panels require at least 10 times as much land per unit of power produced as coal- or natural gas-fired power plants, according to the Brookings Institution.[141] The Brookings Institution's figure includes the land to produce and transport hydrocarbon energy sources. The Union of Concerned Scientists estimates that utility-scale photovoltaic systems require 3.5 to 10 acres per megawatt, while concentrated solar power requires between four and 16.5 acres per megawatt.[142]

Because nuclear fuel is so energy-dense, a nuclear power plant requires even less land than coal and natural gas-fired power plants. A 1,000 MW nameplate capacity nuclear plant needs only 1.3 square miles of land area. [143] (This is about twice the capacity of each reactor at the Prairie Island nuclear plant in Red Wing, Minnesota, which are the two smallest operating reactors in the U.S.)[144] A comparable solar installation needs between 45 and 75 square miles to produce the same amount of electricity, and a comparable wind installation needs between 260 and 3,360 square miles.[145]

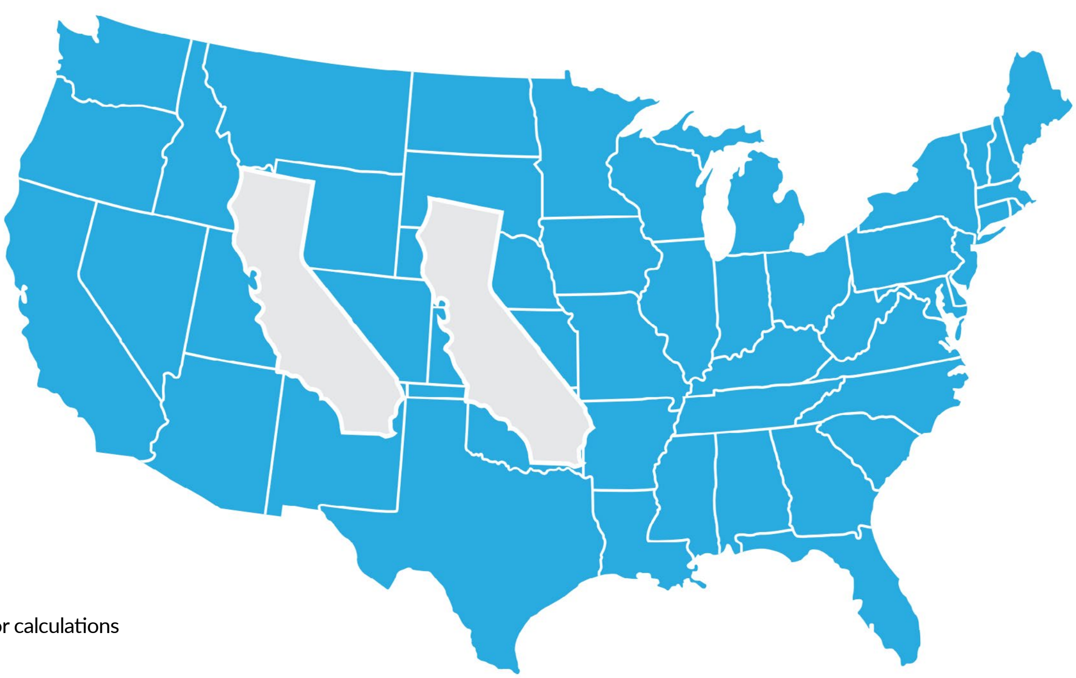
The deputy director of research at the Massachusetts Institute of Technology's Center for Energy and Environmental Policy Research estimates that almost 800 average-sized wind turbines would be needed to match the output of a 900-megawatt nuclear reactor.[146] Doing the same with solar panels would require around 8.5 million panels.[147]

Vaclav Smil, in his 2010 book *Energy Myths and Realities: Bringing Science to the Energy Policy Debate,* wrote that re-

Figure 12

Two Californias:

The land necessary to meet America's current electricity needs with wind energy



Source: Author calculations

lying on wind turbines for all U.S. electricity would "require installing about 1.8 terawatts of new generating capacity," which would require 900,000 square kilometers, or about twice the size of the state of California.[148]

A peer-reviewed study, published in the journal PLOS One, makes plain the infeasibility of the land area necessary to meet the assumptions of 10 global renewable energy scenarios, including those of the IEA, Greenpeace, World Wildlife Fund (WWF), and others.[149] The land required for electricity generation under all decarbonization scenarios would at least double, with one scenario requiring land use on the order of 500 to 900 million hectares by 2030. One author points out in an article for The Breakthrough Institute that "the latter figure is roughly the same as the total land area of the United States!"[150]

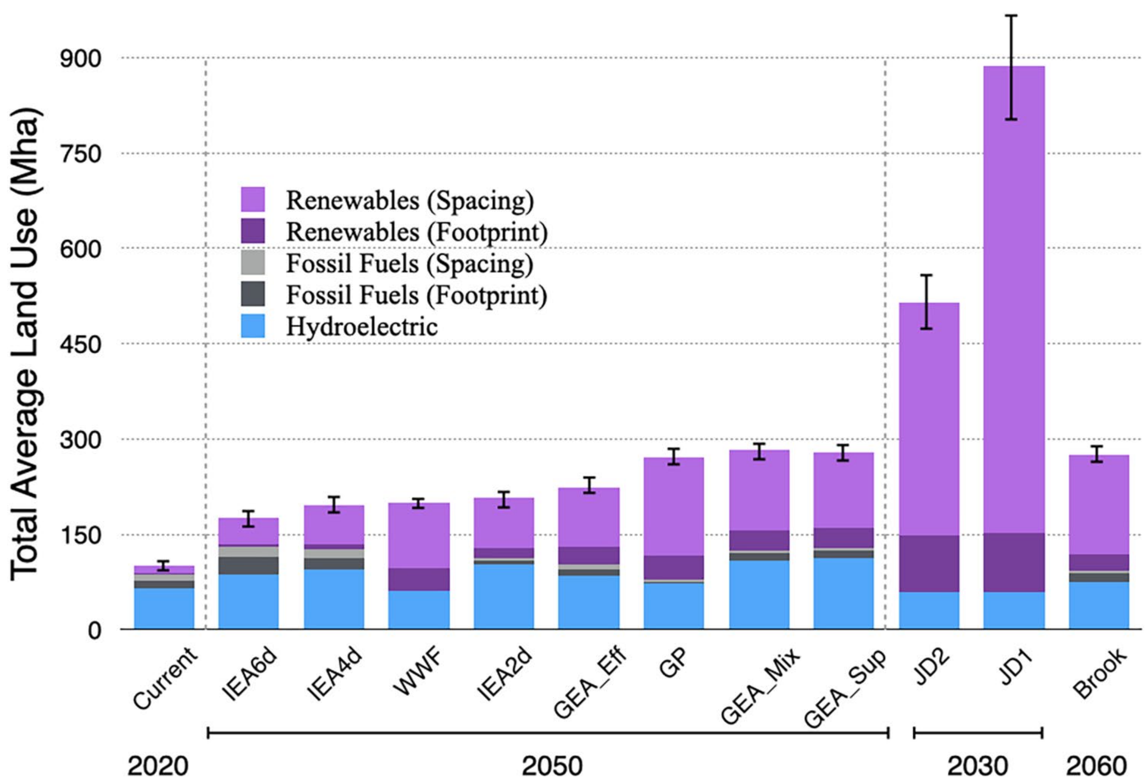
From Lovering et al., authors of the PLOS One study, Figure 13 reproduces the total average land use, in millions of hectares, for the 10 decarbonization scenarios considered. The IEA's "business as usual scenario" (IEA6d in Figure 13), which includes a healthy share of oil, gas, and coal use, still requires a doubling of land dedicated to energy production. Scenarios from WWF and Greenpeace "also had low total land use, but that was in part due to their lower overall projected electricity consumption." The "Brook" scenario in Figure 13 had "lower land-use despite higher overall electricity consumption, primarily due to their reliance on nuclear power." JD2 and JD1 from Figure 13 "were converting all global energy use to electricity" and "rely extensively on wind and solar."

These massive land footprint estimates, including Lovering et al., do not account for the additional transmission lines needed to transport electricity from the area of production to population centers where the electricity may be used. In "Mission Impossible: Mineral Shortages and the Broken

Figure 13

Land Area (Mha) for Future Electricity Generation Scenarios, Broken Down by Source of Land Use:

Hydroelectric, fossil fuels, non-hydro renewables, and spacing from wind and natural gas



Permitting Process Put Net Zero Goals Out of Reach," Debra Struhsacker and I describe the challenge of building adequate transmission, citing the following congressional testimony by Durbin and Hayes:

> Mr. Martin Durbin, Senior Vice President of Policy, and President of the Global Energy Institute at the U.S. Chamber of Commerce, testified at the April 24, 2023 hearing before the Senate Environment and Public Works Committee that over one million miles of transmission lines need to be built in order to achieve NZE by 2050. At this same hearing, Ms. Christina Hayes, Executive Director of Americans for a Clean Energy Grid, told lawmakers that in the early 2010s, about 1,700 line-miles of high-voltage transmission lines were permitted each year in the U.S., dropping to a current rate of around 700 line-miles per year. At this rate it will take 1,400 years to permit one million miles of transmission lines, dramatically illustrating that policymakers have embraced grossly unrealistic goals and timelines in which to achieve any semblance of an energy transition.[151]

With few exceptions, land that is being used for electricity generation isn't useful for anything else. Avenues of research seek to utilize the "unoccupied" land around solar panels for agriculture, though the Union of Concerned Scientists notes that "there is less opportunity for solar projects to share land with agricultural uses."[152] Wind turbines, which have wide spacing, are sometimes co-located on farms. Others seek to install solar panels in "dual use" areas, such as above parking lots, canals, rooftops on homes and commercial buildings, or other urban areas. The scalability of those efforts should be decided by economics (including the costs of government subsidies) and with robust community involvement when necessary. However, a few disadvantages arise:

1. The spacing area around wind turbines and solar panels can fragment habitat, reduce biodiversity, and harm bird and bat populations (especially true for wind turbines), regardless of whether the land is successfully repurposed for agriculture. Construction disturbances may alter or remove fertile topsoil, exacerbating erosion, as well as irreparably alter drainage patterns. The crops suitable for agriculture around wind turbines and solar panels may also be different than those grown on prime farmland (for instance, crops that grow well in the shade under solar panels).
2. Rooftop solar is more expensive to construct and operate than utility-scale solar due to its distributed infrastructure, and net metering costs utilities because rooftop customers are usually paid retail rates rather than wholesale rates.[153,154]
3. Peer-reviewed evidence is mounting that solar panels and wind turbines alter local surface temperatures. Two 2018 studies by Harvard University researchers estimated that large-scale wind farms to meet renewable energy goals would warm "average surface temperatures over the continental United States by 0.24 degrees Celsius" (0.432 degrees Fahrenheit).[155] In fact, the "warming effect" is "actually larger than the effect of reduced emissions for the first century of its operation."[156] Deployment of rooftop solar panels in Sydney, Australia, "caused air temperature to rise by 1.5 °C during the daytime and decrease by 2.7°C at nighttime."[157]

Agricultural concerns are compounded considering that, according to the American Farmland Trust, 83 percent of new solar projects are installed on farmland, and "almost 50% placed on the most productive, versatile, and resilient" farmland according to the U.S. Department of Agriculture.[158] Leasing for solar can be lucrative for farmers: A majority of farmers in a 2024 survey report being offered more than $1,000 per acre for solar leasing.[159] Depending on region, crop type, equipment, operating costs, and commodity prices, many farmers would find a guaranteed per acre rent of that price to be the right economic choice for them.[160]

Some concentrating solar thermal plants (CSP) also use water for cooling, which may be between 600 and 650 gallons of water per megawatt-hour of electricity produced in a wet-recirculating system.[161] Dry-cooling technology reduces water use substantially but is less effective at temperatures above 100 degrees Fahrenheit, which is routinely exceeded in areas of the southwestern U.S. with some of the highest solar energy potential.

Wind and solar projects often face backlash from impacted residents whose concerns are not sufficiently listened to or addressed. Renowned energy journalist Robert Bryce wrote "Not In Our Backyard: Rural America is Fighting Back Against Large-Scale Renewable Energy Projects in 2021" for Center of the American Experiment.[162] A "preponderance of scientific evidence shows that wind-turbine noise may have serious health impacts on humans," Bryce found, and residents also see negative impacts on residential property values and visual landscape. Bryce found that in Minnesota, "nearly all of the wind projects" are "located in counties that are poorer than the statewide average," and noise complaints against the 200-megawatt Bent Tree Wind Farm project in Freeborn County were "unresolved and substantial."

Bryce writes that "many academics have minimized the land-use needs of renewables," but "the problem is fundamentally about physics." The physics of energy density dictate that the footprint of wind and solar in the U.S. may be so large that it sacrifices too many other, worthwhile uses of land.

Section VII: Realistic Assumptions about Recycling and Technological Advances

The material intensity of alternative energy sources is often handwaved under the assumption that major advances in technology and enormous recycling programs will dramatically reduce material requirements in the future. This assumes technology will advance rapidly enough to be commercially viable by the ambitious net-zero timelines set by policymakers. This cannot be depended upon.

It is reasonable to assume there will be advancements in battery technology that may change the chemistry of cathodes and anodes in lithium-ion batteries. The types and quantities of minerals needed for battery manufacturing may well change. The current dominant compositions of lithium-ion battery cathodes are 1) nickel-manganese-cobalt-oxide (NMC) cathodes and 2) nickel-cobalt-aluminum (NCA) cathodes.

Lithium-iron-phosphate (LFP) cathodes are gaining popularity but have a lower energy density than nickel-based cathodes. Consequently, EVs powered by LFP batteries, which became a major cathode chemistry in 2023 and comprises about 40 percent of EV battery sales by capacity, have a reduced driving range.

Manufacturing from scrap metals and end-of-life equipment may lead to a significant "secondary supply" of some minerals and reduce the need for mining ("primary supply"), but it will not completely eliminate the need for new mining. Secondary supply is predicted to increase with time as equipment constructed with primary-supply minerals reaches the end of useful life and is recycled. The first generation of EV batteries are approaching the end of their life now and will become a larger feedstock for recycling.

Certain minerals, including aluminum and copper, are more amenable to commercial-scale recycling and have well-established pathways from electronic waste and manufacturing scrap. Copper is one of the few materials that can be recycled repeatedly without any loss of quality. The upper range estimate for copper's recycling rate is 70 percent, since a portion of copper is used in exceedingly small parts in complex electronics and cannot be recycled.

Lithium, nickel, cobalt, and rare earth elements do not have widespread recycling programs. A 2023 material stock flow model of the IEA's net-zero emissions scenario suggests that the demand for rare earth elements will continue to surge through 2050 and beyond.[163] However, "increased recycling will have a relatively low impact on the demand for primary resources" in the short term and "with current recycling rates, the secondary supply of REEs will contribute <1% to the demand in 2050."

In 2024, the IEA estimates that "a successful scale-up of recycling can lower the need for new mining activity" by 40 percent for copper and cobalt and almost 25 percent for lithium and nickel and still meet announced international climate pledges.[164] However, the "successful scale-up" entails boosting collection rates and strengthening "domestic infrastructure" through "incentives and mandates." The IEA also notes that, "Recycling is not free from environmental and social impacts," as there may be "pollution from waste residues, water contaminants and harmful emissions."

As the scale of global recycling grows, some governments and environmental organizations are beginning to focus on health and safety issues of recycling. Most electronics recycling occurs in poorer nations willing to undertake the labor-intensive, unregulated, and sometimes hazardous processes involved, sometimes with child labor.[165] Some minerals in solar panels, like lead and cadmium, are harmful to human health and the environment. Battery recycling capacity is also expected to be dominated by China, as "China is on track to retain 80% of global pretreatment capacity and 75% of material recovery capacity in 2030."[166]

It is foolhardy to assume that technological advancements and increased recycling will significantly reduce material requirements in the foreseeable future. "Business-as-usual" requirements are unlikely to decrease as societies become more prosperous, and demand for minerals and electricity to support artificial intelligence data centers is already growing. Technology may not advance, or proceed to commercial scales, quickly enough to meet policymakers' ambitious energy transition timelines. Further, it is not possible to recycle something that has yet to be manufactured.

New mining will be necessary to meet material demands for wind, solar, and batteries regardless of new technology and recycling impacts. Whether new mining is done in the U.S. with modern environmental and safety standards, thus managing environmental impacts, or whether it is done "out of sight, out of mind," in foreign countries with lax standards, is the important consideration.

Section VIII: Conclusion

Energy policy should be driven by facts, not by surface-level assumptions. All forms of energy entail environmental impacts. An honest accounting of the negative impacts of wind, solar, and battery storage shows that they are far less than the unqualified good that proponents suggest. The material intensity, land use demands, and lifecycle challenges of wind and solar must be acknowledged by policymakers. Similarly, the scalability, reliability, and small land use footprints of coal, natural gas, oil, and nuclear are substantial benefits.

- **Existing estimates of the material intensity of U.S. and global net-zero carbon emissions scenarios should spark concern, especially for certain materials.** Even sources that may underestimate the enormity of an energy transition suggest that there will be serious shortfalls for copper, with nearly all of the world's current production being needed for annual renewables requirements, and demand for lithium would increase by a factor of 10.
- **Material demands for steel, concrete, and aluminum are rarely estimated, but may see significant demand.** Demand for steel is expected to at least quintuple by 2050. Simplified estimates of the concrete needed to build only the wind turbines for U.S. net-zero scenarios (which incorporate other energy sources, like solar and nuclear) could require a total of 347 million metric tons of concrete by 2035 and 755 million metric tons of concrete by 2050.
- **A hypothetical U.S. grid powered by nuclear plants would have the lowest material requirements.** Simplified estimates suggest that U.S. electricity demand in 2026 could be met through 464 1-GW nuclear plants alongside natural gas peaking. This would use only 12,811 tons of uranium for fuel annually and generate only 371 tons of high-level waste for the entire U.S.
- **The land use footprint of wind and solar is disproportionately large.** Wind and solar generation require at least 10 times as much land per unit of power produced as coal- or natural gas-fired power plants, increasing habitat loss, agricultural displacement, and zoning conflicts. If the U.S. were to power itself entirely on wind turbines, the land area required would be the size of two Californias. One global net-zero scenario would need nearly as much land area as the entire U.S.
- **Birds, bats, whales, and other wildlife species are demonstrably harmed by onshore wind, offshore wind, and solar projects**. There is increasing evidence that offshore wind turbines negatively impact whale populations. Onshore wind and solar installations also pose a collision risk to birds and bats, with certain vulnerable species being more prone to strikes. Additionally, habitat fragmentation interferes with nesting, migration, and wintering behaviors in certain species.
- **Wind, solar, and battery storage infrastructure's**

short lifespan means compounding environmental and economic costs. Turbines and panels operate for only 20 to 25 years, while natural gas plants may last 40 years, and nuclear plants operate between 40 and 80 years. Often, wind turbines and solar panels are repowered well before their 20-year lifespan, compounding costs further.

- **Recycling and technological advances will not eliminate material demands.** Recycling pathways are not yet built for most materials needed for a wind and solar grid. While improvements in efficiency and recycling may help, they cannot replace the need for newly mined and manufactured materials.
- **Nuclear, natural gas, oil, and coal provide reliable, high-density energy.** These sources support baseload electricity and peaking generation with smaller land footprints and few material inputs.

In addition, this report demonstrates that if policymakers find a zero-carbon electricity grid desirable, it is possible with the least material impacts through *nuclear power.* Nuclear power's high energy density eliminates the need for large-scale energy storage while producing power on a small landscape footprint, few material inputs, and manageable waste disposal challenges.

Energy policy decisions should reflect full environmental and economic realities. The feasibility and desirability of energy technologies must be evaluated with a comprehensive understanding of the costs and benefits.

Endnotes

1 Struhsacker, Debra, and Sarah Montalbano. "Mission Impossible: Mineral Shortages and the Broken Permitting Process Put Net Zero Goals Out of Reach." Center of the American Experiment, October 2024. https://files.americanexperiment.org/wp-content/uploads/2024/10/Mission-Impossible-report-2024.pdf?v=1728416598.

2 Struhsacker, Montalbano. "Mission Impossible." https://files.americanexperiment.org/wp-content/uploads/2024/10/Mission-Impossible-report-2024.pdf?v=1728416598.

3 "What Are Critical Minerals?" USGS, November 1, 2024. https://www.usgs.gov/programs/mineral-resources-program/science/what-are-critical-minerals-0.

4 "Material and Resource Requirements for the Energy Transition." Energy Transitions Commission, July 2023. https://www.energy-transitions.org/wp-content/uploads/2023/08/ETC-Materials-Report_highres-1.pdf.

5 Energy Transitions Commission, Material and Resource Requirements for the Energy Transition. https://www.energy-transitions.org/wp-content/uploads/2023/08/ETC-Materials-Report_highres-1.pdf

6 Energy Transition Commission, Material and Resource Requirements for the Energy Transition. https://www.energy-transitions.org/wp-content/uploads/2023/08/ETC-Materials-Report_highres-1.pdf

7 U.S. Geological Survey, 2025, Mineral commodity summaries 2025 (ver. 1.2, March 2025): U.S. Geological Survey, p. 94, 95, https://doi.org/10.3133/mcs2025.

8 U.S. Geological Survey, 2025, Mineral commodity summaries 2025 (ver. 1.2, March 2025): U.S. Geological Survey, p. 32, 33, https://doi.org/10.3133/mcs2025.

9 U.S. Geological Survey, 2025, Mineral commodity summaries 2025 (ver. 1.2, March 2025): U.S. Geological Survey, p. 32, 33, https://doi.org/10.3133/mcs2025.

10 U.S. Geological Survey, 2025, Mineral commodity summaries 2025 (ver. 1.2, March 2025): U.S. Geological Survey, p. 64, 65, https://doi.org/10.3133/mcs2025.

11 Energy Transition Commission, Material and Resource Requirements for the Energy Transition. https://www.energy-transitions.org/wp-content/uploads/2023/08/ETC-Materials-Report_highres-1.pdf

12 "U.S. Department of Energy Announces Plans to Create Low-Carbon Cement and Concrete Center of Excellence to Reduce Industrial Emissions." Energy.gov, July 19, 2024. https://www.energy.gov/eere/iedo/articles/us-department-energy-announces-plans-create-low-carbon-cement-and-concrete.

13 Eberle, Annika, Aubryn Cooperman, Julien Walzberg, Dylan Hettinger, Richard F. Tusing, Derek Berry, Daniel Inman, et al. 2023. Materials Used in U.S. Wind Energy Technologies: Quantities and Availability for Two Future Scenarios. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-81483. https://www.nrel.gov/docs/fy23osti/81483.pdf

14 "U.S. Wind Generation Hit Record in April 2024, Exceeding Coal-Fired Generation - U.S. Energy Information Administration (EIA)." U.S. Energy Information Administration (EIA), August 13, 2024. https://www.eia.gov/todayinenergy/detail.php?id=62784.

15 "Recycling Wind Energy Systems in the United States Part 1." National Renewable Energy Laboratory, January 2025. https://www.nrel.gov/docs/fy25osti/87970.pdf.

16 U.S. Geological Survey, 2025, Mineral commodity summaries 2025 (ver. 1.2, March 2025): U.S. Geological Survey, p. 54, 55, https://doi.org/10.3133/mcs2025.

17 U.S. Geological Survey, 2025, Mineral commodity summaries 2025 (ver. 1.2, March 2025): U.S. Geological Survey, p. 54, 55, https://doi.org/10.3133/mcs2025.

18 U.S. Geological Survey, 2025, Mineral commodity summaries 2025 (ver. 1.2, March 2025): U.S. Geological Survey, p. 54, 55, https://doi.org/10.3133/mcs2025.

19 Hanifa, Mohd, R. Agarwal, U. Sharma, P.C. Thapliyal, and L.P. Singh. "A Review on CO2 Capture and Sequestration in the Construction Industry: Emerging Approaches and Commercialised Technologies." *Journal of CO2 Utilization* 67 (January 2023): 102292. https://doi.org/10.1016/j.jcou.2022.102292.

20 "Greenhouse Gas Equivalencies Calculator." EPA, November 2024. https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

21 "Wind Quantity Dataset." Renewable Energy Materials Properties Database (REMPD) Wind Quantity Dataset. Accessed April 2, 2025. https://apps.openei.org/REMPD/quantity/wind.

22 Eberle, Annika, Aubryn Cooperman, Julien Walzberg, Dylan Hettinger, Richard F. Tusing, Derek Berry, Daniel Inman, et al. 2023. Materials Used in U.S. Wind Energy Technologies: Quantities and Availability for Two Future Scenarios. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-81483. https://www.nrel.gov/docs/fy23osti/81483.pdf

23 "Solar Quantity Dataset." REMPD Solar Quantity. Accessed April 2, 2025. https://apps.openei.org/REMPD/quantity/solar.

24 Friedman, Daniel J., Peter L. Hacke, Mowafak Al-Jassim, Silvana Ovaitt, and Susannah Shoemaker. 2024. 2024 Photovoltaic Inverter Reliability Workshop Summary Report & Proceedings. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5900- 90315. https://www.nrel.gov/docs/fy24osti/90315.pdf.

25 Margolis, Robert. "Solar Futures Study Fact Sheet." Energy.gov, September 2021. https://www.energy.gov/sites/default/files/2021-09/Solar_Futures_Study_Fact_Sheet.pdf.

26 "Solar Industry Research Data." Solar Energy Industries Association, March 12, 2025. https://seia.org/research-resources/solar-industry-research-data/.

27 Energy Transition Commission, Material and Resource Requirements for the Energy Transition. https://www.energy-transitions.org/wp-content/uploads/2023/08/ETC-Materials-Report_highres-1.pdf

28 "The Ultimate Fast Facts Guide to Nuclear Energy." Energy.gov, January 2019. https://www.energy.gov/sites/prod/files/2019/01/f58/Ultimate Fast Facts Guide-PRINT.pdf.

29 Energy Transition Commission, Material and Resource Requirements for the Energy Transition. https://www.energy-transitions.org/wp-content/uploads/2023/08/ETC-Materials-Report_highres-1.pdf

30 Energy Transition Commission, Material and Resource Requirements for the Energy Transition. https://www.energy-transitions.org/wp-content/uploads/2023/08/ETC-Materials-Report_highres-1.pdf

31 "Nuclear Energy Factsheet." Center for Sustainable Systems, 2024. https://css.umich.edu/publications/factsheets/energy/nuclear-energy-factsheet.

32 "Nuclear Energy Factsheet." Center for Sustainable Systems, 2024. https://css.umich.edu/publications/factsheets/energy/nuclear-energy-factsheet.

33 Tsao, Stephanie, and Mark Morey. "U.S. Hourly Electricity Demand Peaked in July with Widespread Heatwaves." EIA.gov, October 10, 2024. https://www.eia.gov/todayinenergy/detail.php?id=63445#:~:text=Last%20summer%2C%20U.S.%20electricity%20demand,in%202022%20(743%20GWh).

34 "Short-Term Energy Outlook." EIA.gov, March 6, 2025. https://www.eia.gov/outlooks/steo/.

35 "Advanced Small Modular Reactors." Idaho National Laboratory, October

31, 2024. https://inl.gov/trending-topics/small-modular-reactors/.

36 "NRC Certifies First U.S. Small Modular Reactor Design." Energy.gov, January 20, 2023. https://www.energy.gov/ne/articles/nrc-certifies-first-us-small-modular-reactor-design.

37 IEA (2021), Share of top producing countries in total processing of selected minerals and fossil fuels, 2019, IEA, Paris https://www.iea.org/data-and-statistics/charts/share-of-top-producing-countries-in-total-processing-of-selected-minerals-and-fossil-fuels-2019, Licence: CC BY 4.0

38 "China's Mining Investment under Belt and Road Initiative Sets New Record – Report - Mining.Com." Mining.com, March 29, 2025. https://www.mining.com/chinas-mining-investment-under-belt-and-road-initiative-sets-new-record-report/.

39 Annual report of the secretary of the Interior for the fiscal year 1915, vol. 1. Accessed April 2, 2025. https://babel.hathitrust.org/cgi/pt?id=njp.32101065268557&seq=44.

40 Struhsacker & Montalbano. "Mission Impossible." https://files.americanexperiment.org/wp-content/uploads/2024/10/Mission-Impossible-report-2024.pdf?v=1728416598.

41 Lv, Amy, and Tony Munroe. "China Bans Export of Critical Minerals to US as Trade Tensions Escalate." *Reuters*, December 3, 2024. https://www.reuters.com/markets/commodities/china-bans-exports-gallium-germanium-antimony-us-2024-12-03/.

42 Orr, Isaac, Debra Struhsacker, and John Phelan. "Unearthing Prosperity: How Environmentally Responsible Mining Will Boost Minnesota's Economy." Center of the American Experiment, August 2018. https://files.americanexperiment.org/wp-content/uploads/2020/11/Updating-Prosperity-Nov-2020-1.pdf.

43 "Frequently Asked Questions (Faqs) - What Is U.S. Electricity Generation by Energy Source?" Frequently Asked Questions (FAQs) - What is U.S. electricity generation by energy source? Accessed February 10, 2025. https://www.eia.gov/tools/faqs/faq.php?id=427&t=8#:~:text=In%202023%2C%20about%204%2C178%20billion,2.

44 Eberle, Annika, Aubryn Cooperman, Julien Walzberg, Dylan Hettinger, Richard F. Tusing, Derek Berry, Daniel Inman, et al. 2023. Materials Used in U.S. Wind Energy Technologies: Quantities and Availability for Two Future Scenarios. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-81483. https://www.nrel.gov/docs/fy23osti/81483.pdf

45 Lakshmi, A. Anantha, and Diana Mariska. "Indonesia: Workers Allege 'production First, Safety Later' Culture at IMIP Nickel Complex Leads to Unsafe Conditions & Rising Accidents." Business & Human Rights Resource Centre, November 28, 2024. https://www.business-humanrights.org/en/latest-news/indonesia-imip-nickel-park-workers-allege-poor-safety-accidents-deaths-union-retaliation-restricted-movement-of-chinese-staff/.

46 Moore, Ellen. "Multiple Dams Fail at Indonesian Nickel-Mining Facilities." Earthworks, March 28, 2025. https://earthworks.org/blog/multiple-dams-fail-at-indonesian-nickel-mining-facilities/.

47 "3 Pekerja Tertimbun Longsor Di Kawasan Pt IMIP, YTM Desak Evaluasi Menyeluruh [3 Workers Buried in Landslide in PT IMIP Area, YTM Urges Comprehensive Evaluation]." kabarsulteng.id, March 24, 2025. https://www.kabarsulteng.id/2025/03/24/3-pekerja-tertimbun-longsor-di-kawasan-pt-imip-ytm-desak-evaluasi-menyeluruh/.

48 "Forced Labor in Cobalt Mining in the Democratic Republic of the Congo." Office of Child Labor, Forced Labor, and Human Trafficking, May 30, 2023. https://www.dol.gov/sites/dolgov/files/ILAB/DRC-FL-Cobalt-Report-508.pdf.

49 "Acid Spill from Chinese-Owned Copper Mine Contaminates Vital Waterway in Zambia - Mining.Com." Mining.com, March 18, 2025. https://www.mining.com/acid-spill-from-chinese-owned-copper-mine-contaminates-vital-waterway-in-zambia/.

50 "A River 'Died' Overnight in Zambia after an Acidic Waste Spill at a Chinese-Owned Mine." *Politico*. March 16, 2025. https://www.politico.com/news/2025/03/16/a-river-died-overnight-in-zambia-after-an-acidic-waste-spill-at-a-chinese-owned-mine-00232234.

51 "A River 'Died' Overnight in Zambia after an Acidic Waste Spill at a Chinese-Owned Mine." *Politico*. March 16, 2025. https://www.politico.com/news/2025/03/16/a-river-died-overnight-in-zambia-after-an-acidic-waste-spill-at-a-chinese-owned-mine-00232234.

52 Struhsacker & Sarah Montalbano. "Mission Impossible." https://files.americanexperiment.org/wp-content/uploads/2024/10/Mission-Impossible-report-2024.pdf?v=1728416598.

53 Mamula, Ned, Ann Bridges, and Drew Horn. *Undermining power: How to overthrow Mineral, Energy, Economic & National Security Disinformation*. United States: Terradynamics Corporation, 2024.

54 United States, National Marine Fisheries Service., Office of Protected Resources, "Recovery plan for the north Atlantic right whale (Eubalaena glacialis)" (2005).

55 Rolland, Rosalind M., Susan E. Parks, Kathleen E. Hunt, Manuel Castellote, Peter J. Corkeron, Douglas P. Nowacek, Samuel K. Wasser, and Scott D. Kraus. "Evidence That Ship Noise Increases Stress in Right Whales." *Proceedings of the Royal Society B: Biological Sciences* 279, no. 1737 (February 8, 2012): 2363–68. https://doi.org/10.1098/rspb.2011.2429.

56 "Frequent Questions-Offshore Wind and Whales." NOAA Fisheries, March 14, 2024. https://www.fisheries.noaa.gov/new-england-mid-atlantic/marine-life-distress/frequent-questions-offshore-wind-and-whales#:~:text=There%20are%20no%20known%20links,whales%20and%20other%20marine%20mammals.

57 "BOEM and NOAA Fisheries North Atlantic Right Whale and Offshore Wind Strategy." Bureau of Ocean Energy Management, January 2024. https://www.boem.gov/sites/default/files/documents/environment/BOEM_NMFS_NARW_OSW_0.pdf.

58 BOEM & NOAA Fisheries, "Right Whale and Offshore Wind Strategy." https://www.boem.gov/sites/default/files/documents/environment/BOEM_NMFS_NARW_OSW_0.pdf

59 BOEM & NOAA Fisheries, "Right Whale and Offshore Wind Strategy." https://www.boem.gov/sites/default/files/documents/environment/BOEM_NMFS_NARW_OSW_0.pdf

60 Quintana-Rizzo, E, S Leiter, TVN Cole, MN Hagbloom, AR Knowlton, P Nagelkirk, O O'Brien, et al. "Residency, Demographics, and Movement Patterns of North Atlantic Right Whales Eubalaena Glacialis in an Offshore Wind Energy Development Area in Southern New England, USA." *Endangered Species Research* 45 (July 29, 2021): 251–68. https://doi.org/10.3354/esr01137 .

61 Quintana-Rizzo et. al., "Right whale wind energy areas." https://doi.org/10.3354/esr01137

62 "Oceanographic Effects of Offshore Wind Structures and Their Potential Impacts on the North Atlantic Right Whale and Their Prey." American Clean Power Association, October 2023. https://cleanpower.org/wp-content/uploads/gateway/2023/10/ACP_OSW-Hydrodynamics-and-NARW_Whitepaper_2023.pdf.

63 American Clean Power Association, "Oceanographic Effects of Offshore Wind." https://cleanpower.org/wp-content/uploads/gateway/2023/10/ACP_OSW-Hydrodynamics-and-NARW_Whitepaper_2023.pdf

64 Sennott, Will, and Kellen Riell. "Whale Carcasses on Martha's Vineyard

Fuel Speculation about Wind Turbines." *The New Bedford Light*, June 22, 2023. https://newbedfordlight.org/whale-carcasses-on-marthas-vineyard-fuel-speculation-about-wind-turbines/.

65 "North Atlantic Right Whale Updates." NOAA Fisheries, February 18, 2025. https://www.fisheries.noaa.gov/national/endangered-species-conservation/north-atlantic-right-whale-updates#right-whale-5120-found-dead-near-marthas-vineyard.

66 NOAA Fisheries, "North Atlantic Right Whale Updates." https://www.fisheries.noaa.gov/national/endangered-species-conservation/north-atlantic-right-whale-updates#right-whale-5120-found-dead-near-marthas-vineyard.

67 Kershaw, Francine. "Smart Siting of Offshore Wind Protects Right Whales in Gulf of Maine." National Resources Defense Council, March 29, 2024. https://www.nrdc.org/bio/francine-kershaw/smart-siting-offshore-wind-protects-right-whales-gulf-maine.

68 "Wind Turbines and Bats." WINDExchange. Accessed April 2, 2025. https://windexchange.energy.gov/projects/bats.

69 "How Are Bats Affected by Wind Turbines?" USGS, March 14, 2025. https://www.usgs.gov/faqs/how-are-bats-affected-wind-turbines.

70 "Reducing Bat Fatalities From Interactions with Operating Wind Turbines." National Renewable Energy Laboratory, November 2013. https://www.nrel.gov/docs/fy14osti/60427.pdf.

71 "New Study of Bat Habitats and Wind Energy Can Help Energy Providers Minimize Collisions." *USGS*, July 30, 2024. U.S. Geological Survey. https://www.usgs.gov/news/national-news-release/new-study-bat-habitats-and-wind-energy-can-help-energy-providers.

72 Huang, Ta-Ken, Xiao Feng, Jonathan J. Derbridge, Kaitlin Libby, Jay E. Diffendorfer, Wayne E. Thogmartin, Gary McCracken, Rodrigo Medellin, and Laura López-Hoffman. "Potential for Spatial Coexistence of a Transboundary Migratory Species and Wind Energy Development." *Scientific Reports* 14, no. 1 (July 24, 2024). https://doi.org/10.1038/s41598-024-66490-3.

73 WINDExchange, "Wind Turbines and Bats." https://windexchange.energy.gov/projects/bats.

74 Frick, W.F., E.F. Baerwald, J.F. Pollock, R.M.R. Barclay, J.A. Szymanski, T.J. Weller, A.L. Russell, S.C. Loeb, R.A. Medellin, and L.P. McGuire. "Fatalities at Wind Turbines May Threaten Population Viability of a Migratory Bat." *Biological Conservation* 209 (May 2017): 172–77. https://doi.org/10.1016/j.biocon.2017.02.023.

75 WINDExchange, "Wind Turbines and Bats." https://windexchange.energy.gov/projects/bats.

76 WINDExchange, "Wind Turbines and Bats." https://windexchange.energy.gov/projects/bats.

77 "How Many Birds Are Killed by Wind Turbines?" American Bird Conservancy, January 26, 2021. https://abcbirds.org/blog21/wind-turbine-mortality/.

78 Hoen, B.D., Diffendorfer, J.E., Rand, J.T., Kramer, L.A., Garrity, C.P., and Hunt, H.E., 2018, United States Wind Turbine Database V8.0 (February 25, 2025): U.S. Geological Survey, American Clean Power Association, and Lawrence Berkeley National Laboratory data release, https://doi.org/10.5066/F7TX3DN0.

79 Smallwood, K. Shawn, Douglas A. Bell, and Skye Standish. "Dogs Detect Larger Wind Energy Effects on Bats and Birds." *The Journal of Wildlife Management* 84, no. 5 (March 26, 2020): 852–64. https://doi.org/10.1002/jwmg.21863.

80 Bennun, L., van Bochove, J., Ng, C., Fletcher, C., Wilson, D., Phair, N., Carbone, G. (2021). Mitigating biodiversity impacts associated with solar and wind energy development. Guidelines for project developers. Gland, Switzerland: IUCN and Cambridge, UK: The Biodiversity Consultancy. https://iucn.org/sites/default/files/2022-06/02_biodiversity_impacts_associated_to_on-shore_wind_power_projects_0.pdf

81 Subramanian, Meera. "The Trouble with Turbines: An Ill Wind." *Nature* 486, no. 7403 (June 21, 2012): 310–11. https://doi.org/10.1038/486310a.

82 Subramanian, "The Trouble with Turbines." https://doi.org/10.1038/486310a

83 Loss, Scott R., Tom Will, and Peter P. Marra. "Direct Mortality of Birds from Anthropogenic Causes." *Annual Review of Ecology, Evolution, and Systematics* 46, no. 1 (December 4, 2015): 99–120. https://doi.org/10.1146/annurev-ecolsys-112414-054133.

84 Loss et al., "Direct Anthropogenic Bird Mortality." https://doi.org/10.1146/annurev-ecolsys-112414-054133.

85 Zimmer, Katarina. "Wind Turbines Kill Too Many Birds and Bats. How Can We Make Them Safer?" Canary Media, January 2, 2024. https://www.canarymedia.com/articles/wind/wind-turbines-kill-too-many-birds-and-bats-how-can-we-make-them-safer.

86 Thaxter, Chris B., Graeme M. Buchanan, Jamie Carr, Stuart H. Butchart, Tim Newbold, Rhys E. Green, Joseph A. Tobias, Wendy B. Foden, Sue O'Brien, and James W. Pearce-Higgins. "Bird and Bat Species' Global Vulnerability to Collision Mortality at Wind Farms Revealed through a Trait-Based Assessment." *Proceedings of the Royal Society B: Biological Sciences* 284, no. 1862 (September 13, 2017): 20170829. https://doi.org/10.1098/rspb.2017.0829.

87 Subramanian, "The Trouble with Turbines." https://doi.org/10.1038/486310a.

88 Bennun et al, "Mitigating Wind and Solar Biodiversity impacts." https://iucn.org/sites/default/files/2022-06/02_biodiversity_impacts_associated_to_on-shore_wind_power_projects_0.pdf

89 Lloyd, John D., Cameron L. Aldridge, Taber D. Allison, Chad W. LeBeau, Lance B. McNew, and Virginia L. Winder. "Prairie Grouse and Wind Energy: The State of the Science and Implications for Risk Assessment." *Wildlife Society Bulletin* 46, no. 3 (June 17, 2022). https://doi.org/10.1002/wsb.1305.

90 Bennun et al, "Mitigating Wind and Solar Biodiversity impacts." https://iucn.org/sites/default/files/2022-06/02_biodiversity_impacts_associated_to_on-shore_wind_power_projects_0.pdf

91 Loss, Scott R., Tom Will, and Peter P. Marra. "Refining Estimates of Bird Collision and Electrocution Mortality at Power Lines in the United States." *PLoS ONE* 9, no. 7 (July 3, 2014). https://doi.org/10.1371/journal.pone.0101565.

92 Bennun et al, "Mitigating Wind and Solar Biodiversity impacts." https://iucn.org/sites/default/files/2022-06/02_biodiversity_impacts_associated_to_on-shore_wind_power_projects_0.pdf

93 Bennun et al, "Mitigating Wind and Solar Biodiversity impacts." https://iucn.org/sites/default/files/2022-06/02_biodiversity_impacts_associated_to_on-shore_wind_power_projects_0.pdf

94 Milligan, Megan C., Aaron N. Johnston, Jeffrey L. Beck, Kurt T. Smith, Kaitlyn L. Taylor, Embere Hall, Lee Knox, et al. "Variable Effects of Wind-energy Development on Seasonal Habitat Selection of Pronghorn." *Ecosphere* 12, no. 12 (December 2021). https://doi.org/10.1002/ecs2.3850.

95 Smallwood, K. Shawn. "Utility-scale Solar Impacts to Volant Wildlife." *The Journal of Wildlife Management* 86, no. 4 (March 24, 2022). https://doi.org/10.1002/jwmg.22216.

96 Diehl, Robert, Bruce Robertson, Karl Kosciuch. 2021. Investigating the "Lake Effect" Influence on Avian Behavior From California's Utility-Scale Photovoltaic Solar Facilities . California Energy Commission. Publication

Number: CEC-500-2024-055. https://www.energy.ca.gov/sites/default/files/2024-06/CEC-500-2024-055.pdf

97 Conkling, Tara J., Amy L. Fesnock, and Todd E. Katzner. "Numbers of Wildlife Fatalities at Renewable Energy Facilities in a Targeted Development Region." *PLOS ONE* 18, no. 12 (December 15, 2023). https://doi.org/10.1371/journal.pone.0295552.

98 Lewis, Stephany. "Solar Energy Production's Toll on Wild Birds - Association of Avian Veterinarians." Association of Avian Veterinarians, August 24, 2023. https://www.aav.org/blogpost/1525799/492796/Solar-Energy-Production-s-Toll-on-Wild-Birds.

99 Knickmeyer, Ellen, and John Locher. "Emerging Solar Plants Scorch Birds in Mid-Air." *Associated Press*, August 18, 2014. https://apnews.com/general-news-fc2fed5e8363445ca68f588c2dc62dd6.

100 "Solar Impacts on Wildlife and Ecosystems." Department of Energy, November 2021. https://www.energy.gov/sites/default/files/2021-11/Solar%20Impacts%20on%20Wildlife%20and%20Ecosystems%20Request%20for%20Information%20Summary.pdf.

101 "Conservation Groups Ask Interior Department to Cancel Solar Project over Desert Tortoise Impacts." *Western Watersheds Project*, March 18, 2024. Western Watersheds Project. https://www.westernwatersheds.org/2024/03/conservation-groups-ask-interior-department-to-cancel-solar-project-over-desert-tortoise-impacts/.

102 Blood, Michael R. "11 Years after a Celebrated Opening, Massive Solar Plant Faces a Bleak Future in the Mojave Desert." *Associated Press*, January 30, 2025. https://apnews.com/article/california-solar-energy-ivanpah-birds-tortoises-mojave-6d91c36a1ff608861d5620e715e1141c.

103 Marvel, Jon. "Watersheds Messenger #205." *Western Watersheds Project*, 2011. https://www.westernwatersheds.org/news-media/online-messenger/ivanpah-solar-thermal-threatens-thousands-desert-tortoise.htm

104 Department of Energy, "Solar Impacts on Wildlife." https://www.energy.gov/sites/default/files/2021-11/Solar%20Impacts%20on%20Wildlife%20and%20Ecosystems%20Request%20for%20Information%20Summary.pdf

105 "NREL Research Identifies Motivations, Methods for Achieving a Circular Economy for Wind Energy." National Renewable Energy Laboratory, February 16, 2021. https://www.nrel.gov/news/program/2021/nrel-research-identifies-motivations-methods-for-achieving-a-circular-economy-for-wind-energy.html.

106 "Wind Energy End-of-Service Guide." WINDExchange. Accessed February 10, 2025. https://windexchange.energy.gov/end-of-service-guide#:~:text=Partial%20Repowering,the%20existing%20towers%20and%20foundations.

107 Wiser, Ryan, Millstein, Dev, Hoen, Ben, et al., "Land-Based Wind Market Report: 2024 Edition," (2024), https://doi.org/10.2172/2434282. Accessed February 10, 2025. https://emp.lbl.gov/sites/default/files/2024-08/Land-Based%20Wind%20Market%20Report_2024%20Edition.pdf

108 Wiser, Ryan, Millstein, Dev, Hoen, Ben, et al., "Land-Based Wind Market Report: 2024 Edition," (2024), https://doi.org/10.2172/2434282. Accessed February 10, 2025. https://emp.lbl.gov/sites/default/files/2024-08/Land-Based%20Wind%20Market%20Report_2024%20Edition.pdf

109 "Wind Energy End-of-Service Guide." WINDExchange. Accessed February 10, 2025. https://windexchange.energy.gov/end-of-service-guide#:~:text=Partial%20Repowering,the%20existing%20towers%20and%20foundations.

110 Staffell, Iain, and Richard Green. "How Does Wind Farm Performance Decline with Age?" *Renewable Energy* 66 (June 2014): 775–86. https://doi.org/10.1016/j.renene.2013.10.041.

111 Julin, Kiran. "New Research Evaluates How US Wind Plant Performance Changes with Age | Energy Technologies Area." Energy Technologies Area, May 13, 2020. https://eta.lbl.gov/news/new-research-evaluates-how-us-wind.

112 "Wind Energy End-of-Service Guide." WINDExchange.. https://windexchange.energy.gov/end-of-service-guide.

113 "Wind Energy End-of-Service Guide." WINDExchange. https://windexchange.energy.gov/end-of-service-guide#:~:text=Partial%20Repowering,the%20existing%20towers%20and%20foundations.

114 "Wind Energy End-of-Service Guide." WINDExchange.. https://windexchange.energy.gov/end-of-service-guide.

115 "Wind Energy End-of-Service Guide." WINDExchange.. https://windexchange.energy.gov/end-of-service-guide.

116 Cooperman, Aubryn, Annika Eberle, and Eric Lantz. "Wind Turbine Blade Material in the United States: Quantities, Costs, and End-of-Life Options." *Resources, Conservation and Recycling* 168 (May 2021): 105439. https://doi.org/10.1016/j.resconrec.2021.105439.

117 Wasser, Miriam. "The Fallout from Vineyard Wind's Broken Turbine Blade." *WBUR News*, August 1, 2024. https://www.wbur.org/news/2024/08/01/massachusetts-vineyard-wind-nantucket-debris.

118 "Avangrid, CIP Announce First Power from Nation-Leading Vineyard Wind 1 Project." *Vineyard Wind*, January 3, 2024. Vineyard Wind. https://www.vineyardwind.com/press-releases/2024/1/3/cip-avangrid-announce-first-power-from-nation-leading-vineyard-wind-1-project.

119 "Going Green - Wind Turbines & Lubricant Testing." Savant Labs, August 22, 2024. https://www.savantlab.com/testing-highlights/going-green-wind-turbines-lubricant-testing/#:~:text=A%20five%2Dmegawatt%20wind%20turbine,from%209%20to%2016%20months.

120 Carrara, S., Alves Dias, P., Plazzotta, B. and Pavel, C., Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system, EUR 30095 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-16225-4, doi:10.2760/160859, JRC119941.

121 Lillo-Sánchez, L., G. López-Lara, J. Vera-Medina, E. Pérez-Aparicio, and I. Lillo-Bravo. "Degradation Analysis of Photovoltaic Modules after Operating for 22 Years. A Case Study with Comparisons." *Solar Energy* 222 (July 2021): 84–94. https://doi.org/10.1016/j.solener.2021.04.026.

122 Jordan, D.C., D.B. Sulas-Kern, S. Johnston, H.R. Moutinho, C. Xiao, C.S. Jiang, M. Young, A.G. Norman, C. Deline, I. Repins, R. Bhoopathy, O. Kunz, Z. Hameiri, C. Sainsbury. 2020. High Efficiency Silicon Module Degradation - From Atoms to Systems: Preprint. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5K00-77483. https://www.nrel.gov/docs/fy20osti/77483.pdf

123 IRENA and IEA-PVPS (2016), "End-of-Life Management: Solar Photovoltaic Panels," International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems. Accessed February 10, 2025. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf

124 Atasu, Atalay, Serasu Duran, and Luk N. Van Wassenhove. "The Dark Side of Solar Power." *Harvard Business Review*, June 18, 2021. https://hbr.org/2021/06/the-dark-side-of-solar-power.

125 Hoffs, Charlie. "Solar Panels Should Be Reused and Recycled. Here's How." The Equation, October 19, 2022. https://blog.ucsusa.org/charlie-hoffs/solar-panels-should-be-reused-and-recycled-heres-how/.

126 Curtis, Taylor L., Heather Buchanan, Ligia Smith, and Garvin Heath. 2021. A Circular Economy for Solar Photovoltaic System Materials: Drivers, Barriers, Enablers, and U.S. Policy Considerations. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-74550. https://www.nrel.gov/docs/fy21osti/74550

127 Hurdle, Jon. "As Millions of Solar Panels Age Out, Recyclers Hope to Cash In." *Yale Environment 360*, February 28, 2023. https://e360.yale.edu/features/solar-energy-panels-recycling.

128 Penrod, Emma. "US Solar Farms Are Aging. Is It Time to Begin Repowering?" *UtilityDive*, October 6, 2023. https://www.utilitydive.com/news/us-solar-farms-are-aging-is-it-time-to-begin-repowering/690978/.

129 "Electricity and Energy Storage." World Nuclear Association. Accessed April 2, 2025. https://world-nuclear.org/information-library/current-and-future-generation/electricity-and-energy-storage.

130 World Nuclear Association, "Electricity and Energy Storage." https://world-nuclear.org/information-library/current-and-future-generation/electricity-and-energy-storage

131 World Nuclear Association, "Electricity and Energy Storage." https://world-nuclear.org/information-library/current-and-future-generation/electricity-and-energy-storage

132 "Energy Storage Systems Face A Battery Recycling and Disposal Crisis?" Energy Storage World Forum, December 21, 2019. https://energystorageforum.com/news/energy-storage/energy-storage-systems-facing-battery-recycling-disposal-crisis.

133 Recycling and Disposal of Battery-Based Grid Energy Storage Systems: A Preliminary Investigation. EPRI, Palo Alto, CA: 2017. 3002006911. https://www.epri.com/research/products/000000003002006911

134 Hsu, Jeremy. "Fire at World's Largest Battery Facility Is a Clean Energy Setback." New Scientist, January 20, 2025. https://www.newscientist.com/article/2464625-fire-at-worlds-largest-battery-facility-is-a-clean-energy-setback/.

135 Martucci, Brian. "After Moss Landing, What's next for Battery Storage?" Utility Dive, February 28, 2025. https://www.utilitydive.com/news/moss-landing-fire-battery-storage-industry-lithium/741283/.

136 Gearino, Dan, and Kiley Price. "Moss Landing Battery Fire Leads to Health Fears, Evidence of Contamination and Concerns about Overreaction." Inside Climate News, February 1, 2025. https://insideclimatenews.org/news/01022025/moss-landing-battery-fire-contamination-health-fears/.

137 Gearino and Price, "Moss Landing Battery Fire."

138 Brekke, Dan. "California Battery Facility Fire Raises Concerns over Energy Storage Plant Regulation." NPR, April 16, 2025. https://www.npr.org/2025/04/16/nx-s1-5352459/california-battery-facility-fire-raises-concerns-over-energy-storage-plant-regulation.

139 Brekke, "Battery Fire Raises Concerns."

140 "Monterey County officials provide update on Moss Landing lithium battery facility fire," posted January 17, 2025, by KPIX | CBS NEWS BAY AREA, YouTube, 22 min., 23 sec. https://www.youtube.com/watch?v=ZW_x8Zb2I-WE&t=418s&ab_channel=KPIX%7CCBSNEWSBAYAREA.

141 Gross, Samantha. "Renewables, Land Use, and Local Opposition in the United States." Brookings Institution, January 2020. https://www.brookings.edu/wp-content/uploads/2020/01/FP_20200113_renewables_land_use_local_opposition_gross.pdf.

142 "Environmental Impacts of Solar Power." Union of Concerned Scientists, March 5, 2013. https://www.ucs.org/resources/environmental-impacts-solar-power.

143 "The RIC Report: The Nuclear Necessity." Bank of America, May 9, 2023. https://advisoranalyst.com/wp-content/uploads/2023/05/bofa-the-ric-report-the-nuclear-necessity-20230509.pdf.

144 "Nuclear Explained U.S. Nuclear Industry." U.S. Energy Information Administration (EIA), August 24, 2023. https://www.eia.gov/energyexplained/nuclear/us-nuclear-industry.php.

145 Bank of America, "The RIC Report." https://advisoranalyst.com/wp-content/uploads/2023/05/bofa-the-ric-report-the-nuclear-necessity-20230509.pdf.

146 "How Many Wind Turbines Would It Take to Equal the Energy Output of One Typical Nuclear Reactor?" MIT Climate Portal, January 4, 2024. https://climate.mit.edu/ask-mit/how-many-wind-turbines-would-it-take-equal-energy-output-one-typical-nuclear-reactor.

147 MIT Climate Portal, "How Many Wind Turbines?" https://climate.mit.edu/ask-mit/how-many-wind-turbines-would-it-take-equal-energy-output-one-typical-nuclear-reactor.

148 Smil, Vaclav. Energy myths and realities: Bringing science to the energy policy debate | American Enterprise Institute - AEI, 2010. https://www.aei.org/research-products/book/energy-myths-and-realities/.

149 Lovering, Jessica, Marian Swain, Linus Blomqvist, and Rebecca R. Hernandez. "Land-Use Intensity of Electricity Production and Tomorrow's Energy Landscape." *PLOS ONE* 17, no. 7 (July 6, 2022). https://doi.org/10.1371/journal.pone.0270155.

150 Blomqvist, Linus. "What Are the Land-Use Intensities of Different Energy Sources?" The Breakthrough Institute, July 6, 2022. https://thebreakthrough.org/blog/whats-the-land-use-intensity-of-different-energy-sources.

151 Struhsacker & Montalbano, "Mission Impossible." https://files.americanexperiment.org/wp-content/uploads/2024/10/Mission-Impossible-report-2024.pdf

152 Union of Concerned Scientists, "Environmental Impacts of Solar." https://www.ucs.org/resources/environmental-impacts-solar-power.

153 Trabish, Herman K. "Utility-Scale Solar Is Significantly Cheaper than Rooftop. Does That Make It Better?" Utility Dive, July 23, 2015. https://www.utilitydive.com/news/utility-scale-solar-is-significantly-cheaper-than-rooftop-does-that-make-i/402517/.

154 Leslie, Jacques. "Utilities Grapple with Rooftop Solar and the New Energy Landscape." Yale e360, August 31, 2017. https://e360.yale.edu/features/utilities-grapple-with-rooftop-solar-and-the-new-energy-landscape.

155 Burrows, Leah. "Large-Scale Wind Power Would Require More Land and Cause More Environmental Impact than Previously Thought." Harvard John A. Paulson School of Engineering and Applied Sciences, October 30, 2018. https://seas.harvard.edu/news/2018/10/large-scale-wind-power-would-require-more-land-and-cause-more-environmental-impact.

156 Burrows, "More Land than Previously Thought." https://seas.harvard.edu/news/2018/10/large-scale-wind-power-would-require-more-land-and-cause-more-environmental-impact

157 Khan, Ansar, and Mattheos Santamouris. "On the Local Warming Potential of Urban Rooftop Photovoltaic Solar Panels in Cities." *Scientific Reports* 13, no. 1 (September 20, 2023). https://doi.org/10.1038/s41598-023-40280-9.

158 Sorensen, Ann, Theresa Nogeire, and Mitch Hunter. "Potential Placement of Utility-Scale Solar Installations on Agricultural Lands in the U.S. to 2040." American Farmland Trust, November 2022. https://farmlandinfo.org/wp-content/uploads/sites/2/2023/03/AFT_FUT2040-solar-white-paper.pdf.

159 Morgan, Tyne. "Farmers Are Now Being Offered $1,000 per Acre or More to Lease Their Land for Solar." AgWeb, October 31, 2024. https://www.agweb.com/news/business/taxes-and-finance/farmers-are-now-being-offered-1-000-acre-or-more-lease-their-land-solar.

160 Walter, Cassidy. "How Much Does It Cost to Become a Farmer?" Successful Farming, November 22, 2024. https://www.agriculture.com/how-much-does-it-take-to-become-a-farmer-7521627.

161 Union of Concerned Scientists, "Environmental Impacts of Solar." https://www.ucs.org/resources/environmental-impacts-solar-power.

162 Bryce, Robert. "Not in Our Backyard." Center of the American Exper-

iment, April 2021. https://files.americanexperiment.org/wp-content/uploads/2021/04/Not-in-Our-Backyard-Robert-Bryce.pdf.

163 Liang, Yanan, René Kleijn, and Ester van der Voet. "Increase in Demand for Critical Materials under IEA Net-Zero Emission by 2050 Scenario." *Applied Energy* 346 (September 2023): 121400. https://doi.org/10.1016/j.apenergy.2023.121400.

164 "Recycling of Critical Minerals – Strategies to Scale up Recycling and Urban Mining." International Energy Agency, November 2024. https://iea.blob.core.windows.net/assets/3af7fda6-8fd9-46b7-bede-395f7f8f9943/RecyclingofCriticalMinerals.pdf.

165 Lundgren, Karin. "The Global Impact of E-Waste Addressing the Challenge." International Labour Organization, 2012. https://www.ilo.org/sites/default/files/wcmsp5/groups/public/@ed_dialogue/@sector/documents/publication/wcms_196105.pdf.

166 IEA, "Recycling of Critical Minerals." https://iea.blob.core.windows.net/assets/3af7fda6-8fd9-46b7-bede-395f7f8f9943/RecyclingofCriticalMinerals.pdf

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