BREAKTHROUGH INSTITUTE

UPDATED MINING FOOTPRINTS AND RAW MATERIAL NEEDS FOR CLEAN ENERGY

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EXECUTIVE SUMMARY

Shallow attacks on low-carbon energy technologies—solar, wind, or nuclear power—often involve pointing to unsightly mines carved into the Earth's surface. Many such superficial critiques frequently only reinforce cynicism rather than sincerely explore problems and solutions. After all, mined minerals remain inseparable from modern industrial society, from steel bridges to aluminum power lines to the copper wire within home electrical boxes.

But it does not help that alarmed claims about mining regularly serve as ammunition in the circular firing squads all too commonly seen in energy transition discussions. Committed renewable energy absolutists warn against catastrophic impacts from uranium mining and characterize nuclear power stations as grotesquely wasteful mountains of concrete and steel. Meanwhile, nuclear energy proponents hit back at the vast quantities of copper, steel, and aluminum required to support sprawling solar and wind farms. The result of such sniping is that the public is now receptive to both narratives: that solar, wind, and batteries demand a heavy toll from the earth in the form of mining, and that the uranium and construction costs of nuclear power belie its low-impact, low-carbon reputation.

The mining impact considerations of the energy transition are undoubtedly important, but these misleading narratives have taken on a life of their own and now warrant correction. A rational comparison of the metal and mining footprints of clean electricity technologies—contrasted with the material requirements of fossil electricity—can help ground the debate over the future of our energy system. Doing so is the purpose of this report.

One would think that the material requirements of clean energy technologies are already well understood. In practice, though, commonly cited reports and peer-reviewed scholarly papers have tended to lag several years behind the current real-world state of play, particularly for rapidly evolving and growing technologies like solar and wind power. At the same time, such previously published comparisons have had to rely on older literature with often-dated values for steel and concrete usage in nuclear power plants. The result of these known shortcomings is that arguing commentators select evidence that best aligns with their predetermined position.

Our updated analysis can help constructively ground clean energy discussions moving forward. In particular, this report goes beyond other analyses by directly comparing the mining footprint of the materials required for different clean electricity technologies, using rock-to-metal ratios that represent the mass of earth moved to produce the desired raw material. Our analysis found that the earth and material extracted to supply just the fuel required for coal electricity is at least 20 times the total mining footprint of onshore wind energy, and the fuel required for gas electricity is at least two times greater (Figure ES-1). Among low-carbon technologies, the mining footprint of nuclear energy is approximately 30% and 23% that of utility-scale solar PV and onshore wind, respectively. Our results help clarify trends in critical mineral requirements, highlight the key drivers of clean energy and mining trade-offs, and identify opportunities to further optimize mining and raw material footprints.

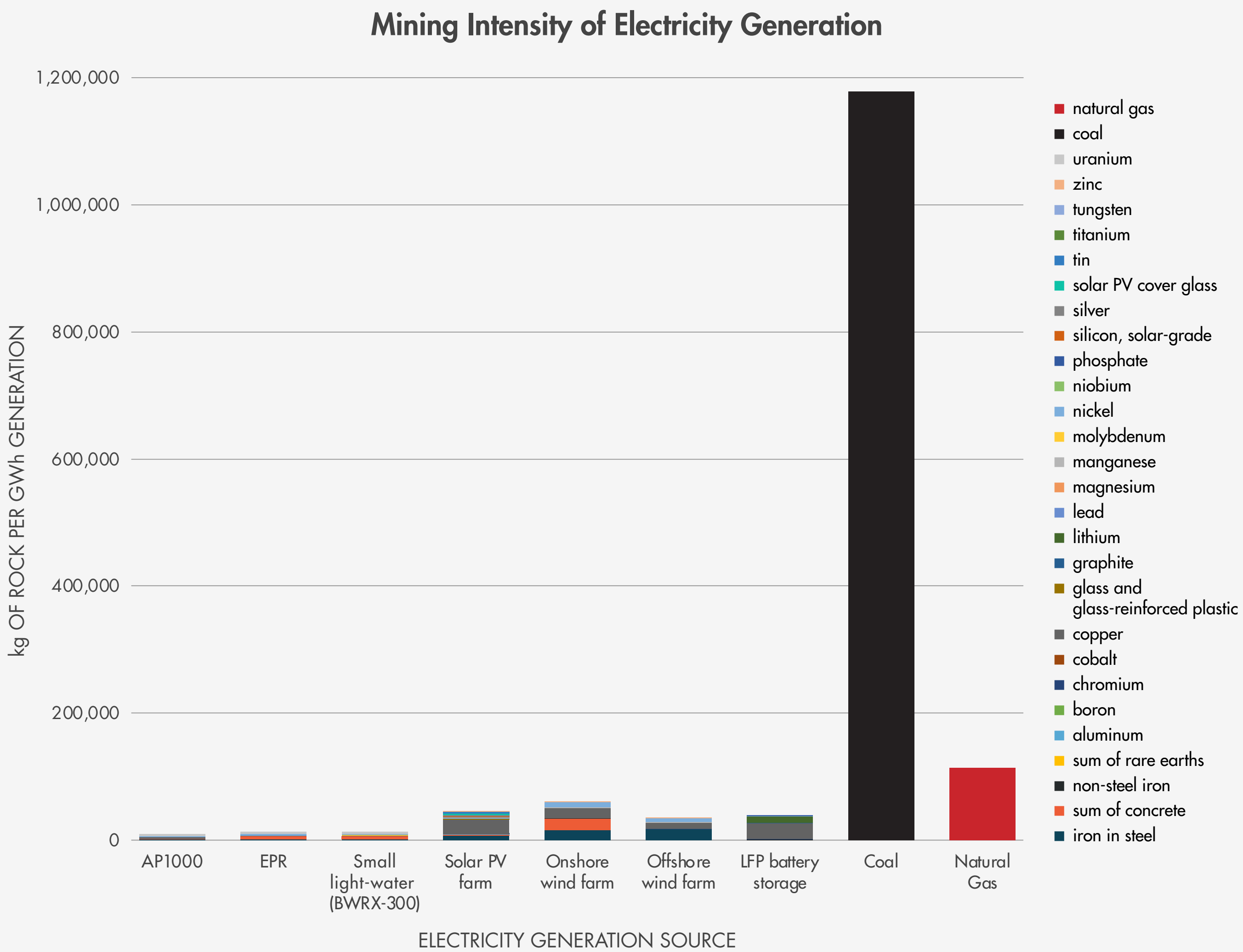

Figure ES-1: *Rock moved per gigawatt-hour (GWh) of electricity produced by different technologies. Coal value considers only coal mining, without including power plant infrastructure. Gas value considers only natural gas fuel inputs and does not include drilling impacts, processing, pipelines, or power plant infrastructure. We assumed hardrock mining comprises 34.8% and 60% of global uranium and lithium production, respectively. LFP battery storage considers battery cell materials only, assuming 1 GWh of output by a 2 GWh, 500 MW system cycling once daily over a 25-year life.*

Key findings:

- The extractive footprint of conventional coal and gas thermal power plants per unit of electricity generated is more than 20 times and 2 times, respectively, greater than that of low-carbon nuclear power, wind power, or solar power, even when accounting for battery storage.
- Among low-carbon energy sources, nuclear power requires just 0.6 to 1.4 tons of infrastructure raw materials per gigawatt-hour (GWh) of electricity produced. The material intensities of utility-scale solar (1.8 tons/GWh) and wind (onshore: 7.1 tons/GWh; offshore: 2.0 tons/GWh), however, have improved considerably in recent years, with solar PV and offshore wind material requirements now comparable to that of the most material-intensive nuclear power plants.
- In terms of mining footprint, however, each GWh of electricity produced by nuclear power plants requires the excavation of only 30% and 23% the mass of rock and metal needed for a GWh of utility-scale solar or onshore wind electricity, respectively.
- Nuclear power plants consume just 11% to 38% the mass of critical materials per GWh that solar, wind, and battery technologies do, potentially helping insulate energy transition efforts against commodity supply chain volatility.
- Copper, steel, nickel, lithium, uranium, and silver offer the greatest opportunities to reduce the mining impacts of clean electricity technologies through further recycling, innovative mining approaches, and material use efficiency improvements.

GENERAL ANALYTICAL APPROACH

We synthesized material usage in utility-scale solar, onshore wind, offshore wind, large light-water nuclear, and small light-water nuclear power installations at the balance-of-plant level, based on recent literature. This balance-of-plant scope included not only generating equipment like solar PV modules and wind turbine components, but also all on-site operational infrastructure including mountings and foundations, cabling, inverters, transformers, and other balance-of-system components. We also conducted a limited assessment of battery energy storage materials, restricted to battery cells in scope.

Our primary sources used in the analysis were the 2023 Renewable Energy Materials Properties Database (REMPD) compiled by the National Renewable Energy Laboratory (NREL) and the 2022 *Capital Cost Evaluation of Advanced Water-Cooled Reactor Designs with Consideration of Uncertainty and Risk* report by MIT nuclear engineering researchers W. Robb Stewart and Koroush Shirvan.[1,2] In striving to best represent the current technological state of play, we further updated and supplemented these data using other publicly available literature and industry reports. For nuclear energy technologies, our analysis considered the Westinghouse AP-1000 reactor, the Framatome Evolutionary Power Reactor (EPR), and the General Electric-Hitachi BWRX-300, a smaller 300 MWe design currently under development.[3] Material use estimates for non light-water advanced nuclear reactor designs remain insufficiently characterized for us to investigate rigorously in this report.

To calculate material demand per unit of nameplate generating capacity (e.g., tons per gigawatt [GW]), we used basic assumptions on power plant capacity factor and lifetime to convert and express material intensities in terms of mass per unit of electricity produced (e.g., kg per gigawatt-hour [GWh]). We then leveraged rock-to-metal data compiled by the United States Geological Survey (USGS)[4,5] and derived through original calculations by Breakthrough Institute staff to convert the material demands of each clean electricity technology into its mining footprint (i.ed., tons of rock and earth moved per GW capacity). We compared these values to a mining footprint similarly calculated for coal energy and the tonnage of natural gas typically consumed for gas-fired electricity.

For most materials, we tracked only raw materials directly incorporated into on-site infrastructure and equipment, without considering additional upstream material needs that compensate for factors like manufacturing scrap wastage. The sole exceptions to this practice are uranium and solar-grade polysilicon, which are both highly relevant to this analysis while benefiting from well-constrained supply chain information. Rock-to-metal ratios furthermore do not account for initial mine development and auxiliary mine infrastructure construction, and thus likely underestimate the true mining footprint of newly mined material. At the same time, our calculations assumed that all power plant raw materials are newly mined rather than sourced from secondary recycled production, which would in turn reduce the mining footprint of electricity production in practice.

For a more extensive summary of our methodology, please refer to the Appendix of this report.

MATERIAL REQUIREMENTS FOR CLEAN ELECTRICITY GENERATION

Our results largely validate the common wisdom that low-carbon nuclear electricity requires marginally to significantly fewer raw material inputs than utility solar and wind power.[6] The total infrastructure material requirement of nuclear energy is about 0.6 to 1.4 tons per GWh, 35%-79% that of utility-scale solar PV (1.8 tons/GWh). Meanwhile, onshore wind exhibits a relatively high material use (7.1 tons/GWh) among the clean electricity technologies examined, almost four times that of solar PV (Figure 1). Furthermore, the chief material inputs of nuclear power plants are concrete and common iron in steel, meaning that nuclear electricity boasts a favorably low critical mineral requirement relative to solar and even wind (Figure 2).

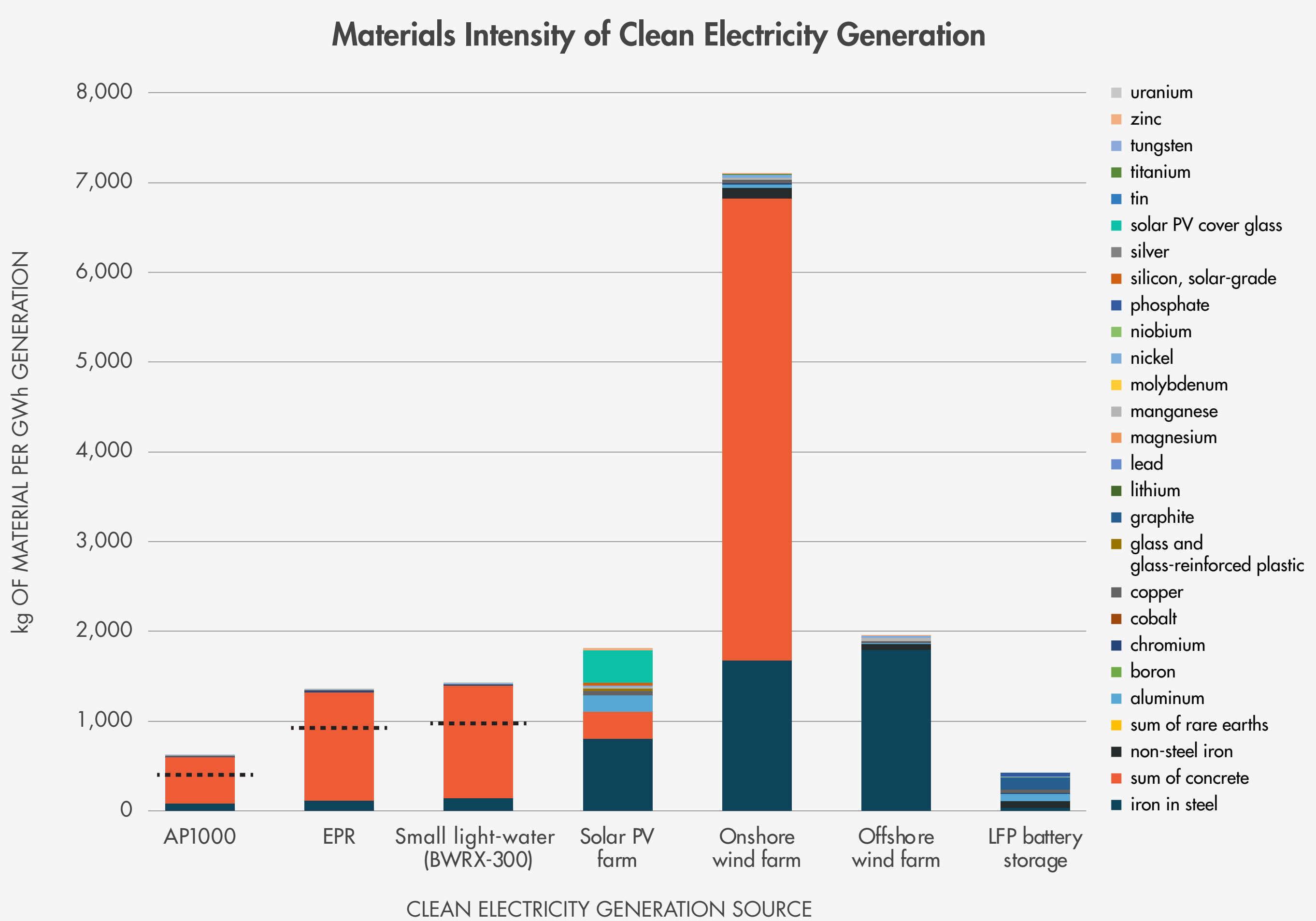

Figure 1: Material requirements per GWh of electricity produced by different low-carbon electricity generation technologies. Black dotted lines denote lower total nuclear material requirements per GWh if assuming a higher 92% capacity factor and an 80-year lifetime. LFP battery storage considers battery cell mineral inputs only and assumes 1 GWh of output from a 2 GWh, 500 MW battery system cycling once daily over a 25-year life.

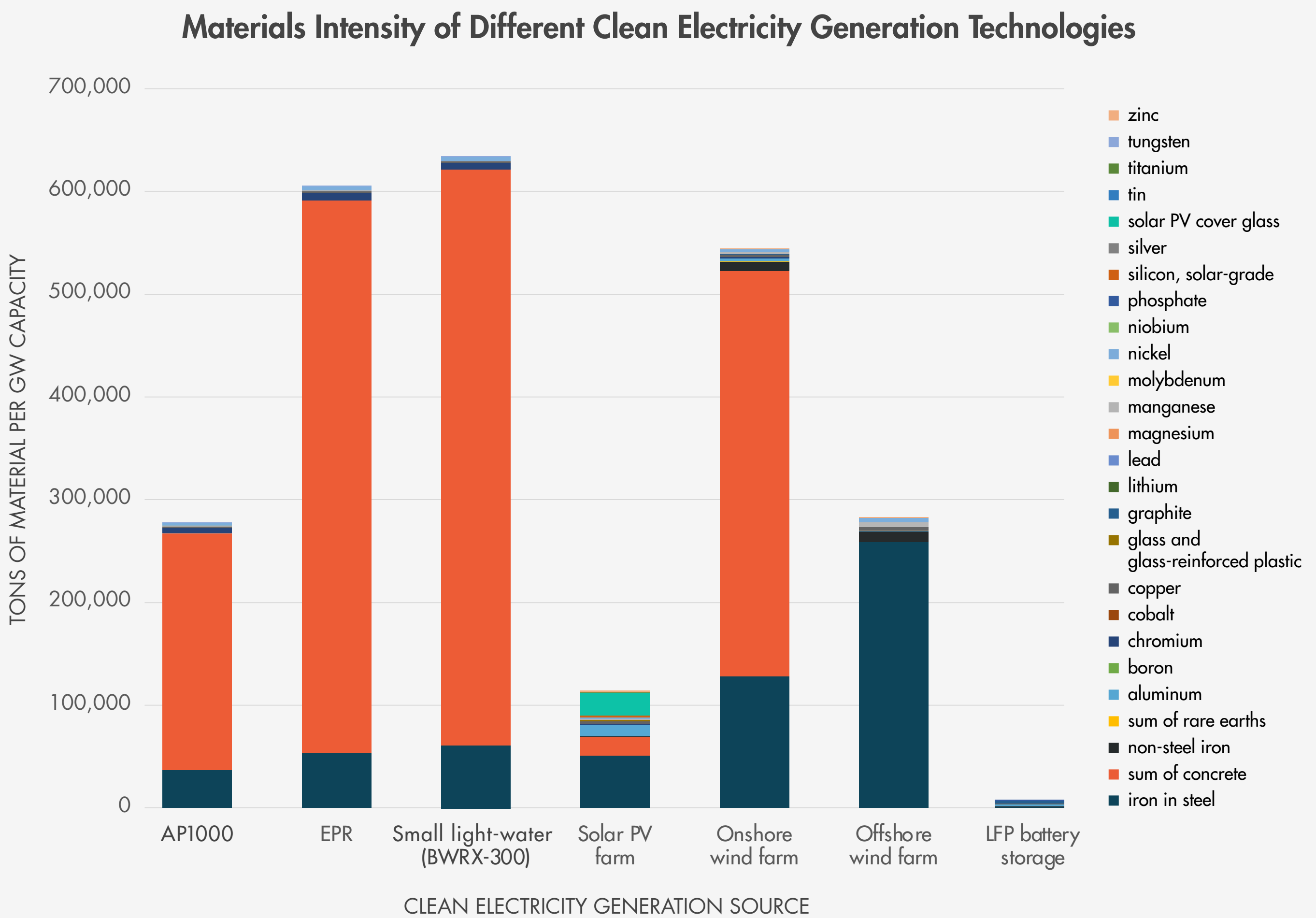

Figure 2: *Material requirements per GW of nameplate generating capacity for different low-carbon electricity generation technologies, color-coded by raw material. LFP battery storage considers battery cell mineral inputs only and assumes a 2 GWh, 500 MW battery system accompanying a 1 GW solar or wind facility.*

That said, these results highlight commendable progress in improving the material intensity of solar and wind infrastructure. These prodigious advances are driven by improvements in solar and wind capacity factor and project lifetime, in addition to gains in material efficiency. Compared to the commonly cited yet now-outdated Department of Energy (DOE) *Quadrennial Technology Review* 2015 report[7] (Figure 3), solar and wind material consumption has fallen dramatically. Onshore wind concrete usage has improved from 8,000 to 5,000 kg per GWh of electricity produced, for instance, with the total material requirement of onshore wind electricity shrinking by 30%.

Meanwhile, the 2015 DOE report's bewildering concrete and cement solar PV farm values, if we very conservatively assume 0.4 tons of cement per cubic meter of concrete with a resulting cubic meter of concrete weighing 1.6 tons, would imply a concrete requirement on the order of 15,000 kg per GWh, a value likely 50 times higher than reasonable current-day usage in utility-scale ground-mount solar PV installations. Modern usage of solar PV cover glass and steel in solar PV farms is at least 85% and 90% lower, respectively, than values presented in the 2015 DOE report. Our total material requirement of 1.8 tons per GWh of utility solar electricity, assuming the aforementioned concrete characteristics for the DOE report's numbers, would be around 8% of the material requirement implied by the 2015 report.

Meanwhile, newer sources on nuclear power plant steel and concrete consumption suggest some designs may require somewhat larger (up to +50%) volumes of demand than estimates based on the 1970s-1980s literature,[8],[9] often referenced in the DOE report and other studies. However, we note that, even by adopting aggressive assumptions, our findings indicate that the Westinghouse AP1000 reactor design's raw material consumption is likely comparable to or better than that of nuclear designs evaluated in 1970s-1980s studies.

Our sole literature-based estimate for a small light-water reactor design, the BWRX-300 concept, exhibits a material intensity on par with the Framatome EPR, at the higher end of the nuclear power plant designs we evaluated. While the steel and concrete volumes we assumed for the BWRX-300 were derived from a modeling-based MIT engineering study,[10] we emphasize that this design has yet to be finalized and built in practice, so these values may be subject to greater uncertainty. At face value, our results seem to suggest that the BWRX-300's advantages from simplified construction and inherent safety features (which eliminate the need for redundant active safety systems found in conventional reactors)[11] may be offset by reduced economies of scale.

That said, other small light-water reactors and non light-water advanced reactor designs may differ substantially in material needs from the relatively large BWRX-300, which also retains many technical similarities with existing reactor technologies. Public academic and industry literature on non light-water advanced nuclear material requirements remains underdeveloped, with many advanced nuclear developers still in the process of refining their reactor and power plant designs. In private communications with our team, non light-water advanced nuclear developers expressed confidence that steel and concrete requirements for their designs will be markedly lower than our literature-based estimates for the BWRX-300. Advanced reactors may require some materials that are not commonly used by conventional light-water reactors, such as graphite, sodium, specialized salts, or helium, but these will represent small portions of power plant material consumption.

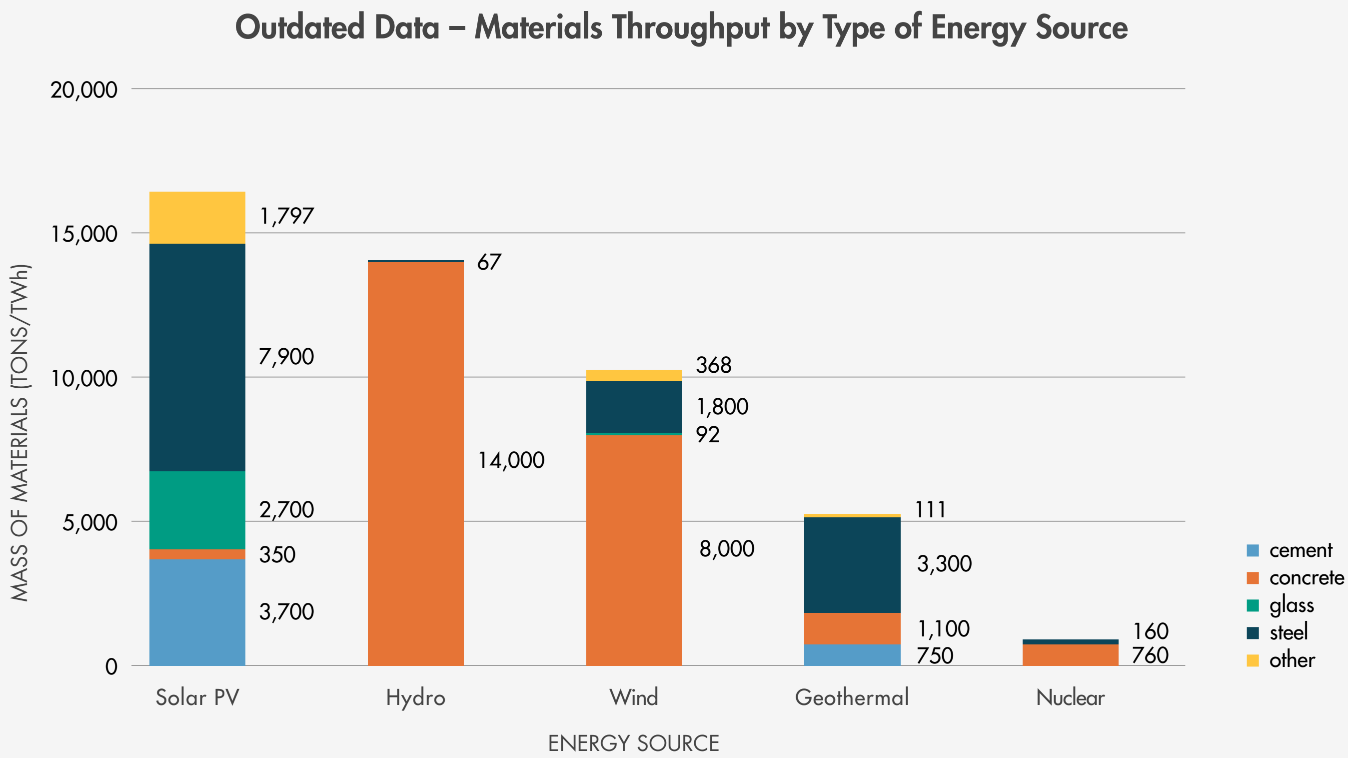

Figure 3: *Older, outdated claimed values for material intensity per unit of electricity generated, adapted from a figure by Environmental Progress based on values listed in the 2015 United States Department of Energy* Quadrennial Technology Review.[12]

Note: Tons per TWh is equal to kg per GWh. These values diverge significantly from modern industry material requirements, which are far lower.

When we evaluated material demand on a power plant nameplate capacity basis alone, the material footprints of nuclear power, onshore wind, and offshore wind were comparable, ranging between around 300,000 and 600,000 tons of infrastructure material per GW (see Figure 2). Per unit of name-plate capacity, solar PV installations showed the lowest total material requirement (just over 100,000 tons of material per GW). Thus, future improvements to solar and wind energy output and lifetime have the theoretical potential to help bring the material requirements per GWh of these technologies closer toward parity with nuclear power.

For utility-scale LFP battery storage, we assumed a 1 GW solar or wind farm with on-site storage would size a battery system to provide four-hour storage duration, with a capacity of 2 GWh and a rated power capacity of 500 MW. Importantly, our simple analysis considered only the raw materials required for the needed capacity of LFP battery cells and omitted significant pack-level and bal-ance-of-system material needs. We found that while critical minerals comprise the majority of LFP battery cell materials considered, this additional total material footprint from adding storage to a solar or wind installation does not appear to be large. All the same, incorporating battery storage at wind and solar farms does further increase their material demands relative to nuclear power. These material needs would scale linearly with the amount of battery capacity installed. The additional materials associated with balance-of-system components are uncertain, but may be considerable.

We emphasize that we chose aggressive values for nuclear power plant raw material needs, as described in the Appendix. Our most significant assumptions that may overestimate nuclear plant material demand include our adoption of steel and concrete requirements estimated for first-of-a-kind builds, our high site-wide average concrete density assumption, and our data source's assumption that all power plants include a traditional cooling tower. Furthermore, a juxtaposition of nuclear, solar, and wind material requirements on a balance-of-plant basis may omit system-level considerations such as the more extensive transmission lines and substations potentially required to effectively connect remote wind and solar installations to the regional grid.[13]

Certainly, other distributed solar and wind deployment options exist, posing different material use implications. Rooftop solar installations, for instance, would eliminate metal needs from racking, albeit with the trade-offs of lower capacity factor, a different daily generation profile, reduced economies of scale, and higher costs in most markets.[14] The NREL REMPD database includes cadmium-telluride utility-scale, commercial c-Si rooftop, and residential c-Si rooftop solar material use estimates, which could serve as a basis for an extended future analysis. On the other hand, some brownfield or distributed solar configurations like landfill solar or car park solar may actually require more robust mounting systems and concrete foundations with higher material requirements.[15,16,17]

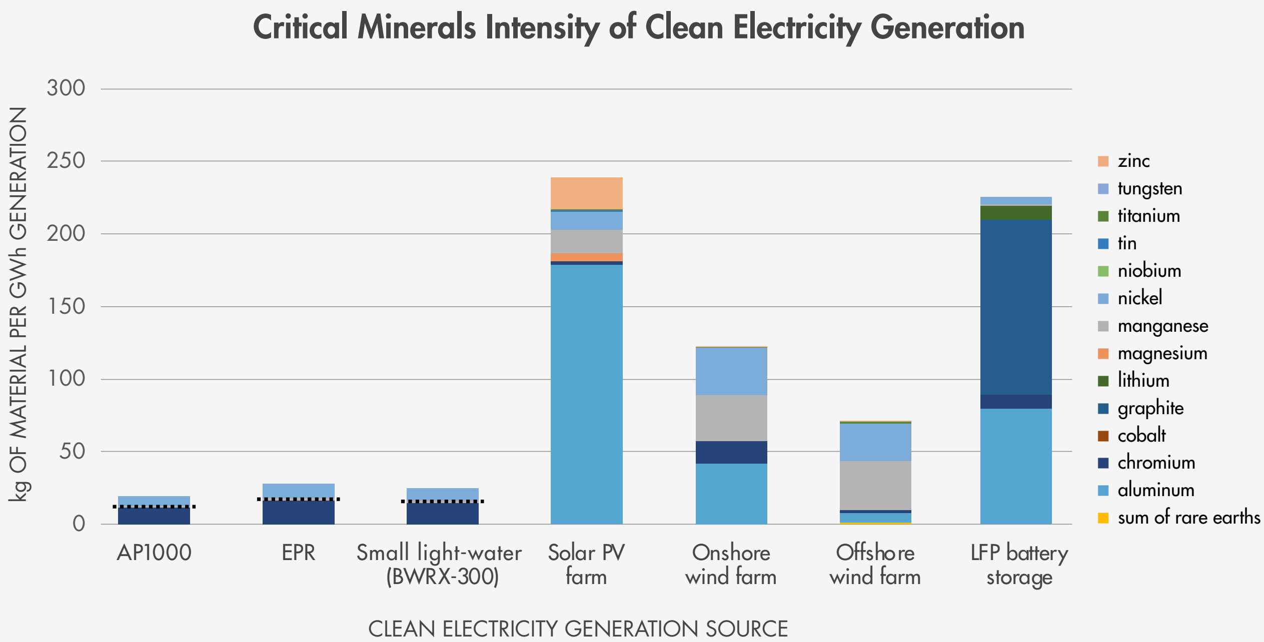

Figure 4: Critical materials per GWh of electricity for different low-carbon electricity generation technologies. Black dotted lines denote lower total nuclear critical material requirements per GWh if assuming a higher 92% capacity factor and an 80-year lifetime. LFP battery storage considers battery cell critical minerals only, assuming 1 GWh of output from a 2 GWh, 500 MW battery system cycling once daily over a 25-year life.

But, ultimately, bulk materials like structural steel and concrete are arguably of the least concern when assessing the raw material demand of low-carbon technologies. Other mundane materials like plastics, solar PV cover glass, boron, or phosphate are similarly unlikely to pose supply shortages. If we exclude these more common material inputs from consideration, our analysis shows that nuclear power requires just 11% to 38% the total mass of critical materials per GWh relative to other clean electricity technologies (Figure 4).

Even scarcer critical materials with more limited geologic resources are not likely to pose fundamental constraints to the adoption of clean electricity technologies.[18] Nevertheless, transitory supply constraints may increase the costs and time required to deploy new clean energy capacity during the energy transition over the coming decades. Nuclear power may help support the continued expansion of clean energy capacity in the face of such bottlenecks and avert some degree of additional critical mineral demand, thanks to its different and reduced profile of critical minerals. At the same time, as solar, wind, and battery technologies continue to progress, aided by growing stocks of available recyclable materials, their sensitivity to critical mineral supply chain vulnerability will further improve in their own right.

THE MINING FOOTPRINT OF CLEAN ELECTRICITY TECHNOLOGIES

No discussion on the mining required to support mass construction of clean power infrastructure would be complete without first emphasizing that all clean electricity technologies require far less material extracted from the earth than coal- and gas-fired power plants do. We calculated that the production of 1 GWh of electricity from even an efficient supercritical coal-fired power plant requires digging up close to 1,200 metric tons of rock and coal just to supply the coal alone (Figure 5). This requirement immediately implies a mining footprint for coal more than 20 times greater than that for wind or solar energy. Similarly, generating 1 GWh of electricity from natural gas requires 120 metric tons of gas as fuel, a tonnage over two to three times greater than the mining footprint of wind or solar power. Other published research indicates that the energy transition may likely decrease the total mining footprint of the global energy system.[19]

These masses of material, furthermore, do not account for the metals required to build the fossil-fired power plant itself and its supporting rail and pipeline connections. In fairness, these may be minor next to the tonnage of required fuel. Additionally, this simple calculation does not consider how oil and gas exploration also produces drill waste while irrecoverably consuming considerable quantities of cement and steel for well casing (although this is also currently the case for geothermal energy).[20] In any case, it is clear that the material footprint of a unit of fossil thermal electricity greatly exceeds that of wind, solar, or nuclear power.

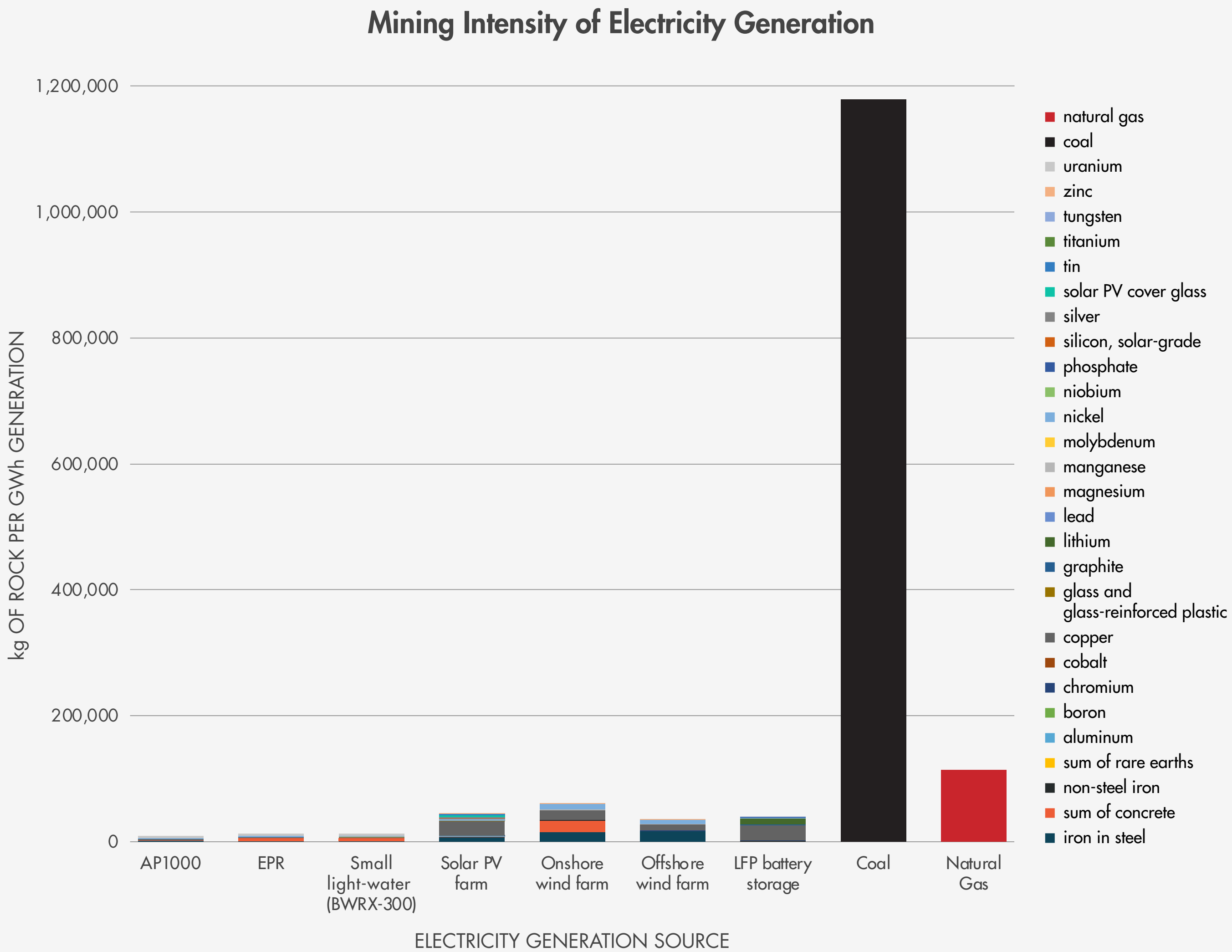

Figure 5: Material and rock moved per GWh of electricity produced by different technologies. Coal value considers only coal mining, without including power plant infrastructure. Gas value considers only natural gas fuel inputs and does not include drilling impacts, processing, pipelines, or power plant infrastructure. We assumed hardrock mining comprises 34.8% and 60% of global uranium and lithium production, respectively. LFP battery storage considers battery cell materials only, assuming 1 GWh of output by a 2 GWh, 500 MW system cycling once daily over a 25-year life.

Rock-to-Metal Ratio (RMR) of Critical Minerals and Other Materials Examined in This Study

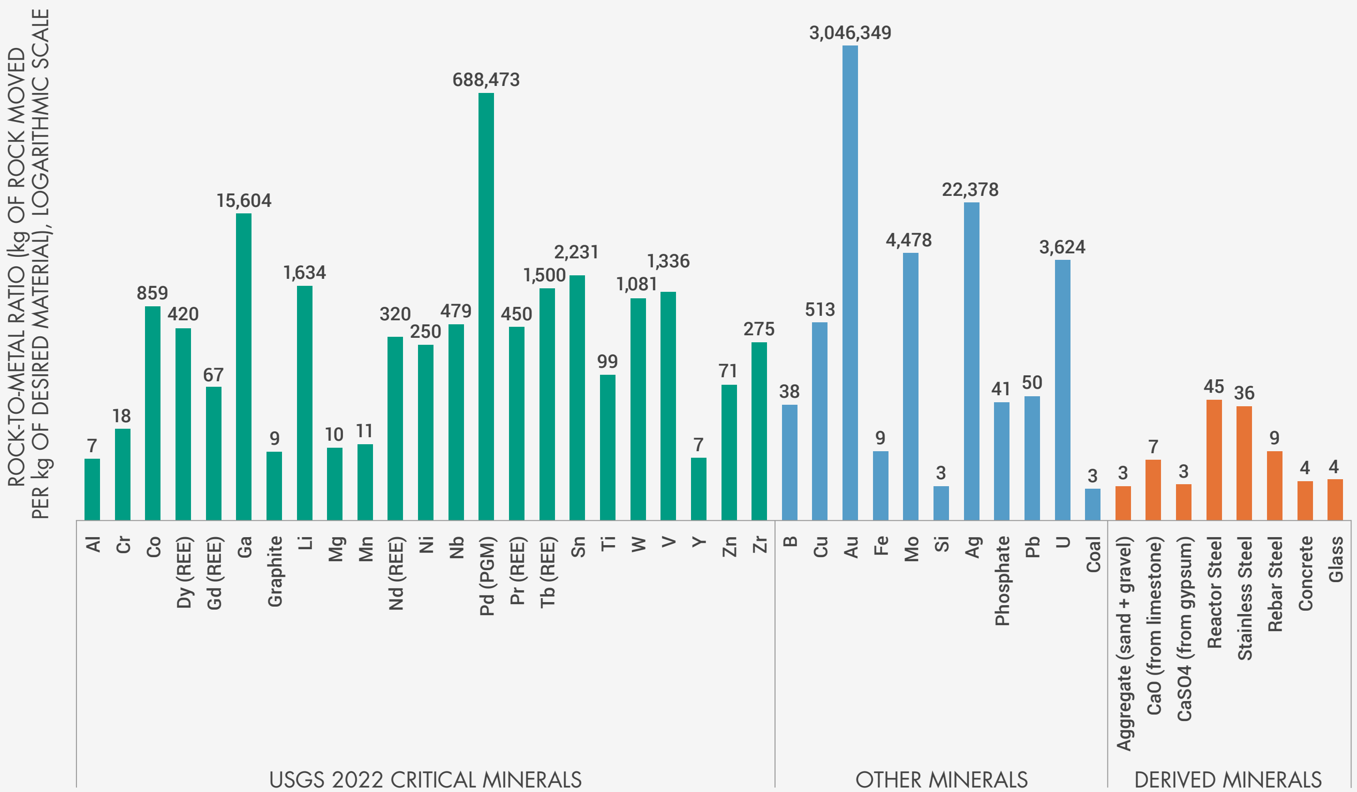

Figure 6: Rock-to-metal ratios for the final set of clean energy materials considered in this analysis, plotted on a logarithmic scale. Uranium and lithium values are for hardrock mining only.

Yet the considerable improvements in total extraction that clean electricity technologies offer hardly mean that society shouldn't look for further opportunities to reduce mining impacts throughout the energy transition. Our analysis found that nuclear energy offers a considerably lighter mining footprint than utility-scale solar power, onshore wind power, and offshore wind power. This difference primarily stems from nuclear power's reliance on large volumes of steel and concrete, which are bulk commodities sourced from higher-grade iron ore mines and rock quarries that produce relatively little waste rock per unit of desired material (Figure 6).[21,22] Consequently, we calculated a mining footprint for a GWh of nuclear electricity that is roughly 30% that of solar PV farms and is 23% to 39% that of onshore and offshore wind, respectively (Figure 7).

Certain metals exert disproportionate influence in determining the mining footprint of wind and solar power. Copper mining constitutes a significant fraction of this. On its own, the copper mining footprint per GWh of onshore wind or solar electricity (23.1 and 15.9 tons of rock, respectively) exceeds the entire total mining footprint of a GWh of nuclear electricity (13.5 tons of rock). While silver metallization pastes are used in only minute quantities in solar PV modules (10 mg per W),[23] the relatively high mining footprint of silver mining contributes significantly as well to the mining impact of solar energy (7.8% of solar's total). Our assessed rock-to-metal data for batteries also highlight the considerable mining footprint of copper—as well as lithium—per unit of stored electricity output. Meanwhile, the lower capacity factor and shorter operational lifetime of wind and solar installations disproportionately increase their relative per-unit generation mining footprints, compared to their mining footprints calculated per GW of installed capacity (Figure 8).

Anti-nuclear advocates have regularly invoked uranium mining impacts alongside steel and concrete consumption in characterizing nuclear energy as wasteful of raw materials.[24] We found that the uranium mining footprint is 29% to 40% of the total mining footprint of nuclear power plant infrastructure. This percentage (and quantity) is sensitive to uranium production methods, with around 65% of the 2020 global primary uranium supply originating from solution-based or byproduct production[25]. Popular anti-nuclear messaging that mischaracterizes uranium fuel production as a land-gobbling mining nightmare vastly exaggerates uranium mining impacts.[26] Such arguments must reckon with the conclusions of our analysis that nuclear energy exhibits similar to better material use efficiency and smaller mining footprints than wind and solar electricity.

Overall, these results suggest that society's most powerful leverage for reducing the excavation footprint of the energy transition will involve efforts targeting copper, nickel, lithium, silver, uranium, and steel. Improved mining approaches, greater use of recycled inputs, increased technology lifetimes and efficiencies, and reductions in the quantity of these minerals required per unit of energy technology could help further improve the environmental performance of wind, solar, nuclear, and battery power. Unconventional resources such as uranium and copper solution mining, direct lithium brine extraction, or collection of seafloor nodules rich in nickel and copper could also dramatically reduce the direct land surface mining footprint of clean energy technologies.

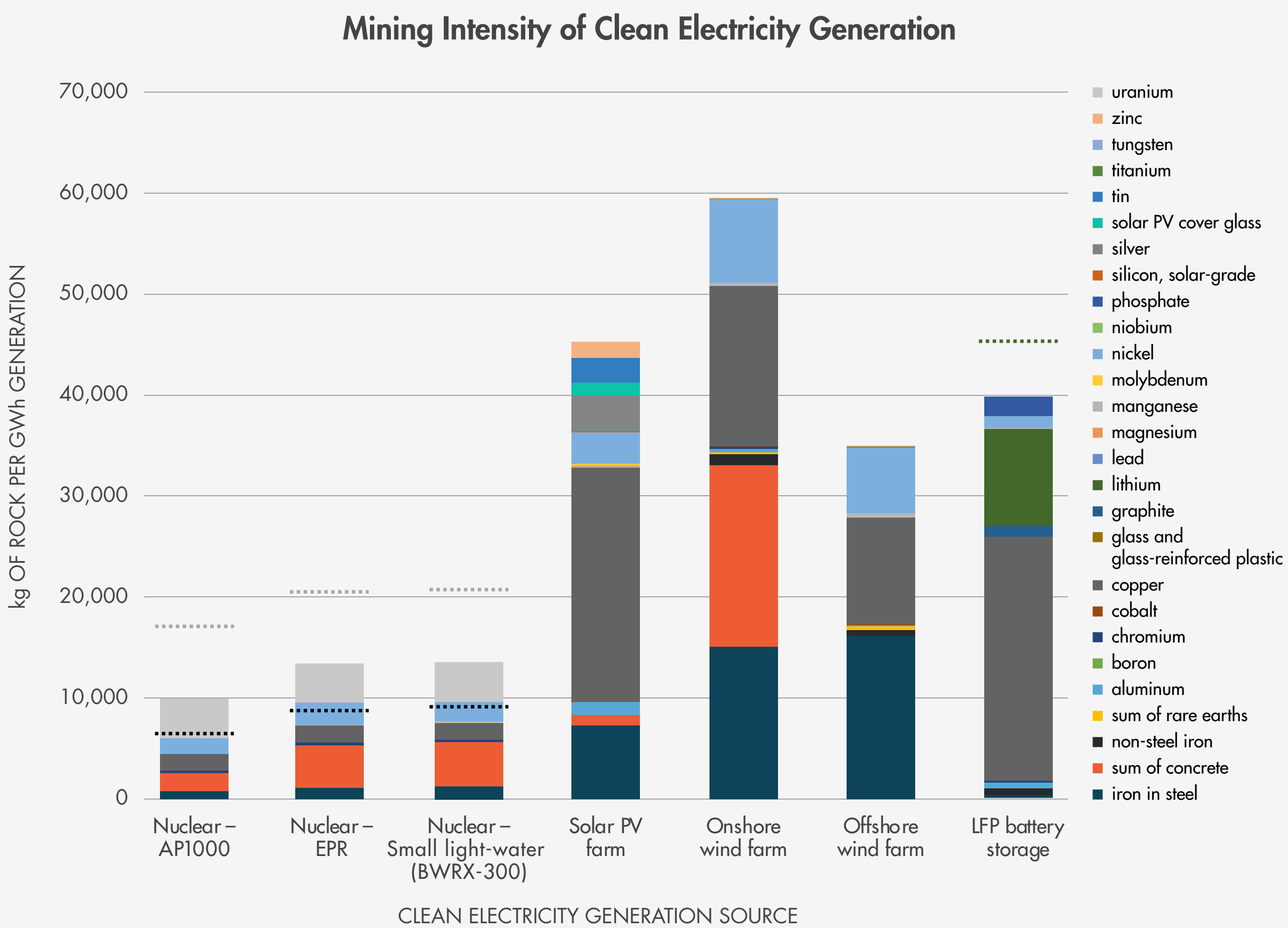

Figure 7: Material and rock moved per GWh of electricity produced by low-carbon electricity generation technologies, color-coded based on mining impact from each raw material. Black dotted lines denote lower total nuclear material requirements per GWh if assuming a higher 92% capacity factor and an 80-year lifetime. We assumed hardrock mining comprises 34.8% and 60% of global uranium and lithium production, respectively. Dashed lines indicate total height of bars if 100% hardrock mining were assumed for uranium and lithium (calculated for original, lower nuclear capacity factor and lifetime). LFP battery storage considers battery cell mineral inputs only, and assumes 1 GWh of output from a 2 GWh, 500 MW battery system cycling once daily over a 25-year life.

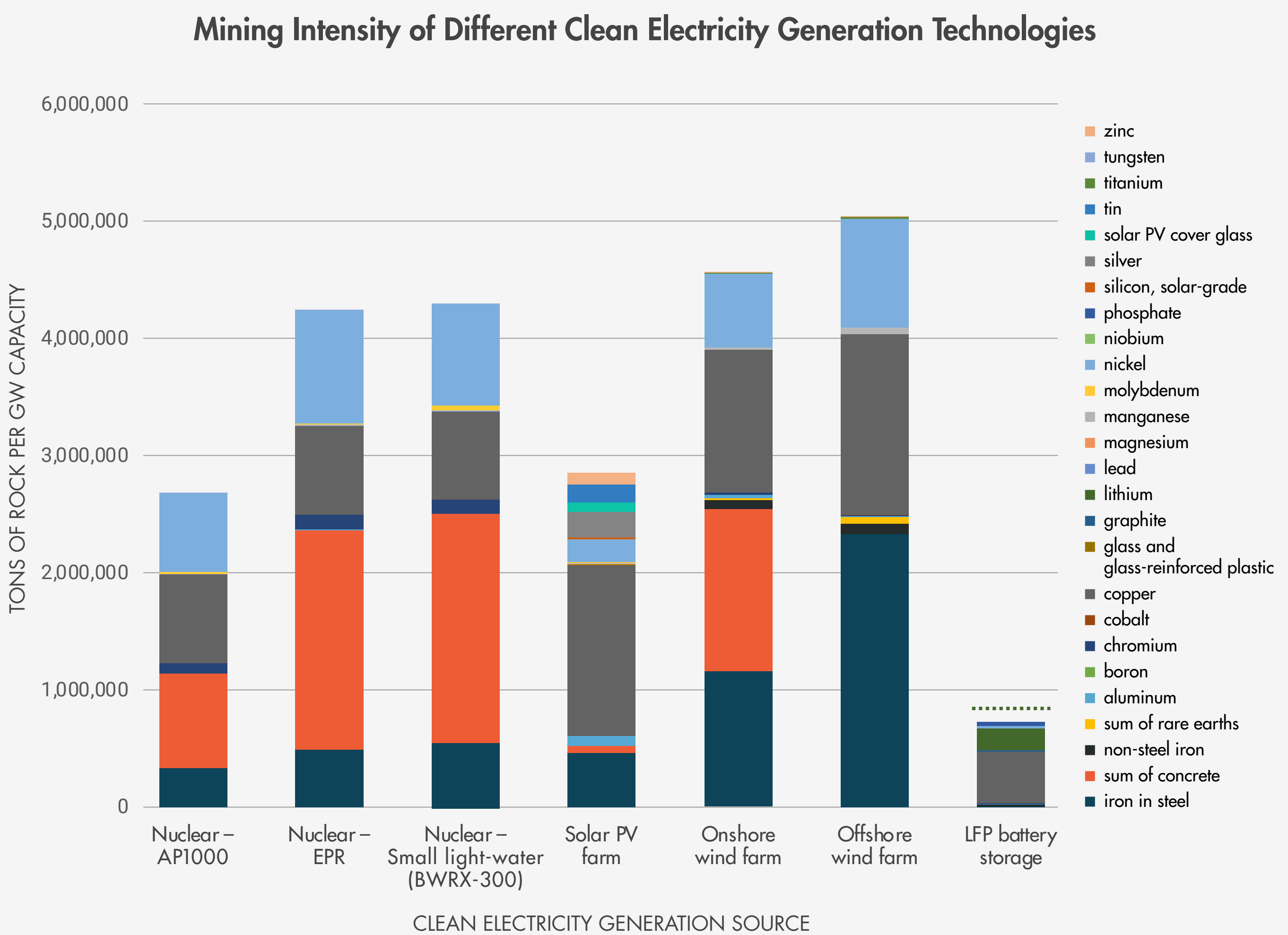

Figure 8: Rock moved per GW of nameplate generating capacity for different low-carbon electricity generation technologies, color-coded based on mining impact for each raw material. LFP battery storage considers battery cell mineral inputs only and assumes a 2 GWh, 500 MW battery system accompanying a 1 GW solar or wind facility. Dashed line indicates total height of bar if 100% hardrock mining were assumed for lithium.

We do emphasize that our quantification of mining impacts for newly mined minerals will tend to produce an underestimate of earth moved. Importantly, the rock-to-metal methodology that we and our cited sources employed does not account for excavation during the initial stage of mine construction and development prior to the start of actual mineral production. Our assessed rock-to-metal values may also omit impacts from on-site activities throughout a mine's lifetime that are not directly production-related, such as the excavation of secondary access passages in an underground mine. Ultimately, considering not only the wide variation in mining contexts and approaches globally but also differences in power plant equipment and technology from project to project, non-negligible uncertainties in such estimates are unavoidable and expected. Nevertheless, the geology of different raw materials and the general characteristics of wind turbines, solar arrays, and nuclear reactors are sufficiently constrained for this analysis to, at the very least, provide a firm basis for further refinement and discussion.

CONCLUSIONS

Technological progress has historically played a decisive role in alleviating society's impacts upon the natural environment. Such trends will doubtlessly continue for clean energy minerals as well, through reductions in both the material demands and mining impacts associated with low-carbon electricity technologies.

As of 2023, silver usage in solar PV modules had fallen to around half of the amount used in solar PV equipment just five years earlier, in 2018.[27] Additional innovations to improve material use efficiency in solar, wind, and nuclear power could maintain such trends well into the future. And with 1.7 times more electricity still produced globally from coal than from wind, solar, and nuclear combined in 2022,[28] the overall mining impacts of electricity production will only continue to improve in the years to come. Efforts to improve the environmental footprint of steel, copper, nickel, lithium, and silver supply chains appear to offer the highest return on investment in particular.

Recycled raw material inputs can also play a significant role. Our results imply that offshore wind turbines built using entirely recycled steel, for example, would eliminate half of their mining impacts even if all other raw materials originated from new mining. Nickel, copper, and steel have well-established, large-scale commodity markets with significant recycling throughput, which new solar, wind, and nuclear construction already benefit from today.

But the scale of increasing broad societal demand for metals like steel and copper will make sourcing all or even most metals from recycled production infeasible in practice.[29] Furthermore, the turnover rate of infrastructure metals is slow, while the availability of newer and more exotic recycled inputs like lithium and rare earth metals will require the better part of two decades to achieve meaningful scale.[30] Factor in the aggressive pace of growth in low-carbon power infrastructure required for decarbonization—not just in populous emerging economies but also in the wealthy world[31]—and the continued need for new mining to support the energy transition appears inevitably large.

As such, the smaller mining impact of nuclear electricity relative to wind and solar still carries relevance for societal efforts to optimize mining footprints globally over the next few decades. Nuclear power's lower and non-overlapping reliance on supply-constrained critical minerals also promises to help insulate the energy transition against commodity-related risks and trade disruptions.

In the end, even if nearly every conceivable low-carbon electric future is certain to be less extractive than the coal-gobbling status quo of today's energy system, society should strive to chart energy transition paths that spare land and avoid further pollution and social conflict wherever practical. Some innovations, like thinner solar cells birthed from the sweat of the lab bench, will undoubtedly debut to universal acclaim. Other measures, like regulations that penalize excessive pollution or labor abuse, may produce some hand-wringing over higher battery or electric motor prices. But throughout all of this, we must recall and affirm that our goal is not just cheap low-carbon energy, but cheap low-carbon energy done right. Solving the problem of responsible, affordable, and cleaner mining and metals will drive key progress toward that goal.

APPENDIX - METHODOLOGY

Background

Discussions regarding material demands for renewable energy technologies have tended to repeatedly reference the same set of studies and reports. These include well-known publications from the United Nations Economic Commission for Europe,[32] the Department of Energy's quadrennial report,[33] reports by the International Energy Agency,[34],[35] and numerous peer-reviewed papers (e.g., Deetman et al.,[36] Nijnens et al.,[37] Wang et al.,[38] Tokimatsu et al.,[39] Månberger and Stenqvist,[40] work by Elshkaki and Graedel,[41] and others). Comparison with industry reports shows that many of these popular sources are now out-of-date, largely reflecting the rapid rate of technological improvement in wind and solar power.

Similarly, many of these and other sources rely on relatively old studies of nuclear power plant material needs, such as Bryan and Dudley,[42] Peterson et al.,[43] White and Kulcinski,[44] and others. These reports contain useful information, including estimates of materials other than steel and concrete—like copper or tin—that the relatively limited number of subsequent original studies have not reported on. However, these older studies cannot be utilized directly for new nuclear builds without careful assessment and modification. For example, some of them did not assume that a nuclear power plant would require cooling towers. While cooling towers are indeed not required for coastal or riverine nuclear power plants that can make use of once-through cooling (for instance, nearly all nuclear power plants in China, Taiwan, South Korea, and Japan are coastally sited and do not use cooling towers),[45] balance-of-plant material estimates must clearly highlight such assumptions.

We reviewed newer academic and governmental research literature and industry intelligence in order to compile updated material use estimates for each low-carbon electricity generation technology of interest. Even these sources may not reflect the very latest equipment entering operation in 2024, but we judged the resulting values as at least reasonable for new infrastructure deployed from 2020 to 2022. This update alone represents a useful contribution to the readily available public literature and can serve as a foundation for future iteration and analysis.

Our final synthesized values are presented in Tables A-1 and A-2. Note that we excluded any listed material inputs required in quantities below a threshold of 2 tons per GW of nameplate capacity. We detail our technology-specific methodology in the subsequent sections. Excel spreadsheets documenting the references used, specific calculations, and final values can be downloaded from the webpage hosting the online version of this report.

Table A-1: Material requirements per GWh of electricity produced by low-carbon electricity generation technologies, as presented in Figure 1. LFP battery storage includes battery cell inputs only for a 2 GWh, 500 MW battery system, discharging once daily over a 25-year life.

kg/GWh	Nuclear						
	AP1000	EPR	Small light-water (BWRX-300)	Solar PV farm	Onshore wind farm	Offshore wind farm	LFP battery storage
iron in steel	82.946	120.548	138.567	809.059	1675.799	1791.732	31.562
sum of concrete	516.047	1203.608	1254.698	298.326	5144.201	0	0
sum of iron	0	0	0	0.698	118.2	69.649	75.616
sum of rare earths	0	0	0	0	0.561	1.093	0
aluminum	0.224	0.224	0.224	178.891	42.022	6.939	80
boron	0	0	0	0	0.157	0.013	0
chromium	11.183	16.06	14.113	2.426	15.656	1.813	9.205
cobalt	0	0	0	0	0.039	0.035	0
copper	3.29	3.29	3.29	45.028	30.907	20.769	47.123
glass and glass-reinforced plastic	0	0	0	25.479	0	0	0
graphite	0	0	0	0	0.065	0.042	120.548
lithium	0	0	0	0	0	0	9.863
lead	0.105	0.105	0.105	0.079	0	0	0
magnesium	0	0	0	5.216	0	0	0
manganese	1.415	2.041	1.981	16.251	30.868	33.908	0.932
molybdenum	0.004	0.004	0.022	0.032	0	0	0
nickel	6.044	8.669	7.702	12.43	32.89	25.924	4.932
niobium	0.004	0.004	0.004	0	0	0	0
phosphate	0	0	0	0	0	0	46.027
silicon, solar-grade	0	0	0	38.844	0	0	0
silver	0	0	0	0.159	0	0	0
solar PV cover glass	0	0	0	352.296	0	0	0
tin	0	0	0	1.078	0	0	0
titanium	0	0	0	0.396	0.796	0.865	0
tungsten	0.011	0.011	0.011	0	0	0	0
zinc	0	0	0	22.007	0.483	0.367	0
uranium	3.13	3.13	3.13	0	0	0	0

Table A-2: Material requirements per gigawatt of nameplate generating capacity for different low-carbon electricity generation technologies, as presented in Figure 2. LFP battery storage includes battery cell inputs only for a 2 GWh, 500 MW battery system accompanying a 1 GW solar or wind facility.

tons/GW	Nuclear						
	AP1000	EPR	Small light-water (BWRX-300)	Solar PV farm	Onshore wind farm	Offshore wind farm	LFP battery storage
iron in steel	37057	53856	61906	51029	128450	258977	576
sum of concrete	230549	537724	560549	18816	394303	0	0
non-steel iron	0	0	0	44	9060	10067	1380
sum of rare earths	0	0	0	0	43	158	0
aluminum	100	100	100	11283	3221	1003	1460
boron	0	0	0	0	12	2	0
chromium	4996	7175	6305	153	1200	262	168
cobalt	0	0	0	0	3	5	0
copper	1470	1470	1470	2840	2369	3002	860
glass and glass-reinforced plastic	0	0	0	1607	0	0	0
graphite	0	0	0	0	5	6	2200
lithium	0	0	0	0	0	0	180
lead	47	47	47	5	0	0	0
magnesium	0	0	0	329	0	0	0
manganese	632	912	885	1025	2366	4901	17
molybdenum	2	2	10	2	0	0	0
nickel	2700	3873	3441	784	2521	3747	90
niobium	2	2	2	0	0	0	0
phosphate	0	0	0	0	0	0	840
silicon, solar-grade	0	0	0	2450	0	0	0
silver	0	0	0	10	0	0	0
solar PV cover glass	0	0	0	22220	0	0	0
tin	0	0	0	68	0	0	0
titanium	0	0	0	25	61	125	0
tungsten	5	5	5	0	0	0	0
zinc	0	0	0	1388	37	53	0

Utility-scale solar PV

Our raw material input assumptions for utility-scale solar PV installations were primarily adapted from the new NREL REMPD database,[46] which considers a representative 100 MW (DC) crystalline silicon ground-mount solar PV facility. The REMPD's scope covers all balance-of-plant infrastructure including cabling, racking, modules, inverters, transformers, and other balance-of-system equipment.

We further refined the NREL REMPD material usage values by cross-referencing the data with more recent industry intelligence, documentation, and reporting. For aluminum, solar-grade polysilicon, silver, and solar cover glass, we found that the REMPD values are higher than current industry figures, and we revised these values by adopting the lower numbers. In the case of steel, REMPD numbers give a comparable but slightly higher value than steel usage as reported by a recent Bloomberg New Energy Finance (BNEF) brief,[47] yet we retained the REMPD values as the BNEF article projects further increases in steel usage as the industry moves toward longer mounting foundation poles and screws. Meanwhile, for copper, we compiled a composite estimate, finding the REMPD module and other balance-of-plant copper usage figures to be appropriate, but revising on-site cabling copper usage downwards based on BNEF research.[48]

To derive total iron usage for solar PV farms, we assumed that "chromium steel" reported in the REMPD corresponds to SAE Grade 304 stainless steel and that "low-carbon steel" corresponds to mild steel equivalent to AISI Grade 1010, with a 99% iron content. We assumed that the REMPD already accounts for all other alloy constituents, such as chromium, nickel, and manganese.

Finally, we adopted the REMPD's value for concrete, but further divided this concrete requirement by 2 in order to be maximally conservative. The REMPD analysis only assumed limited concrete usage in foundation pads for transformers and other on-site balance-of-system equipment. Many older solar PV material use studies relied upon outdated estimates or reports that assumed concrete feet or anchors for solar module mountings. However, typical ground-mount utility-scale solar PV installations no longer use concrete in solar array mountings. We note though that some brownfield installations (e.g., landfill solar)[49] and distributed PV configurations (e.g., car park solar) may still require concrete ballast or foundations in practice.

In converting solar material usage per unit capacity to material required per unit generation, we assumed a 24% capacity factor and a 30-year project lifetime for utility-scale solar PV.

Onshore and offshore wind

For onshore and offshore wind installations, we also employed the NREL REMPD database. It reports material usage for a representative onshore wind farm of 200.6 MW with 3.4 MW direct-drive turbines.[50] The REMPD's representative offshore wind farm is a 1005 MW facility employing 15 MW geared turbines.[51] Our study's scope covers all balance-of-plant infrastructure grouped into the following categories: array and export cabling, substation, turbine, turbine substructures/foundations, and facility substation. When we cross-referenced the REMPD values against older Vestas environmental product declaration studies from 2011-2017,[52],[53],[54] the REMPD's material usage was similar if not better than the Vestas data for all major materials, so we adopted the REMPD data in their entirety.

As with solar, to determine total iron usage, we assumed approximate steel grades based on the material type categories listed in the REMPD wind product, as shown in Table A-3. We again assumed that the REMPD already accounts for all other alloy constituents.

In deriving wind material requirements per unit generation, we assumed a 35% capacity factor and a 25-year project lifetime for onshore wind, and a 55% capacity factor and a 30-year project lifetime for offshore wind farms.

Table A-3: Assumed steel types and iron mass fractions corresponding to categories of steel named in the NREL Renewable Energy Materials Properties Database.

Material type category	Assumed steel type
Chromium steel	SAE Grade 304 stainless steel, 67.005% iron
Low-carbon steel	AISI Grade 1010 mild steel, 99% iron
Reinforcing steel	SAE Grade 1020 carbon steel, 99% iron
Electrical steel	Assume 96% iron
Casting steel	Low-alloyed cast steel, 98% iron
Galvanized steel	Assume 98% iron
Magnetic steel	Assume 67% iron at minimum, possible underestimate

Nuclear power plants

To arrive at material usage estimates for nuclear power plants, we surveyed the research literature with three specific power plant designs in mind: the Westinghouse AP-1000 (1117MW), the Framatome EPR (1600 MW), and the GE-Hitachi BWRX-300 (300 MW). The foundation for our calculations was the 2022 *Capital Cost Evaluation of Advanced Water-Cooled Reactor Designs with Consideration of Uncertainty and Risk* report by Stewart and Shirvan,[55] which models most balance-of-plant concrete and steel requirements for these three designs. Stewart and Shirvan considered all major on-site structures, piping, and a generic cooling tower. However, their study scope does not include equipment such as reactor and turbine equipment or control systems, which we considered separately in our analysis.

A few pessimistic commentators have alleged very high nuclear power plant material requirements (307,000 tons of steel and 1,400,000 tons of concrete per GW), citing construction documents for the Hinkley Point C EPR project,[56] and may argue the Stewart and Shirvan numbers are too conservative. We considered that, first, the EPR is an especially materials-intensive large light-water reactor design, featuring a double steel and concrete containment dome, a "core catcher" structure beneath the reactor building, and quadruple redundancy of many safety systems.[57] Second, the Hinkley Point C project is unique in having to meet requirements that stipulated intake and return of cooling water at a distance of around two miles and one mile offshore, respectively, using tunnels six to seven meters in diameter.[58],[59] Third, the documents cited by some commentators present estimated rail and sea transportation weights of steel and concrete to the power plant site during construction. These material totals may include temporary construction, scaffolding, equipment, and auxiliary facilities such as roads and docks that would not traditionally be appropriate to include in a balance-of-plant life cycle assessment. We view the engineering-based modeling approach of Stewart and Shirvan to be a more accurate basis for plant-wide calculations.

Furthermore, we note that we have deliberately selected aggressive parameters for nuclear power plant raw material consumption. As such, our presented material use requirements for nuclear power facilities may tend toward overestimation. In particular:

- We report estimated first-of-a-kind (FOAK) concrete and steel requirements from the 2022 MIT modeling study, instead of nth-of-a-kind (NOAK) values. FOAK raw material demand accounts for some degree of rework during construction. NOAK material requirements reported in the source study exhibit improved material use efficiency on the order of ~25%.
- We assumed a concrete density corresponding to 2.75 metric tons of concrete per cubic meter,[60] which is potentially aggressive.

- Our accounting methodology for nuclear power plant equipment may have double-counted some steel requirements for piping that are also covered by the MIT study.
- The MIT source study assumed a generic cooling tower for each nuclear power plant design. In practice, this is not always required, particularly for power plant sites that leverage seawater or riverine cooling.
- Private consultation with nuclear developers suggests that our approach may greatly overestimate stainless steel usage in nuclear power plant structural steel applications, inflating our estimates of some stainless steel alloy constituents like nickel and manganese.
- In converting material requirements per unit capacity (tons per GW) to material demand per unit of energy produced (kg per GWh), our primary calculations conservatively assumed an 85% capacity factor and 60-year lifetime for nuclear power plants. The U.S. average capacity factor for nuclear energy in practice is at least 91% in recent years,[61] while industry and regulatory practices currently allow for 80-year plant lifetimes.

Returning to the specifics of our methodology, the steel usage values presented by Stewart and Shirvan do not specify specific steel subtypes and thus cannot be directly used to calculate alloy constituent requirements. To estimate the fractions of plant-wide steel corresponding to each steel type, we used an older 1986 DOE Energy Economic Data Base (EEDB) Program that quantified specific quantities of structural steel, reinforcing steel, carbon steel piping, and stainless steel piping for a 1144 MWe pressurized water reactor.[62] Using this report to approximate the composition of different steel types within a modern nuclear power plant assumes that the relative usage of different steel grades in nuclear power plants has not changed significantly in the past 40 years. As the fundamental structures in question (reactor building, turbine hall, cooling tower and infrastructure, switchyard, etc.) have not changed, we believe this is reasonable. Based on the DOE EEDB study, we made the following assumptions:

- We apportioned 87.4% of the steel requirement reported by Stewart and Shirvan to structural steel.
  - We assumed 66.8% of this structural steel category consisted of SAE Grade 1020 carbon steel, mostly carbon steel rebar. We categorized the remaining 33.2% of structural steel as SAE Grade 304 stainless steel.
- We assigned the remaining 12.6% of the steel total reported by Stewart and Shirvan to piping.
  - We assumed 88.3% of steel usage in piping consisted of SAE Grade 1020 carbon steel, with the remainder consisting of SAE Grade 304 stainless steel.

As the Stewart and Shirvan study does not consider on-site equipment, we had to add steel and concrete requirements for equipment separately. We calculated reactor steel usage based on publicly available reactor pressure weights for the AP-1000,[63] EPR,[64] and BWRX-300,[65] and assumed that this reactor steel corresponds to ASTM A508 Grade 5 alloy steel for reactor pressure vessels. We then referenced steel rebar, total steel, and total concrete usage values for other reactor plant equipment, turbine plant equipment, electric plant equipment, and miscellaneous equipment presented in Peterson et al.,[66] for a 1970s-era pressurized water reactor (leveraging these values for both the AP-1000 and the BWRX-300) and for the Framatome EPR. To avoid underestimating steel alloy constituents, we assumed that all equipment steel not explicitly classified as rebar (which is the vast majority) consisted of SAE Grade 304 stainless steel. We then added these reactor steel and equipment steel requirements to the Stewart and Shirvan plant-wide estimates.

For all other nuclear power plant materials not related to steel or concrete, we referenced various literature, as documented in our supplementary Excel datasheets. We adopted an aggressive value of 1470 tons of copper per GW of installed nuclear capacity, the highest value among the sources we surveyed. With no rigorous public source on aluminum usage in nuclear power plants available, we selected a figure of 100 tons of aluminum per GW, based on a value of 64 tons/GW used by Gibon and Menacho,[67] who cited the ecoinvent database. Other nuclear non-fuel material requirements are minor, all less than 50 tons/GW and in many cases <10 tons/GW. Overall, we assessed our estimates of non-steel and non-concrete material usage in nuclear power plants as relatively imprecise, but multiplying all of these numbers by even a further factor of 2 to 3 would not meaningfully affect our results.

Lithium-ion batteries

Our model lithium-ion battery storage facility operates over a 25-year lifetime, fully charging and discharging once per day. We quantified raw material needs for our model battery storage facility assuming the storage units employ lithium-iron-phosphate (LFP) battery cell chemistry, adopting material intensity values presented in a 2021 European Federation for Transport and Environment report.[68]

These materials consider only cell-level metal, graphite, and phosphate needs and thus omit numerous other battery energy storage system components. We did not account for cell electrolyte materials, comprising likely ~10% of the cell mass. Other raw material inputs outside the scope of this calculation include binders, separators, battery pack casing, plastics, and—importantly—balance-of-system components such as cabling, temperature control systems, racking, structures, and support pads. We assumed standard SAE Grade 304 stainless steel for all steel battery components, which may overestimate chromium and nickel requirements and underestimate iron requirements.

To deliver a roughly apples-to-apples comparison relative to the assessed 1 GW of solar, wind, or nuclear generation capacity, another important assumption involved the average quantity of battery energy storage deployed at a typical wind or solar installation. Based on real-world project examples (Table A-4), we assumed a relatively conservative 2 GWh, 500 MW LFP battery energy storage facility accompanies a hybrid 1 GW wind or solar farm with onsite storage.

Table A-4: Summary of statistics for four selected recent large utility-scale solar PV projects with onsite grid battery energy storage systems.

Project name	Actual project solar PV capacity (DC) and battery storage capacity and power capacity	Project battery storage capacity, per 1 GW (DC) of installed solar PV capacity
Edwards and Sanborn Solar and Energy Storage Project[69]	875 MW (DC) solar PV capacity; 3 GWh of battery storage, 4-hour duration assumed	3.429 GWh
Oberon Solar and Storage Project[70]	679 MW (DC) solar PV capacity; 1 GWh/250 MW of battery storage	1.473 GWh
Yellow Pine Solar 1[71]	162 MW (DC) solar PV capacity; 260 MWh/65 MW of battery storage	1.605 GWh
Longroad Energy Sun Streams 3[72]	285 MW (DC) solar PV capacity; 860 MWh/215 MW battery storage	3.017 GWh

Simple coal and natural gas comparison

We assumed a 1 GW supercritical coal-fired power plant burns 432 metric tons of coal per hour of operation, corresponding to 432,000 kg of coal burned per GWh. Multiplied by a rock-to-ore ratio of 2.73 for coal (which includes 36% losses during wash recovery), this yields a total of 1,179,000 kg of earth and ore moved per GWh of coal-fired electricity produced.

For natural gas electricity, we assumed a combined cycle heat and power natural gas power plant thermal efficiency of 60% and an energy content (lower heating value) of 50 MJ/kg for natural gas.[73] The assumed thermal efficiency of the power plant was used to derive the heat rate of the power plant, which is 5686.7 BTU/kWh. This was then converted to 6 MJ, where 1 BTU = 1055.06 J. The amount of natural gas used for electricity production was then determined by dividing the heat rate of the power plant by the heat content of the natural gas, yielding 0.12 kg per kWh or 120,000 kg per GWh.

These simple calculations do not consider raw materials expended in coal mining or oil and gas production, midstream infrastructure such as rail and pipeline transportation, power plant infrastructure, or oil and gas drill tailings and waste rock. These are likely small relative to the mining impact of coal fuel itself in the case of coal power, but could add particularly to the impact of gas-fired electricity in practice.

Rock-to-metal ratios, uranium

We used rock-to-metal ratios taken directly from USGS sources[74,75] for all commodities except for a limited number of materials including aggregates, boron, coal, graphite, gypsum, lead, lime, manganese, niobium, phosphate, and uranium, for which we estimated rock-to-metal ratios independently. Note that the USGS produced two separate rock-to-metal ratios for rare earth elements: one treated the host rock leached in ionic clay adsorption methods as waste, and the other did not. We conservatively used the ratios that did not treat this leached host rock as waste, to produce a lower rock-to-metal ratio and a more favorable comparison of wind power relative to other technologies. For manufactured components (steel, concrete, and soda lime glass), we estimated a single rock-to-metal ratio as a weighted average of the rock-to-metal ratios of the material's constituent components.

Estimated rock-to-metal ratios used the following formula:

$$\frac{(\text{Waste Mass} + \text{Ore Mass})}{(\text{Ore Grade} \times \text{Mill Recovery Rate} \times \text{Refining Recovery Rate})}$$

This formula effectively replicates the methodology used in the USGS sources. The exception is that USGS rock-to-metal ratios take into account amounts of materials that are co-produced from the same mass of ore. Our small number of independently estimated rock-to-metal ratios do not, and they therefore double-count mined material to the extent that these commodities are produced as byproducts. The USGS provides byproduct production percentages for a number of these materials, ranging from 0.3% for boron to 10% for uranium.[76] Consequently, we do not expect this level of double counting to produce a significant rock-to-metal overestimate (by underestimating the fraction of the commodity sourced via other mining). Finally, we assumed no byproduct production from aggregate, coal, graphite, gypsum, lime, phosphate, or silicon.

Waste mass is the amount of rock that does not contain any ore, which operators must still excavate during the mining process due to practical factors such as overlying material or limited precision of earth-moving equipment. Consistent with USGS methodology, our independent estimates assumed that two units of waste are removed for each unit of ore in open pit operations and zero units of waste are removed for every unit of ore in underground operations. Note that these amounts can vary widely in practice depending on the specific deposit, so these nominal values likely underestimate the final rock-to-metal ratio.

Ore grade is the percentage of metal or mineral of interest actually contained in the host rock. We only considered grades relevant to mining economical deposits as opposed to general geologic concentrations. We did not apply an ore grade to aggregates used in concrete since they are used as a bulk material. Because ore grades can vary across commodities by orders of magnitude, they are by far the most influential factor in rock-to-metal ratios. This also implies that any future long-term decline in ore grades would significantly impact rock-to-metal ratios and mining footprints.

Mill and refining recovery rates account for material losses from inefficiencies that occur while processing the ore into a usable form. Any commodity can undergo a unique series of steps. Generally though, milling occurs directly after mining and entails crushing rock into workable sizes and separating waste rock from ore by flotation, for example. Refining typically involves additional removal of impurities and smelting. In line with USGS methodology, we applied a single factor to broadly account for milling and refining each.

We did not apply a mill recovery factor to aggregate and gypsum because they are used as bulk materials in concrete and only undergo crushing, which we treated as negligible losses. Boron and lime undergo calcination (roasting), which we treated as part of the milling process. Aggregate, graphite, and gypsum do not undergo refining. Additionally, we excluded boron and phosphate refining because they are strictly chemical in nature, which we treated as negligible losses. We did not account for any losses incurred through any sort of processing or manufacturing of finished products.

When possible, we sourced all inputs from empirical industry data to reflect the actual impacts realized in practice. We also weighted waste rock amounts and ore grades based on industry production method, given that these often vary across different mining operations (e.g., open pit mining is often associated with lower grade ores). However, complete global profiles were not available for every commodity, so in some cases we assigned nominal values or assumed proportions.

The methodology for uranium was identical to that for other commodities up through the milling stage that produces a concentrate (in this case, yellow cake). Ore grades, mining method proportions, and mill recovery factors are all empirical, taken from the 2022 Nuclear Energy Agency and IAEA *Uranium 2022* Book.[77] Beyond that, the conversion, enrichment, and fuel fabrication stages are collectively analogous to the refining stage for other commodities. We assigned 100% recovery for these processes.[78]

Aside from recovery, the enrichment stage warrants distinctive treatment given that nuclear fuel only incorporates the fraction of uranium that contains U-235 isotopes. To account for this, we assumed that every unit of uranium enriched to 4.5% U-235 requires 7.651 units of natural uranium.[79] In a sense, this additional step is analogous to applying another form of ore grade. These steps produce a rock-to-metal ratio for uranium of 3,624. We assumed that 1 GWh generation requires 3.13 kgs of enriched uranium.[80] Note that we did not account for zirconium or gadolinium in nuclear fuel, as these are negligible quantities on a per-GWh basis.

In line with USGS methodology, our estimated rock-to-metal ratios do not account for any production from fluid-based sources like in-situ recovery or brine extraction methods and consider only inputs from hardrock mining. This is because fluid-based methods require minimal excavation—if any—and do not produce a comparable type of waste. In the context of this study's methods, production using these fluid-based methods incurs negligible impact.

These methods are namely relevant for boron, lithium, magnesium, and uranium. Therefore, the rock-to-metal ratios for these commodities represent what should be more appropriately thought of as an upper bound or maximum potential impact should production occur strictly from hardrock mining. As a result, these ratios overestimate the actual impact to a degree dependent on the global proportion of hardrock mining actually employed at any given time.

Given the relatively low amounts of boron and magnesium required across the different energy technologies examined, we consider overestimates from these commodities to be insignificant. However, to account for the more substantial roles uranium and lithium play, we multiplied the kg of rock per GWh of generation demand of either commodity by the respective percentages of global production from hardrock mining. This offers a middle bound representing the actual impact incurred by their production.[81,82]

We encourage the reader to refer to the online version of this report to download our supplementary Excel data spreadsheets.

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