Materials demand for electricity in climate mitigation scenarios

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Analysis

Keywords:

Posted Date: February 23rd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1229622/v1

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Abstract:

Achieving global climate and energy goals will require prodigious increases in non-emitting electricity generation, raising concerns about the scale of materials needed and associated environmental impacts. Here, we estimate power sector demand for materials and related carbon dioxide-equivalent (CO_2eq) emissions from 2020-2050 across different climate-energy scenarios and compare these figures to material geological reserves and carbon budgets. We find that demand increases but cumulatively does not exceed current geological reserves. However, annual production of materials including neodymium (Nd), dysprosium (Dy), tellurium (Te), fiberglass, and solar-grade polysilicon may need to grow considerably. Cumulative CO_2 emissions related to materials for electricity infrastructure may be substantial (4-29 Gt CO_2eq in 1.5°C scenarios) but constitute a small share of global carbon budgets (1-9% of a 320 Gt CO_2eq 1.5°C 66% avoidance budget). Our results highlight how power sector decarbonization will mobilize large quantities of materials, likely necessitating continued development of existing and new mineral resources.

In the coming decades, deep reductions in global greenhouse gas emissions will be necessary to meet international climate goals. As the largest source of current emissions[1], fossil fuel electricity generation will need to be replaced by non-emitting technologies, including capacity to meet expected growth in global electricity demand. Moreover, decarbonization will involve increasing electrification of transportation, buildings and industry, such that most climate mitigation scenarios produced by global integrated assessment models (IAMs) and energy system models predict considerable growth in global electricity demand by 2050[2,3,4,5]. Indeed, the required pace and scale of new non-emitting electricity generating infrastructure worldwide is roughly proportional to the level of climate ambition in such scenarios--substantially exceeding historical growth rates in scenarios that limit the increase in global mean temperatures to 1.5°C above pre-industrial temperature[6].

In turn, transformation and growth of the power sector will require considerable inputs of raw materials, including critical materials such as rare earth (in particular neodymium, dysprosium) and semi-/precious metals as well as emissions-intensive structural materials such as cement, steel, and fiberglass. Because extraction and/or processing of some critical materials remains highly concentrated in just one or a handful of countries [7–10], they have outsized economic and geopolitical importance. Mineral supply chains have been used as political and economic leverage during international disputes in the recent past[8].

In addition, the environmental consequences of material supply chains are increasingly of concern. Mining, processing, and refining of raw ores is often energy- and emissions-intensive. Mining activities can impact the health of laborers and nearby populations and also destroy or degrade ecosystems [11]. Such impacts raise questions of international equity and environmental justice and may also undermine climate benefits. A recent study estimated that the energy used by the mining industry, including coal mining, represents 4-7% of global annual fossil fuel emissions[12]. While much of this impact results from fugitive methane emissions from coal mines, energy consumption for mine activities is estimated to contribute 1% of global fossil emissions (0.4 Gt CO_2e). Process emissions (unrelated to required energy) from cement and steel production represent another ~9% of global fossil fuel and industry emissions in recent years (1.57 and 3.7 Gt CO_2 per year from cement and steel, respectively)[13–15].

The material demands implicit in climate mitigation scenarios are thus a salient topic for policymakers, industry planners, and environmental activists, with potentially important consequences for energy technology costs and rates of deployment. However, material demand, production, and trade are not universally or consistently represented in global IAMs[16]. Efforts to develop such projections are still an ongoing process. Some recent studies have investigated the quantities of particular materials that would be required by the expansion of specific technologies in specific regions[17–25] or by a wider range of technologies at the global level [7,26–33,34]. Yet relatively few analyses have estimated future potential material requirements across more than a handful of power sector decarbonization scenarios or pathways.

Here, we estimate quantities of 15 critical, structural, and bulk materials related to electricity generating infrastructure commissioned between 2020 and 2050 in 75 different IAM mitigation scenarios taken from the SR15 database (Supplementary Table 1) that aim to limit the increase in global mean temperatures to 2°C above pre-industrial temperature or less. We use energy technology and demand trajectories in the IAM scenarios and ranges of material and emissions intensities compiled from the literature to estimate the quantities of materials required in different scenarios. We estimate related CO2 emissions required to produce these materials as well as associated uncertainties. We then compare total and annual material demand to current raw material production rates and estimates of present-day global reserves and resource potential. Similarly, we compare cumulative CO_2eq emissions associated with material requirements – using 100-year global-warming-equivalent values – with the estimated carbon budgets of different temperature targets.

Patterns of material demand and materials-associated emissions, 2020-2050

More ambitious climate scenarios tend to result in greater demand for materials by the power sector from 2020-2050, with concomitant increases in cumulative GHG emissions associated with these materials (Figure 1). These added emissions from materials production in aggressive mitigation scenarios, however, are more than offset by accelerated rates of decarbonization that result in lower overall climate warming. In nearly all cases (84th percentile and below), cumulative emissions associated with raw material needs from power generation infrastructure over the next 30 years in 1.5°C mitigation scenarios amount to <20 Gt CO2eq, or ~50% of current annual GHG emissions. The 1.5°C mitigation scenario with the highest cumulative materials-associated emissions yields 37 Gt CO2eq, about one year's current global GHG emissions, while the 2.5th to 97.5th percentile range of estimates spans 4 to 29 Gt CO2eq.

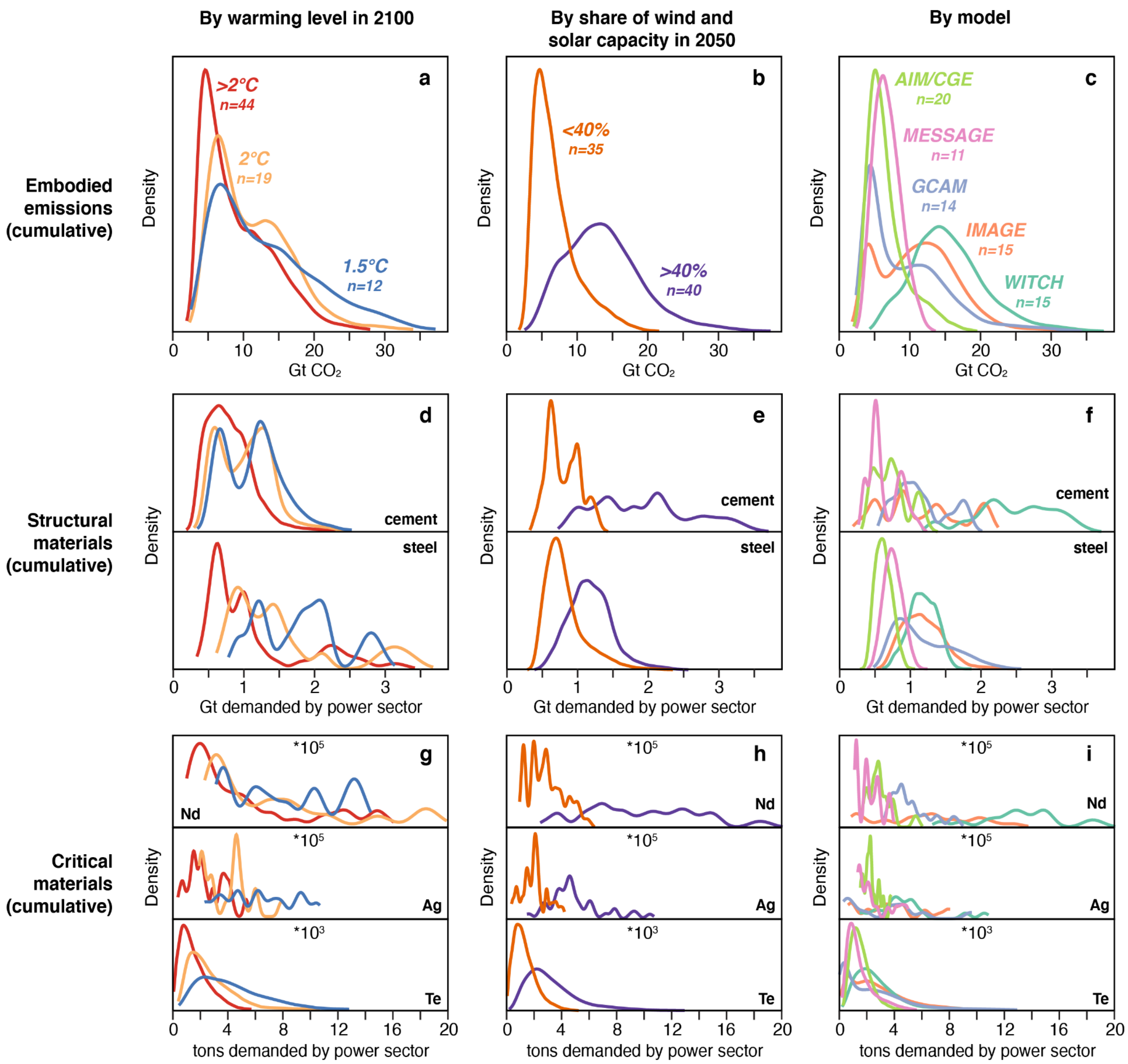

Figure 1 | Probability distributions of materials used for power sector infrastructure in global mitigation scenarios. Probability density functions showing probability distributions of **a, b, c,** cumulative 2020-2050 materials-associated CO2eq emissions. **d, e, f,** cumulative 2020-2050 power sector steel and cement requirements. **g, h, i,** cumulative 2020-2050 power sector neodymium (Nd), silver (Ag), and tellurium (Te) requirements for a selection of 75 integrated assessment models, categorized by **(left column)** end-of-century category of global mean warming outcome, **(middle column)** by share of combined wind and solar capacity as a percentage of total electricity generation capacity in 2050, **(right column)** by modeling group.

For 50% and 66% chances of avoiding 1.5°C warming, the remaining carbon budget from the start of 2022 is roughly 420 and 320 Gt of CO2, respectively[35,36]. The cumulative emissions associated with power sector decarbonization in a 1.5°C mitigation scenario thus represent 1-7% of the remaining 50% avoidance budget and 1-9% of the 66% avoidance budget. The emissions embodied in materials for electricity-generating infrastructure under mitigation scenarios therefore do not pose a meaningful threat to remaining carbon budgets, though the portion of such budgets used for decarbonization will be larger when considering other sectors such as transportation, buildings, industry, and agriculture.

Nevertheless, more rapid decarbonization pathways carry important implications for raw material demand over the next three decades. For many specific materials such as cement, steel, neodymium, silver, and tellurium, cumulative demand in 1.5°C scenarios can be substantially greater than for 2°C scenarios.

For many of the studied materials, demand from clean power generation infrastructure will comprise a considerable proportion of total global production. At the peak pace of a 1.5°C-consistent scenario, for instance, silver demand for solar panels might require ~10% of current world production. Future aluminum and copper demand for power sector infrastructure could require ~18% of current production. CuInGaSe (CIGS) thin-film solar could strain supply chains for indium and selenium even if CIGS thin-film is installed at a relatively low percentage of overall future solar PV capacity (2%) consistent with today's market share.

Yearly demand for solar-grade glass and for fiberglass composites used in wind turbine blades could require a fifth to a quarter or more of current annual global flat glass manufacturing and the entirety of glass fibre production. However, comparisons for these categories may not represent like-to-like comparisons. For instance, some life cycle assessments for wind energy only report the total weight of glass fibre, epoxy, and resin in wind turbine blades. We assume that glass fibre makes up the majority of the mass of these components, so fiberglass demand in wind turbines might be somewhat overestimated. Not all flat glass or fiberglass is suitable for solar or wind applications, while different solar and wind technologies may use different types and grades of glass and fiberglass. Even so, the finding that demand for glass and fiberglass in renewables infrastructure could dominate these supply chains is intriguing.

For some materials (dysprosium, neodymium, solar-grade polysilicon, tellurium), the peak annual power sector demand over coming decades will considerably exceed current global production rates, requiring large increases in production (Table 1). Rare earths for wind turbines alone might require tripling global rare earth metal production, while buildout of CdTe thin-film solar could necessitate an even larger increase in global tellurium production. Estimated future solar-grade polysilicon demand will also outstrip current production, potentially by more than a factor of two. These results are similar to the findings of a recent report by the IEA, which projects a 3-7 fold increase in demand for rare earth metals (the IEA scenario also includes rare earth demand from electric vehicles) and a twofold increase in polysilicon demand between 2020 and 2040[7]. Our overall results align well with values calculated in other studies[27,32,3437].

	Units	1.5°C max annual production rate	2°C max annual production rate	Current production rate
Aluminum	Mt	11.4 (5.62 to 20.7)	7.21 (3.23 to 21.8)	60
Cement	Mt	71.4 (30.7 to 105)	52.8 (22.9 to 137)	4100
Copper	Mt	3.64 (2.07 to 6.25)	2.30 (1.24 to 6.55)	19.7
Fiberglass	Mt	3.16 (1.32 to 6.63)	2.03 (0.904 to 6.70)	4.76
Glass	Mt	20 (13.2 to 55)	12.4 (6.16 to 35)	75.4
Manganese	Mt	.0372 (.00989 to .848)	.0563 (.0103 to .385)	16
Nickel	Mt	0.167 (0.0648 to 0.292)	0.112 (0.0433 to 0.301)	2.1
Solar-grade polysilicon	Mt	1.14 (0.379 to 3.15)	0.620 (0.193 to 2.40)	0.468
Steel	Mt	87.2 (54.6 to 251)	63 (32.2 to 220)	1870
Cadmium	t	1910 (715 to 5240)	1040 (365 to 3940)	23000
Dysprosium	t	5570 (2090 to 13700)	3640 (1410 to 13300)	1800
Gallium	t	38 (16 to 97)	21 (8 to 75)	555
Indium	t	113 (52 to 288)	62 (26 to 224)	720
Neodymium	t	57000 (23100 to 1210000)	38300 (16100 to 123000)	21000
Selenium	t	520 (171 to 1500)	282 (88 to 1130)	3300
Silver	t	2970 (2100 to 7560)	1840 (1050 to 5100)	25000
Tellurium	t	2160 (756 to 6110)	1170 (386 to 4610)	420

Table 1: Comparison of maximum yearly global power sector material demand, expressed as median (2.5th percentile value to 97.5th percentile value) for each material under 1.5°C end-of-century warming scenarios and 2C end-of-century warming scenarios, versus current global annual production rates of each material. All values are in metric tons.

Based on current estimated global reserves of critical materials, aggregate future demand for electricity infrastructure in scenarios will not exceed known mineral resources over the next 30 years, with the possible exception of tellurium (Table 2). Although we do not explicitly assess availability of bulk materials, global resources of iron ore, existing stocks of recyclable steel, sand, gravel, polymers, and cement are all unlikely to limit the future availability of steel, concrete, fiberglass, glass, or polysilicon.

The availability of tellurium could limit CdTe thin-film deployment. In 1.5°C scenarios, median cumulative tellurium demand requires ~88% of estimated tellurium resources. However, expected expansion of copper demand may help alleviate constraints, since most tellurium production today occurs as a byproduct of copper mining[38]. This result also assumes that CdTe thin-film solar makes up 8% of future solar deployment by capacity, consistent with its current share[20,39,40]. This share could decline, or future CdTe arrays might utilize less tellurium. Nor would tellurium availability necessarily constrain overall solar PV deployment, as the industry could reorient towards other PV technologies.

However, cumulative demand for critical materials in some cases does require a substantial share of current reserves. Median total copper demand from 2020-2050 is 81.8 million tons, more than 10% of the estimated reserve of 790 million tons. Similarly, clean electricity infrastructure under 1.5°C scenarios could consume >10% of current global silver reserves, ~7.5% of cadmium reserves, ~7.9% of dysprosium reserves, >15% of indium reserves, >7% of neodymium reserves, ~5% of nickel reserves, and ~10% of selenium reserves. As many of these materials are employed in and across numerous sectors, technologies, and products, increasing demand from the construction of power sector infrastructure over coming decades could potentially tighten economy-wide raw material supply chains and impact raw material and energy project costs. For instance, the IEA projects annual copper demand in the electric vehicles and battery storage sectors to reach 1.1-3.3 million tons per year by 2040[7].

	Units	**1.5°C cumulative demand, 2020-2050**	**2C cumulative demand, 2020-2050**	**Estimated reserves**	**Estimated resources**
Aluminum	Mt	241 (110 to 380)	141 (58.4 to 310)	30000	75000
Cement	Mt	1300 (683 to 2050)	1120 (562 to 1820)	n/a	n/a
Copper	Mt	81.8 (40.8 to 109)	49.5 (23.7 to 100)	790	3500
Fiberglass	Mt	69.5 (22.5 to 99.6)	37.7 (15.4 to 135)	n/a	n/a
Glass	Mt	446 (234 to 756)	280 (113 to 525)	n/a	n/a

Manganese	Mt	0.892 (0.167 to 7.60)	1.26 (0.155 to 44.9)	680	1730
Nickel	Mt	3.80 (1.11 to 4.70)	2.13 (0.901 to 6.28)	74	130
Solar-grade polysilicon	Mt	22.5 (7.21 to 48.9)	11.8 (3.45 to 33.2)	n/a	n/a
Steel	Mt	1960 (1100 to 2950)	1330 (724 to 3360)	n/a	n/a
Cadmium	t	37700 (13700 to 82300)	20000 (6410 to 55000)	500000	6000000
Dysprosium	t	87200 (32900 to 159000)	53400 (22000 to 203000)	1100000	1980000
Gallium	t	771 (312 to 1470)	414 (146 to 1060)	110000	1000000
Indium	t	2280 (976 to 4430)	1230 (454 to 3090)	15000	47000
Neodymium	t	929000 (360000 to 1390000)	546000 (251000 to 1890000)	12800000	23000000
Selenium	t	10100 (3310 to 23800)	5350 (1570 to 15600)	100000	171000
Silver	t	67600 (36900 to 106000)	45100 (19300 to 79100)	530000	1310000
Tellurium	t	42300 (14600 to 95900)	22300 (6730 to 63700)	31000	48000

Table 2: Comparison of cumulative 2020-2050 power sector material demand to current estimates of existing reserves and resources for each material of interest. Cumulative demand values are expressed as median cumulative demand (2.5th percentile value to 97.5th percentile value) for each material under 1.5°C end-of-century warming scenarios and 2C end-of-century warming scenarios. All values are in metric tons.

In terms of global warming impact, a sizable proportion of raw material demand and materials-associated emissions are driven by wind and solar. Scenarios in which electricity generation from solar and wind constitutes more than 40% of all electricity generation in 2050 show considerably higher demand not only for specialty materials associated with those technologies, but also for structural bulk materials such as cement and steel (Figure 1) and copper and aluminum (Supplementary Figure 1). Scenarios with higher wind and solar generation in 2050 also produce greater materials-related emissions over the 2020-2050 period (Figure 1), due to the higher material requirements of these technologies per unit capacity and due to the considerable carbon footprint of solar-grade polysilicon.

Patterns of material demand and materials-associated embodied emissions are also driven by differences in technological assumptions between models. For instance, WITCH-GLOBIOM 3.1 tends to envision higher solar deployment and substantially higher deployment of new wind capacity between 2020 and 2050 compared to other models, resulting in higher power sector demand for materials and higher materials-associated carbon emissions. We note that the Low Energy Demand (LED) scenario[3], which assumes markedly reduced global final energy demand and mitigation efforts consistent with a 1.5°C pathway, does not produce lower cumulative material demand relative to other scenarios (Supplementary Table 2). The LED scenario actually shows high demand for aluminum and copper relative to other 1.5°C scenarios, while steel and cement requirements are marginally reduced but still above the overall median for all scenarios. This is likely due to the scenario's rapid installation rates for clean energy alongside high assumed wind and solar deployment, coupled with avoidance of negative emission technologies.

Materials-associated emissions in some 1.5°C scenarios see the bulk of their cumulative emissions by 2030 (Figure 2). This result reinforces the importance of proactive policies and technology shifts to support decarbonization of the heavy industrial sector. Even modest progress towards industrial decarbonization in the next several years could yield compounded benefits in terms of avoided greenhouse gas emissions as global heavy industry mobilizes to build clean generation infrastructure and other clean technologies.

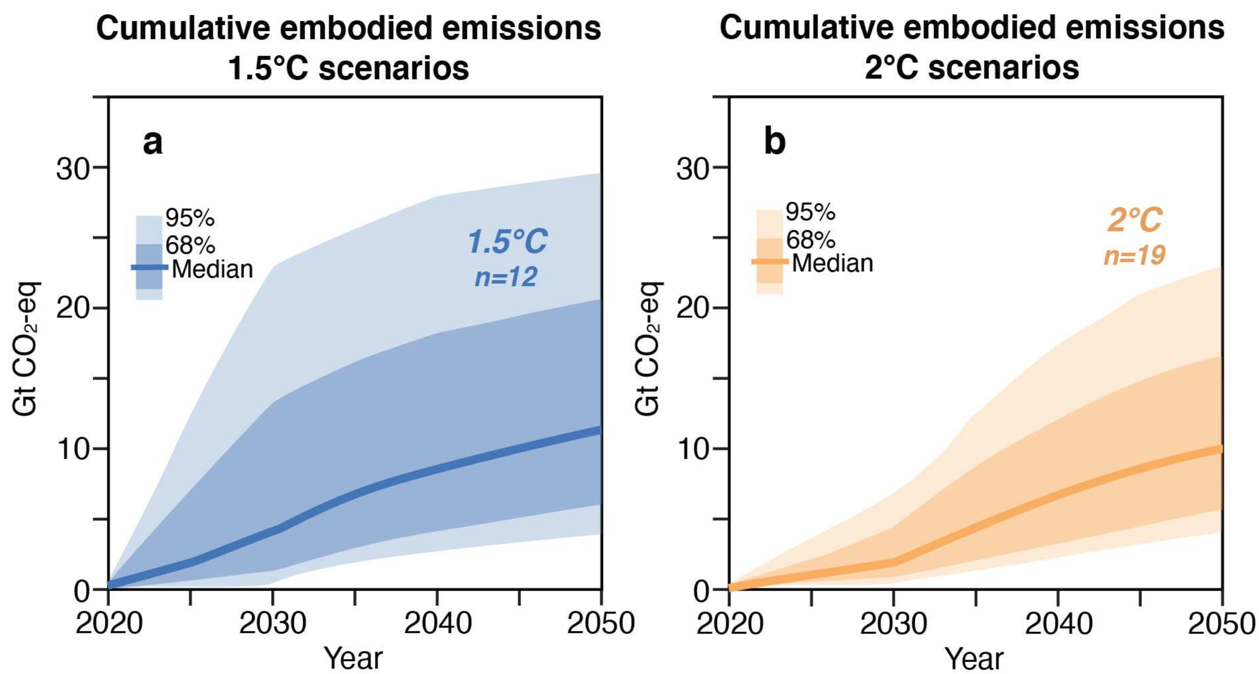

Figure 2: Time series of cumulative materials-associated CO2 emissions from 2020 to 2050 in tons of CO2 for **a**, 1.5°C end-of-century warming scenarios and **b**, 2C end-of-century warming scenarios. The solid lines denote the median. The dark shaded areas show the one-sigma range (16th to 84th percentile), while the light shaded areas show the two-sigma range (2.5th to 97.5th percentile) across scenarios.

Materials and materials-associated carbon intensity of different electricity generation technologies

Our analysis reveals that the majority of the embodied carbon in generation infrastructure is emitted in the production of bulk structural materials, notably steel, cement, and aluminum (Figure 3). Solar-grade polysilicon also represents a significant portion of embodied carbon in the case of crystalline silicon solar PV. Other materials such as rare earth metals (neodymium, dysprosium), critical minerals for thin-film solar (cadmium, indium, selenium, tellurium), common metals for electronics applications (copper, nickel), and other bulk components (flat glass in solar modules and fiberglass composites in wind turbine blades) account for a small to negligible quantity of the overall embodied carbon emissions associated with power generation infrastructure. Note that the values in Figure 3 may differ from other life cycle assessments in the literature as they only include embodied emissions from the materials needed to construct power generation infrastructure.

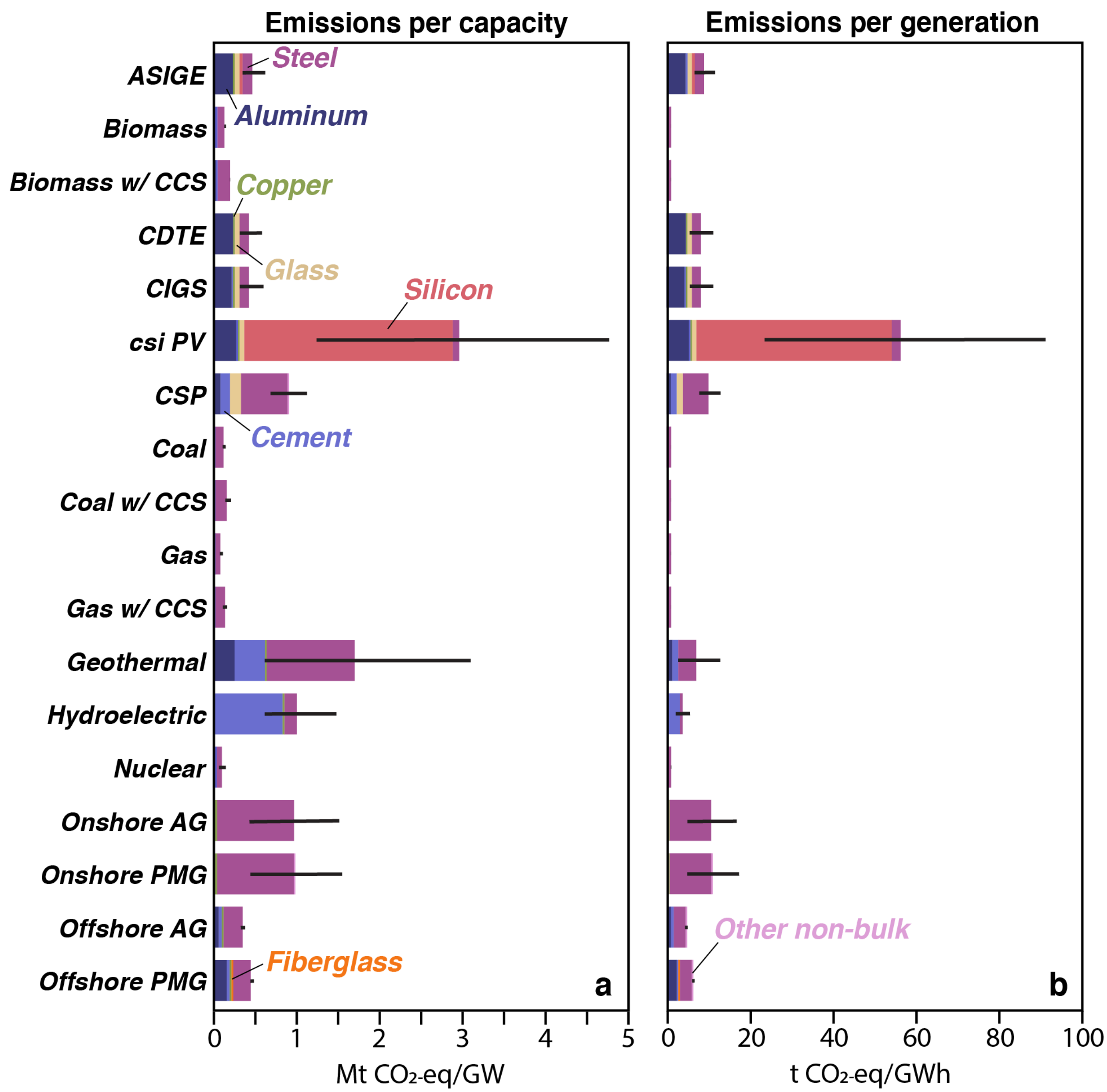

Figure 3 | Material-related carbon intensity of electricity infrastructure. For each electricity-generating technology, bars show CO2-eq emissions per unit of (**a**) generating capacity (**b**)and electricity generated , colored according to material. Black whiskers reflect the range of total carbon intensities spanning the 2.5th to 97.5th percentiles.

Owing to the higher material requirements of solar, wind, hydro, and geothermal generation infrastructure (Figure 4), these technologies exhibit higher materials-associated carbon emissions (Figure 3), largely due to greater steel and concrete needs. Lower material inputs are required for thermal and nuclear infrastructure. Expressing these results in terms of emissions per unit generation as opposed to emissions per unit capacity increases the relative embodied carbon emissions of solar and wind generation relative to other technologies due to the lower capacity factor of solar and wind infrastructure.

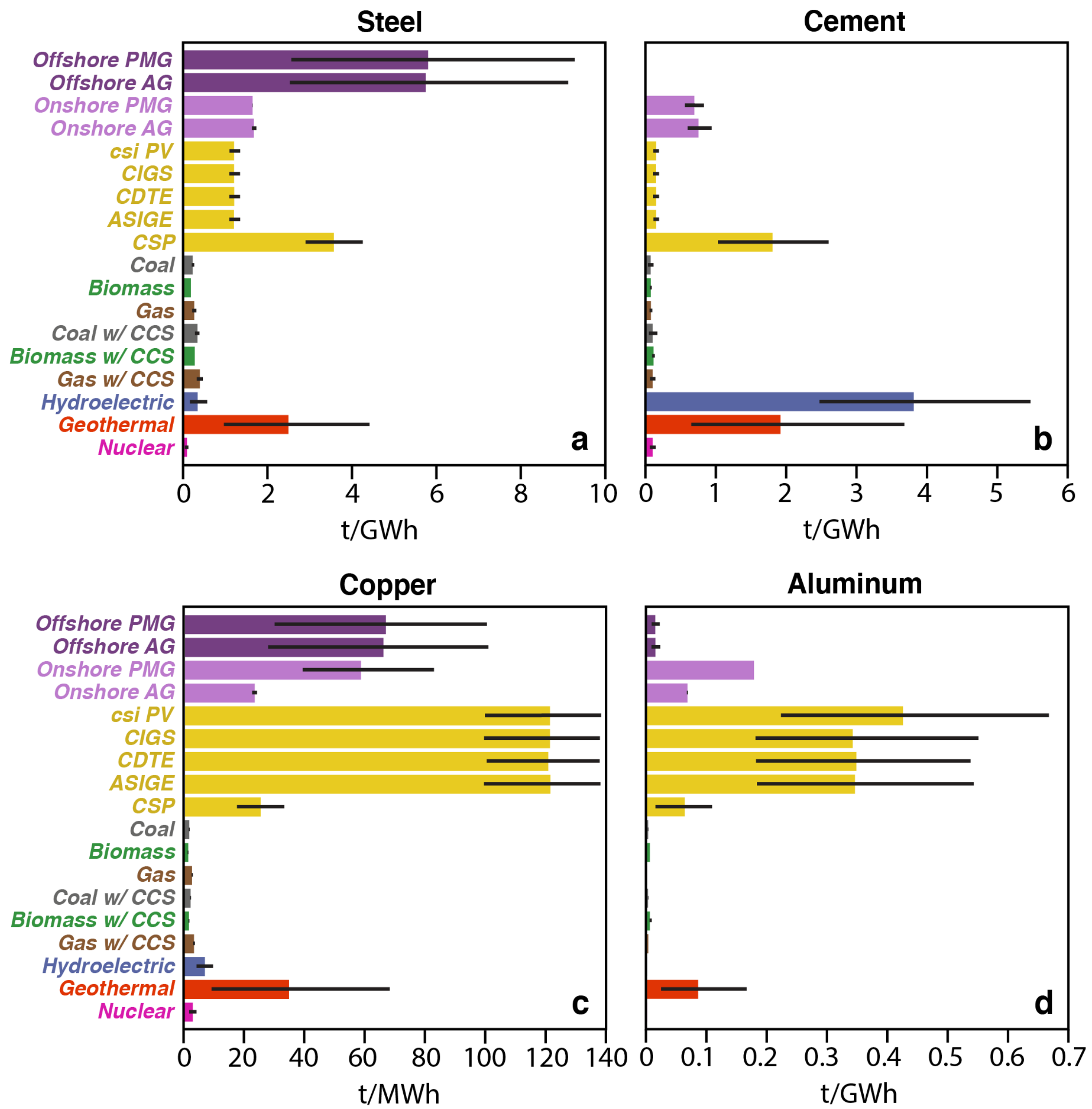

Figure 4: Barplots of material intensity of four selected bulk materials. **a,** steel **b,** cement **c,** Cu **d,** Al in each generation technology, expressed in tons per GWh of electricity generation. Black whiskers reflect the range of total intensities spanning the 2.5th to 97.5th percentiles.

These findings reemphasize that decarbonization of the global steel and cement sectors is a high priority, as these industries make up much of the carbon cost of the new electricity generation infrastructure needed for the clean energy transition. The high embodied carbon footprint of solar-grade polysilicon, heavily driven by the dominance of current production by coal-intensive manufacturing in China, also highlights the importance of China's future transition away from coal-fired energy and the value of diversifying solar-grade polysilicon manufacturing beyond China. Research and development of alternative, less energy-intensive industrial pathways for raw material production can reduce the life cycle climate and environmental impacts associated with these supply chains.

Key limitations

Our model calculates the material demand and embodied emissions associated with the materials used to build the whole-of-site generation infrastructure (Supplementary Figure 2). The embodied emissions per ton of material reflect a cradle-to-factory-gate scope that incorporates emissions associated with mining, ore processing, and refining. Our overall study scope thus explicitly does not include material requirements and emissions associated with fuel production, fabrication of infrastructure components, construction, fuel combustion, operations, and decommissioning and end-of-life processes.

Considering the entire power sector as a whole, our study's results are therefore likely a conservative underestimate of true raw material requirements. Our selected set of materials of interest also remains far from comprehensive. We did not consider material requirements associated with off-site transmission and distribution. Nor do we account for the widespread future deployment of grid-scale battery storage. The study's findings should be understood to strictly encompass the materials contained within generation infrastructure.

Requirements for manganese and nickel in power generation infrastructure are inconsistently reported in the published literature, partially because these are constituents of alloyed steels of varying compositions. As such, our results for estimated manganese and nickel requirements are relatively tenuous. We largely refrain from discussing estimated manganese and nickel demand in detail. The related results are included in the Supplementary Material.

Sensitivity tests

We conducted sensitivity analyses upon a relatively wind-and-solar-heavy 1.5°C model scenario (MESSAGE-GLOBIOM 1.0 SSP1 1.9) to assess the relative impact of various model assumptions upon the overall results. These included varying the number of Monte Carlo simulations used to sample across our dataset of raw material requirements, changing proportions of different solar and wind technology types, varying carbon intensity and decarbonization assumptions, adjusting input recycling rates, and assessing the impact of different infrastructure operating lifetimes (see Methods).

No discernable differences were observed when the model was run using 100, 1000, or 5000 Monte Carlo iterations (Supplementary Figure 3).

Overall, sensitivity testing suggests that our study's embodied carbon calculations are relatively insensitive to subtechnology-specific assumptions. Altering the assumed share of thin-film solar did not substantially affect cumulative 2020-2050 materials-associated CO2 emissions (Supplementary Figure 4). We observed even less of an impact from changing the proportion of permanent magnet drive wind turbines in installed wind capacity and from assuming a global versus regional material CO2 intensity for certain materials. Similarly, modifying input recycling assumptions had little effect. Shortening the modeled lifespan of installed wind and solar by 25% also produced minimal changes. Adjusting the rate of industrial sector decarbonization proved much more influential, corroborating the high importance of deep decarbonization initiatives for heavy industry. These results are unsurprising, as assumptions regarding industrial sector decarbonization are directly related to the calculated CO_2 footprint of power sector material demand.

Predictably, thin-film and permanent magnet assumptions do significantly alter estimates of 2020-2050 material demand for specialty materials associated with those technologies (Supplementary Figure 5). While we have endeavored to make reasonable assumptions regarding the share of thin-film solar types and permanent magnet drive wind turbines in future solar and wind deployments, our material demand estimates are directly sensitive to these choices. We emphasize that future technological trends are difficult to anticipate and are strongly driven by financial incentives to minimize use of costly or constraining raw materials.

Conclusion

The large future buildout of electricity generation infrastructure specified in energy system models will necessitate significant inputs of raw materials. While the minerals and heavy industrial sectors remain relatively carbon-intensive, we estimate that the emissions associated with sourcing raw materials for the power sector represent a relatively small fraction of remaining carbon budgets. Most materials-associated emissions derive from the large-scale use of bulk materials like steel, cement, and copper that are common requirements for most generation technologies. Proactive industrial sector decarbonization can help avoid some of these emissions released when manufacturing raw materials for clean electricity technologies. This emphasizes the importance of coordinating industrial decarbonization efforts with and alongside power sector decarbonization.

We find that global mineral reserves should amply meet needs posed by power sector material demand. However, estimated future power sector material demand will likely constitute a meaningful fraction of current raw material production rates for many materials, and may necessitate expansion of global production by several-fold for certain key inputs like neodymium, fiberglass, dysprosium, solar-grade polysilicon, and tellurium. Proactive efforts to develop and maintain new mineral production are warranted, particularly considering the long lead times required to establish new supply chains[7]. Recycling and innovation to reduce materials demand could play meaningful roles in cutting future requirements for individual raw materials[41], but will not change the overall anticipated increase in material demand. With the energy sector becoming a sizable industrial consumer of some inputs, the mining and mineral processing sector will consequently play a crucial role in supporting the clean energy transition.

The research community could expand further on this modeling work by considering the potential material requirements of transmission and battery storage in addition to generation infrastructure. Similarly, it is important to project further material demand from increases in battery vehicle adoption or from decarbonization of other sectors. The methodology we employed for this analysis can be easily updated to reflect new and emerging technologies.

Acknowledgements

We thank Tim Latimer, Per Peterson, and Joel Jean for helpful conversations and for support in sourcing material intensity values for generation technologies. We are grateful to Daniel

Huppmann for assistance with the IAMC 1.5°C Scenario Explorer, and to Julianne DeAngelo for her help in calculating rates of industrial sector decarbonization.

I. Methods

Selection of technologies of interest, study scope, and materials of interest

We selected electricity generation technologies that corresponded to the most common variables provided in the IAMC 1.5°C Scenario Explorer[42–44]. The IAMC 1.5°C Global timeseries data snapshot release 2.0 was downloaded from https://data.ene.iiasa.ac.at/iamc-1.5°C-explorer/#/downloads. These technologies include onshore and offshore wind, conventional solar PV, concentrating solar power (CSP), hydroelectricity, geothermal, nuclear, and coal, biomass, and fossil gas, both with and without post-combustion carbon capture. We omitted oil-fired generation from consideration on the basis that such infrastructure accounts for a relatively negligible quantity of current and projected future generation capacity and is predicted to retire over coming decades in the models studied.

For onshore and offshore wind, we assumed that wind farms consist of two types of turbines: turbines with asynchronous gearbox (AG) motors, and turbines incorporating permanent magnet generators (PMG). We broke down the conventional solar PV category into crystalline silicon PV as well as three thin-film solar technologies: copper indium gallium diselenide (CIGS), cadmium telluride (CdTe), and amorphous silicon germanium (aSiGe).

We delineate our study boundary for material requirements as limited to generation and transformer infrastructure only, excluding grid transmission beyond the boundaries of a plant. This also importantly excludes upstream materials associated with fuel extraction and processing, and also excludes downstream infrastructure such as CO_2 pipelines in the case of CCS facilities. Such a study scope carries important limitations for our analysis, as significant raw materials inputs are also consumed to construct mines for coal, uranium, and minerals and to build oil and gas drilling equipment, refineries, and pipeline infrastructure. Accounting for such factors would significantly complicate the study design. For instance, fossil gas might be extracted using different drilling techniques (conventional versus unconventional hydraulic fracturing, onshore versus offshore), while the assumed extent of CCS/CCUS infrastructure associated with a power plant varies with not just the facility's generating capacity but also with its proximity to sequestration sites or end users. Given such challenges, we have restricted this study's focus to the materials embodied in generating infrastructure.

We also do not assess materials demand from battery or other energy storage facilities co-located with electricity generation, as IAMC model scenarios do not explicitly specify outputs or assumptions corresponding to such storage.

Finally, we selected the following set of 17 metals and raw materials for which to estimate global demand and associated carbon emissions over the next 30 years: silver (Ag), aluminum (Al), cadmium (Cd), cement, copper (Cu), dysprosium (Dy), fiberglass, gallium (Ga), flat solar-grade glass (glass), indium (In), manganese (Mn), neodymium (Nd), nickel (Ni), selenium (Se), solar-grade polysilicon (denoted as Si), steel, and tellurium (Te). These we qualitatively divide into two categories. “Bulk materials” are major raw material inputs for electricity generation projects that are important components of solar or wind systems and/or are essential basic inputs for most if not all technology types, and include aluminum, cement, copper, fiberglass (a major component of wind turbine blade composites), glass (a major input for solar technologies), solar-grade polysilicon, and steel. The remaining materials (silver, cadmium, dysprosium, gallium, indium, manganese, neodymium, nickel, selenium, tellurium) we designate as “specialty metals”.

These by no means represent an exhaustive list of raw materials used in electricity generation technologies. Nevertheless, this selection of input materials enables an illustrative assessment of how expansion of clean electricity generation capacity over subsequent decades will impact global demand for raw materials.

Material demand of generation technologies

Material intensity data for each technology type were assembled from previously-published literature. The referenced studies and data values are detailed in (Supplementary File 1). Intensities reported on a capacity basis (i.e. kg/kW) were converted to metric tons/GW generating capacity as needed. Intensities specified on a generation basis (i.e. tons/GWh) were also converted to tons/GW using assumed technology lifetimes and capacity, although the use of values derived from per-unit-generation figures was minimal and generally avoided. The details of such calculations are provided in (Supplementary File 1).

LCAs and calculations for wind and solar technologies were generally only included if published in or after 2000, in order to accurately reflect rapid technological progress in these sectors in recent decades. For all other technology types, including solar CSP, hydropower, nuclear, geothermal, and fossil fuels (coal and natural gas), material intensities were accepted regardless of publication date, due to sparser availability of relevant estimates.

In many cases, literature values for cement usage in electricity generation infrastructure are reported in tons of concrete rather than as tons of cement mix. To use these values, we applied a conversion to such values to derive a potential range for cement usage based on an assumed range of strength classes and associated densities used for concrete in power sector infrastructure, and on an assumed range of cement content per cubic meter of concrete. Based on Supplementary Data 6 of Xi et al, 2016[45], which compiles data on concrete of different strength classes used in 33 dam, power station, dock, and infrastructure projects in China, we assume that concrete utilized in the power sector ranges in strength from 35 MPa to less than 15 MPa. The range of classes of concrete within these strength categories exhibits a typical cement content of 165 to 400 kg of cement per cubic meter. We further assume a range of concrete densities of 1600 to 2500 kg/m^3 for concrete of strengths <15 to 35 MPa[46].

Thus, to convert from tons of concrete to tons of cement, we calculated a range of concrete volume based on a density range of 1600 to 2500 kg concrete per cubic meter. A low and high estimate of mass of cement used were subsequently calculated from the low and high concrete volume values, using a range of cement content of 165 to 400 kg of cement per cubic meter. These two values were represented as two separate estimates, constituting an upper and a lower bound for each literature source.

Concrete intensity estimates from the literature expressed as concrete volumes were processed using the same methodology, just omitting the initial conversion of concrete weight to concrete volume.

We employed a number of technology-specific assumptions to resolve uncertainties regarding future technology choices and gaps in material demand estimates. We considered both materials estimates for monocrystalline silicon and polycrystalline silicon PV installations within the broader cSi PV category. For copper, steel, cement, and flat glass requirements for thin-film solar installations, we assumed that demand for these materials per unit capacity matched that of conventional crystalline silicon PV installations. Based on Bodeker et al., 2010[47], we further assumed that aluminum demand per unit capacity in thin-film solar farms was 81% that of conventional PV facilities. Literature on materials demand for biomass electricity generation was limited, and so values for coal infrastructure were employed in the case of copper, nickel, and manganese.

For some technologies, different plant types are considered within the same broader category. Given high uncertainties in the future outlook for concentrating solar power (CSP) solar generation by type, we utilized material intensity figures for both parabolic trough and central power tower plants and consider these all to be independent estimates of material demand for CSP solar deployment. Similarly, material intensity values for geothermal include values from analyses of conventional geothermal plants as well as projections for advanced geothermal systems. The compiled literature values for hydroelectricity similarly encompass both run-of-river and storage reservoir designs, while analyses of fossil fuel plants range across several turbine types.

Few commercial fossil fuel power plants are currently equipped with post-combustion carbon capture equipment, and life cycle assessments on the materials intensity of such facilities remains limited. As such, we employed some assumptions to derive estimated materials demand for fossil fuel installations equipped with CCS infrastructure. Based on the findings reported in Singh et al., 2015[48], we assumed that steel and cement demand for a gas, coal, or biomass power plant with CCS would be 1.53 times that of the equivalent plant without carbon capture equipment. We similarly assumed that copper intensity of a fossil plant with CCS would be 1.2 times that of a plant without CCS. This assumption may overestimate plant-specific material requirements for fossil fuel generation fitted with carbon capture equipment, as carbon capture infrastructure may be more integrated within some designs such as Allam cycle gas turbines than it might be in the case of add-on retrofits.

Our approach further assumes that the material intensity of electricity generation does not change significantly over the period 2020-2050. While the material intensity of generation technologies will almost certainly change over this period, it remains difficult to project the direction and magnitude of these changes for each material and generation technology, subjecting any choice of simplifying assumption to limitations.

Energy sector scenarios

For our projections of future electrical generating capacity by type, we leverage various scenarios available on the IAMC 1.5°C Scenario Explorer[42–44]. From the database, we curated a list of 75 models and scenarios for which to calculate future electricity-sector material demand and materials-associated emissions based on several criteria. First, we selected models that reported electricity generation capacity over time for at least most of the technologies of interest. Second, we largely considered ambitious and middle-of-the-road scenarios that yield end-of-century total radiative forcing of 4.5 W/m^2 or less, excluding higher-end or no-policy scenarios. Finally, we focused our attention on SSP scenarios, otherwise including only a handful of models and scenarios from the ADVANCE project. To this subset of models, we added the MESSAGEix-GLOBIOM 1.0 Low Energy Demand (LED) scenario[3], to explore how a modest reduction in future global energy demand relative to current projections would affect projected demand for the materials of interest.

The final list of selected models and scenarios is detailed in (Supplementary Table 1). IAM scenario data, material intensities, and mineral production tables were exported from the Scenario Explorer database and imported into Python, where downstream calculations were performed using scripts and input files prepared by the authors, which are available along with output files at: https://doi.org/10.5281/zenodo.5799114.

We employed several assumptions to derive or estimate deployed generation capacity for certain technologies under some models and scenarios. The outputs from the IAMC 1.5°C Scenario Explorer dataset do not explicitly provide the proportion of future fossil fuel electricity generation capacity with and without carbon capture (CCS). We thus assume that the fraction of coal (or gas) capacity utilizing CCS is the same as the proportion of electricity generated with carbon capture relative to the total electricity generated using coal (or gas).

Many scenarios, most notably the SSPs, do not provide a breakdown of offshore versus onshore wind capacity or solar PV versus solar CSP capacity within the broader wind and solar categories. To resolve this, we leveraged outputs from the ADVANCE project which do report quantities for both offshore and onshore wind capacity and solar PV and solar CSP capacity. For each year of output data, we averaged the percentage of solar CSP as a fraction of total solar and the percentage of offshore wind as a fraction of total wind across all ADVANCE scenarios from a given modeling group (IMAGE, MESSAGE-GLOBIOM, POLES ADVANCE, WITCH-GLOBIOM), and assume these proportions of offshore wind and solar CSP for all SSPs produced by the same modeling group. For the AIM/CGE 2.0 model, ADVANCE scenario outputs report zero offshore and zero CSP capacity, so we assume for AIM/CGE 2.0 SSPs that all wind capacity is onshore wind and that all solar capacity is solar PV.

We subsequently employed several assumptions to translate IAM projections for solar and wind generation into a more detailed breakdown of specific solar and wind technologies. For onshore and offshore wind generation, we assume that from 2000 to 2020 the proportion of wind turbines employing PMG technology using rare-earth magnets increased from 0% for both categories to 75% of offshore turbines and 25% of onshore turbines. Those fractions are then assumed to increase further to 100% of offshore turbines and 75% of onshore turbines by 2050. These

assumptions are approximately consistent with market data and with scenarios employed in previous studies[39,49,5051,52]
. We assume that the fraction of non-PMG wind turbine capacity is comprised of asynchronous gearbox (AG) designs.

For PV solar, we assume that c-Si solar stays constant at 90% of all new capacity added from 2000-2050. The remaining 10% is comprised of various thin-film solar technologies. The fraction of CIGS solar increases from 0% in 2000 to 2% of new added solar capacity in 2020, thereafter remaining constant for the duration of the model run. The fraction of CdTe solar similarly increases from 0% in 2000 to 8% in 2020, remaining steady thereafter. Note that we assume the remaining fraction of solar to be a-SiGe solar, which starts at 10% of new added solar capacity in 2000, but falls to 0% of new added capacity in 2020 and remains at zero through 2050, thereby contributing nothing to material demand or embodied emissions. This scenario is based on historic installations by generation type[53], with the assumption that the future market landscape does not change from the pattern of installed capacity by generation type currently observed today.

Based on the generation capacity for each technology type in each year, we calculated the raw change in capacity from year to year using the change in total capacity. Additionally, we implemented a calculation to account for the end-of-life retirement of both existing capacity at the start of the model run as well as new subsequently-installed infrastructure, in which retired generation is replaced by new generation of the same type. New capacity installed after 2005 is assumed to retire as a cohort in the year:

Retirement Year = Lifetime + Year of Installation

As the IAM scenario data do not provide capacity data for many generation types prior to 2005, we assume that generation capacity in 2005 possesses an even age distribution, such that the rate of retirement for all existing 2005 capacity in each subsequent year is constant, as follows:

Capacity retired=(Capacity in 2005/(Lifetime))

Not all of retired capacity in a given year is necessarily replaced. If the total capacity for a generation technology is falling (change in capacity <0), then replaced capacity is the retired capacity minus the decline in total capacity. The total new capacity installed in a given year is therefore the sum of replaced capacity and any positive increase in total capacity from the year prior.

We assume static lifetimes for each technology type: 46 years for coal plants, 40 years for gas and geothermal, 30 years for all solar technologies, and 25 years for all wind technologies. Note that we assume that no current generating capacity is retired for both hydroelectric power and nuclear power, under the broad expectation that these technologies enjoy long service lives with the strong possibility of lifetime extension, such that replacement of current standing capacity over the 2020-2050 study period is minimal. In any event, these lifetimes are sufficiently long that relatively little new generation capacity of any kind installed after 2020 is replaced.

Calculation of material demand

Annual quantities of materials consumed in the process of deploying new infrastructure were calculated by multiplying the total new capacity installed in a given year (new capacity added + replaced capacity) by the material intensities per unit capacity for each generation technology. Total year-to-year material requirements for all new installed capacity thus incorporate both material inputs associated with replacement of retired capacity and inputs associated with growing additional capacity. Annual material demand for the years 2020-2050 were then summed to calculate total material demand over the study period.

To capture the full range of material intensity estimates for each generation technology, we employed a Monte Carlo approach in which a triangular distribution of material intensities was created based on the mean and standard deviation of the set of estimates of demand per unit capacity of a given material. In rare cases where only a single material estimate was available for a given material and generation technology, that estimate was used without assuming a distribution. For each Monte Carlo simulation, a material intensity value for each material of interest was selected using the triangular distribution constructed for that material.

Global raw material production and input recycling rates

Recent values for global production of the selected set of materials as well as estimated current reserves and global resource potentials were drawn from recent sources, largely from figures presented in Manberger and Stenqvist 2018[32] and Dominish et al 2019[37] (Supplementary File 2). In addition to global rates of production, we researched the current distribution of production among the major producing countries and combined these figures into region-specific proportions of global output. Similarly, figures for current input recycling rates (the proportion of global material production deriving from secondary or recycled sources) were drawn from published literature (Supplementary File 2).

For projecting utilization of recycled inputs over the study period, we largely assume that current input recycling rates remain constant between 2020 and 2050, and that generation capacity changes in the energy sector do not affect input recycling rates. Input recycling of cadmium, dysprosium, fiberglass, gallium, indium, neodymium, selenium, solar-grade polysilicon, and tellurium is considered to be negligible, as current end-of-life recycling of these materials is deficient or nonexistent. For cement consumption, we also assume that no cement inputs are recycled.

Carbon intensity calculations

We conducted a further literature review to compile cradle-to-gate figures for the per-ton CO2 intensity of the various materials of interest (Supplementary File 2). For most materials, we assumed a single average CO2 intensity due to either scarcity of region-specific life cycle studies (in which case a global average was employed), or due to a dominance of global production by a single region (in which case a regional figure was assumed for all global production). For many materials, we relied upon global warming potential estimates published in Nuss and Eckelman 2014[54].

Meanwhile, we adopted a region-specific approach for silver, aluminum, cement, copper, and steel, as LCAs of production from each major region were more readily available. All carbon and GHG emissions were converted to kg CO_2-eq per ton of material on a GWP100 basis. Note that while comparisons of CO_2-eq emissions with remaining carbon budgets expressed in units of CO_2-only introduces a slight inconsistency between units, the vast majority of embodied emissions associated with materials production in the literature assessed in this analysis is from CO_2 rather than other greenhouse gases.

To calculate the carbon emissions associated with sourcing the raw materials required to build electricity generation infrastructure, we multiplied the estimated demand for each material by its carbon intensity. For materials where a proportion of demand is filled by secondary recycled inputs, we assume the lower carbon intensity of recycled material for that proportion of material demand and apply the higher carbon intensity of primary production to the remainder. For those materials where we account for regional differences in CO_2 intensity, we allocate a portion of primary production to each region based on regional shares of production and apply the respective regional CO_2 intensity.

We also assumed a scenario-specific rate of industrial sector decarbonization over time. To derive an evolving coefficient of changing industrial sector CO_2 intensity over time, we leveraged industrial process emissions reported as an output by 40 models in the IAMC 1.5°C Scenario Explorer. We converted annual emissions into a relative proportion based on a reference year of 2010, then averaged these values for each category of scenarios based on their associated end-of-century warming level (1.5°C high overshoot, Lower 2°C, etc…). Finally, to calculate embodied CO_2 emissions associated with the material demand in a given year for each given model/scenario, we applied the average decarbonization coefficient for that year based on the end-of-century temperature outcome associated with that scenario.

Sensitivity analysis

To assess the sensitivity of our results to some of the various assumptions we employed in our modeling approach, we performed sensitivity tests by varying input parameters and assessing the impact of these changes upon the modeled results. We performed these tests for a single model, MESSAGE-GLOBIOM 1.0 SSP1 1.9, which is a relatively ambitious scenario that limits end-of-century warming to ~1.36°C. This scenario sees an approximately 23-fold increase in solar generation and an 8-fold increase in wind generation between 2020 and 2050, allowing for a clear assessment of the relative importance of assumptions around wind and solar technologies and lifetimes.

First, we tested the impact of altering the number of Monte Carlo simulations used to sample material demand from a distribution of intensities for each material. We compared differences when the model was run using 100, 1000, and 5000 Monte Carlo simulations.

We evaluated scenarios in which we altered assumptions regarding the future share of various solar PV and wind technologies. For solar, we considered a "thin-film phaseout" scenario in which deployment of CdTe and CIGS solar falls from 8% and 2% of solar PV respectively in

2020 to zero by 2030, replaced entirely by c-Si PV. We also considered a "thin-film renewal" scenario in which the proportions of CdTe and CIGS solar in newly-installed solar PV capacity doubles from their 2020 shares to 16% and 4% by 2030, with c-Si PV declining to 80% of installed solar PV by 2030. In both scenarios, these shares are then held constant from 2030 to 2050.

For wind, we evaluated the impact of modifying the proportion of onshore and offshore wind turbines employing permanent magnet drives. In a "100% PMG" scenario, every single onshore and offshore wind turbine uses a permanent rare earth magnet drive after the year 2020. In contrast, the "flat% PMG" scenario envisions a future in which the proportion of onshore and offshore wind turbines employing permanent magnets remains constant at 2020 values.

To assess the sensitivity of cumulative materials-associated embodied CO_2 calculations to decarbonization assumptions, we varied the CO_2 intensity and decarbonization rate of the raw materials sector. We evaluated the effect of assuming a uniform global average CO_2 intensity for each material rather than considering regional CO_2 footprints of materials. We also assessed the impact of doubling and halving the pace of industrial sector decarbonization. Furthermore, we ran scenarios in which rates of input recycling were either doubled, or assumed to be zero.

Finally, we considered the effect associated with lowering the lifetime of solar and wind technologies to 75% of their assumed lifetimes, increasing the rate at which solar and wind capacity would need to be replaced over the course of the 2020-2050 study period.

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Model	Scenario	Category	Fraction of Wind + Solar Capacity in 2050	Fraction of Wind + Solar Generation in 2050
AIM/CGE 2.0	SSP1-19	1.5C_low_OS	0.81	0.68
WITCH-GLOBIOM 3.1	SSP1-19	1.5C_low_OS	0.78	0.72
MESSAGE-GLOBIOM 1.0	SSP1-19	1.5C_low_OS	0.55	0.47
IMAGE 3.0.1	SSP1-19	1.5C_low_OS	0.64	0.67
GCAM 4.2	SSP1-19	1.5C_low_OS	0.72	0.58
GCAM 4.2	SSP1-26	Lower_2C	0.6	0.44
AIM/CGE 2.0	SSP1-26	Lower_2C	0.7	0.54
WITCH-GLOBIOM 3.1	SSP1-26	Lower_2C	0.76	0.71
IMAGE 3.0.1	SSP1-26	Lower_2C	0.52	0.47

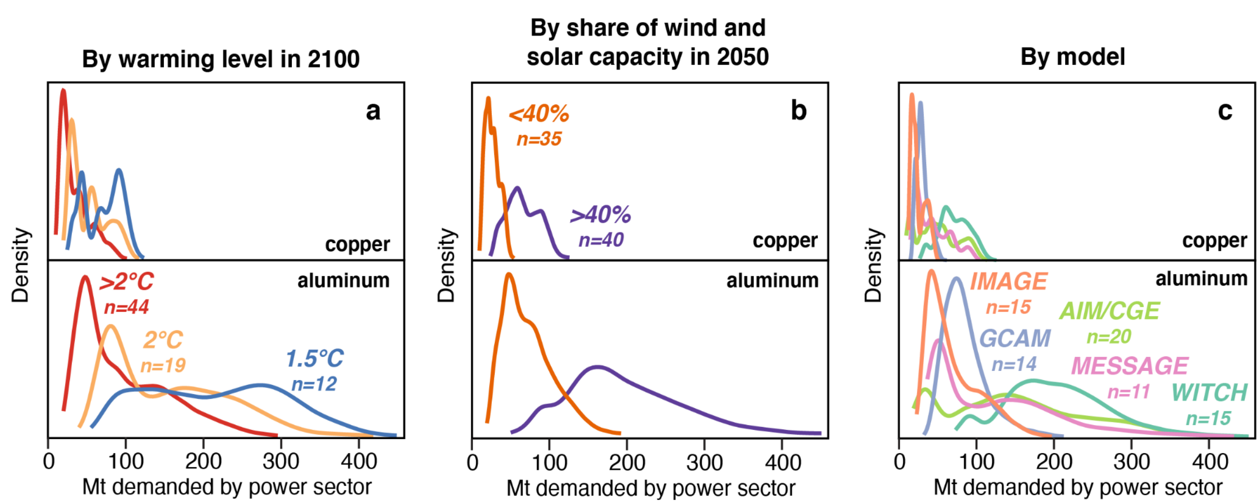
MESSAGE-GLOBIOM 1.0	SSP1-26	Higher_2C	0.5	0.41
GCAM 4.2	SSP1-34	Above_2C	0.5	0.34
AIM/CGE 2.0	SSP1-34	Above_2C	0.59	0.42
WITCH-GLOBIOM 3.1	SSP1-34	Above_2C	0.76	0.7
MESSAGE-GLOBIOM 1.0	SSP1-34	Above_2C	0.47	0.38
IMAGE 3.0.1	SSP1-34	Above_2C	0.45	0.36
AIM/CGE 2.0	SSP1-45	Above_2C	0.52	0.35
WITCH-GLOBIOM 3.1	SSP1-45	Above_2C	0.74	0.58
MESSAGE-GLOBIOM 1.0	SSP1-45	Above_2C	0.45	0.35
IMAGE 3.0.1	SSP1-45	Above_2C	0.4	0.29
GCAM 4.2	SSP1-45	Above_2C	0.46	0.3
AIM/CGE 2.0	SSP2-19	1.5C_low_OS	0.74	0.58
GCAM 4.2	SSP2-19	1.5C_high_OS	0.4	0.25
MESSAGE-GLOBIOM 1.0	SSP2-19	1.5C_low_OS	0.53	0.46
GCAM 4.2	SSP2-26	Higher_2C	0.38	0.23
WITCH-GLOBIOM 3.1	SSP2-26	Lower_2C	0.58	0.62
MESSAGE-GLOBIOM 1.0	SSP2-26	Higher_2C	0.37	0.29
IMAGE 3.0.1	SSP2-26	Lower_2C	0.42	0.31

AIM/CGE 2.0	SSP2-26	Lower_2C	0.63	0.45
GCAM 4.2	SSP2-34	Above_2C	0.34	0.2
AIM/CGE 2.0	SSP2-34	Above_2C	0.54	0.37
WITCH-GLOBIOM 3.1	SSP2-34	Above_2C	0.55	0.56
IMAGE 3.0.1	SSP2-34	Above_2C	0.36	0.26
MESSAGE-GLOBIOM 1.0	SSP2-34	Above_2C	0.32	0.25
AIM/CGE 2.0	SSP2-45	Above_2C	0.42	0.27
WITCH-GLOBIOM 3.1	SSP2-45	Above_2C	0.5	0.46
MESSAGE-GLOBIOM 1.0	SSP2-45	Above_2C	0.28	0.22
IMAGE 3.0.1	SSP2-45	Above_2C	0.32	0.22
GCAM 4.2	SSP2-45	Above_2C	0.31	0.18
MESSAGE-GLOBIOM 1.0	SSP3-34	Above_2C	0.31	0.25
AIM/CGE 2.0	SSP3-34	Above_2C	0.32	0.19
WITCH-GLOBIOM 3.1	SSP3-34	Above_2C	0.54	0.57
IMAGE 3.0.1	SSP3-34	Above_2C	0.3	0.2
AIM/CGE 2.0	SSP3-45	Above_2C	0.22	0.13
IMAGE 3.0.1	SSP3-45	Above_2C	0.26	0.17
MESSAGE-GLOBIOM 1.0	SSP3-45	Above_2C	0.29	0.24

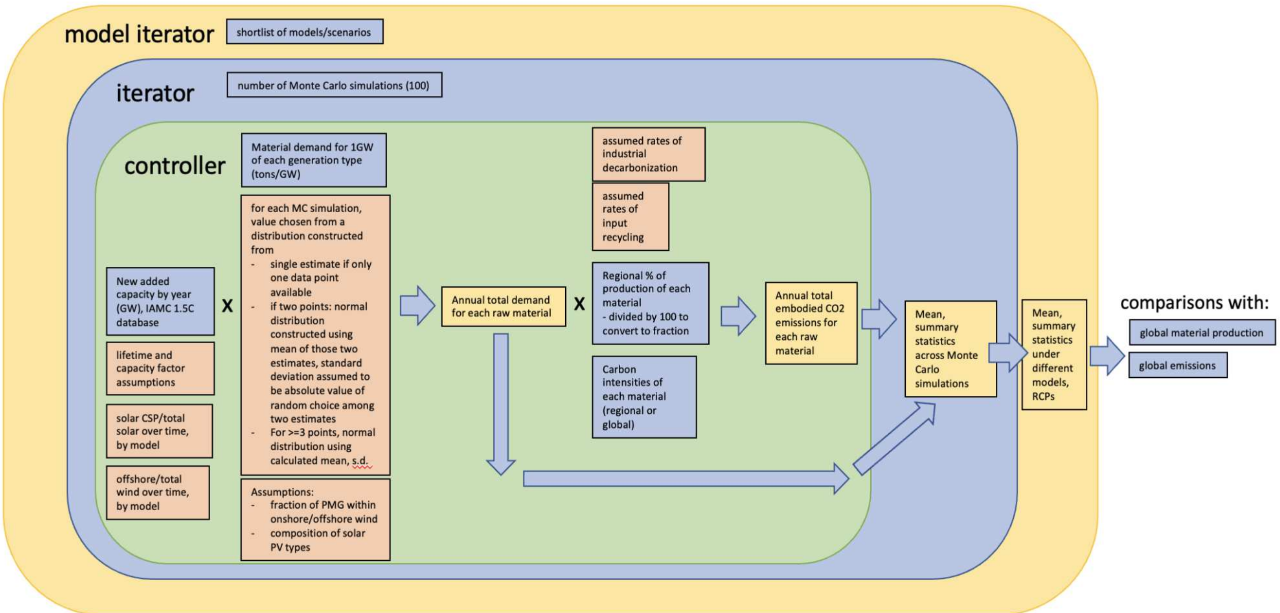
WITCH-GLOBIOM 3.1	SSP3-45	Above_2C	0.45	0.4
WITCH-GLOBIOM 3.1	SSP4-19	1.5C_low_OS	0.76	0.69
AIM/CGE 2.0	SSP4-26	Lower_2C	0.64	0.46
WITCH-GLOBIOM 3.1	SSP4-26	Lower_2C	0.74	0.67
GCAM 4.2	SSP4-26	Higher_2C	0.39	0.24
IMAGE 3.0.1	SSP4-26	Lower_2C	0.51	0.44
AIM/CGE 2.0	SSP4-34	Above_2C	0.58	0.4
IMAGE 3.0.1	SSP4-34	Above_2C	0.36	0.27
WITCH-GLOBIOM 3.1	SSP4-34	Above_2C	0.73	0.65
GCAM 4.2	SSP4-34	Above_2C	0.38	0.23
AIM/CGE 2.0	SSP4-45	Above_2C	0.5	0.33
GCAM 4.2	SSP4-45	Above_2C	0.36	0.21
IMAGE 3.0.1	SSP4-45	Above_2C	0.29	0.21
WITCH-GLOBIOM 3.1	SSP4-45	Above_2C	0.74	0.58
GCAM 4.2	SSP5-19	1.5C_high_OS	0.37	0.22
AIM/CGE 2.0	SSP5-26	Lower_2C	0.36	0.21
GCAM 4.2	SSP5-26	Higher_2C	0.36	0.21
GCAM 4.2	SSP5-34	Above_2C	0.34	0.2
AIM/CGE 2.0	SSP5-34	Above_2C	0.18	0.1
WITCH-GLOBIOM 3.1	SSP5-34	Above_2C	0.54	0.54
IMAGE 3.0.1	SSP5-34	Above_2C	0.21	0.13

AIM/CGE 2.0	SSP5-45	Above_2C	0.14	0.08
GCAM 4.2	SSP5-45	Above_2C	0.31	0.18
IMAGE 3.0.1	SSP5-45	Above_2C	0.18	0.11
WITCH-GLOBIOM 3.1	SSP5-45	Above_2C	0.5	0.47
AIM/CGE 2.0	ADVANCE_2020_1.5C-2100	1.5C_low_OS	0.78	0.63
AIM/CGE 2.0	ADVANCE_2020_WB2C	Lower_2C	0.71	0.53
AIM/CGE 2.0	ADVANCE_2030_Price1.5C	Lower_2C	0.8	0.66
AIM/CGE 2.0	ADVANCE_2030_WB2C	Lower_2C	0.72	0.56
MESSAGEix-GLOBIOM 1.0	LowEnergyDemand	1.5C_low_OS	0.84	0.63

Supplementary Table 1: List of models and scenarios examined in this study, categorized by global warming impact following the scheme utilized by the IAMC 1.5°C Scenario Explorer and by the fraction of wind and solar capacity and generation over total capacity and generation in the year 2050.



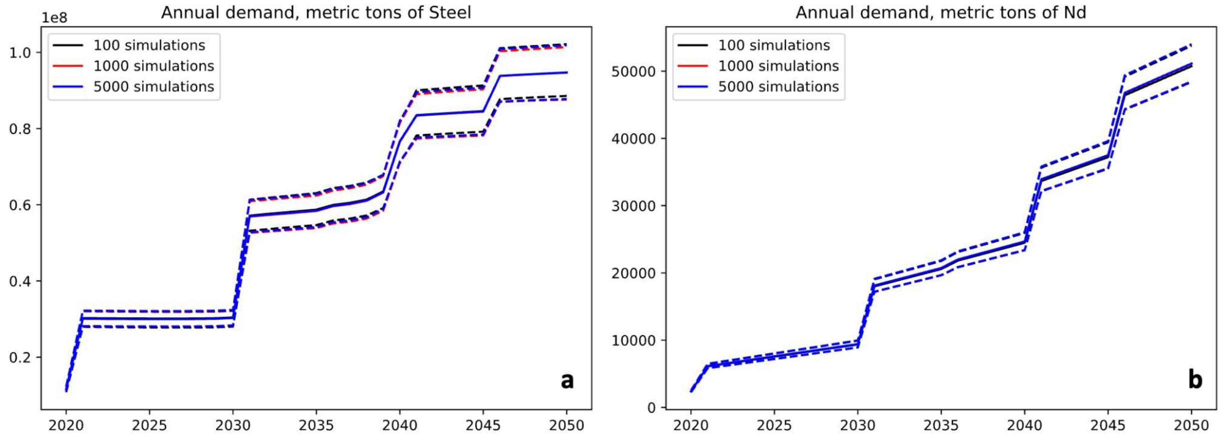
Supplementary Figure 1: Probability density functions showing probability distributions of cumulative 2020-2050 power sector copper and aluminum requirements for a selection of 75 integrated assessment models, categorized by **a, b,** end-of-century category of global mean warming outcome, **c, d,** by share of combined wind and solar capacity as a percentage of total electricity generation capacity in 2050, and **e, f,** by modeling group.



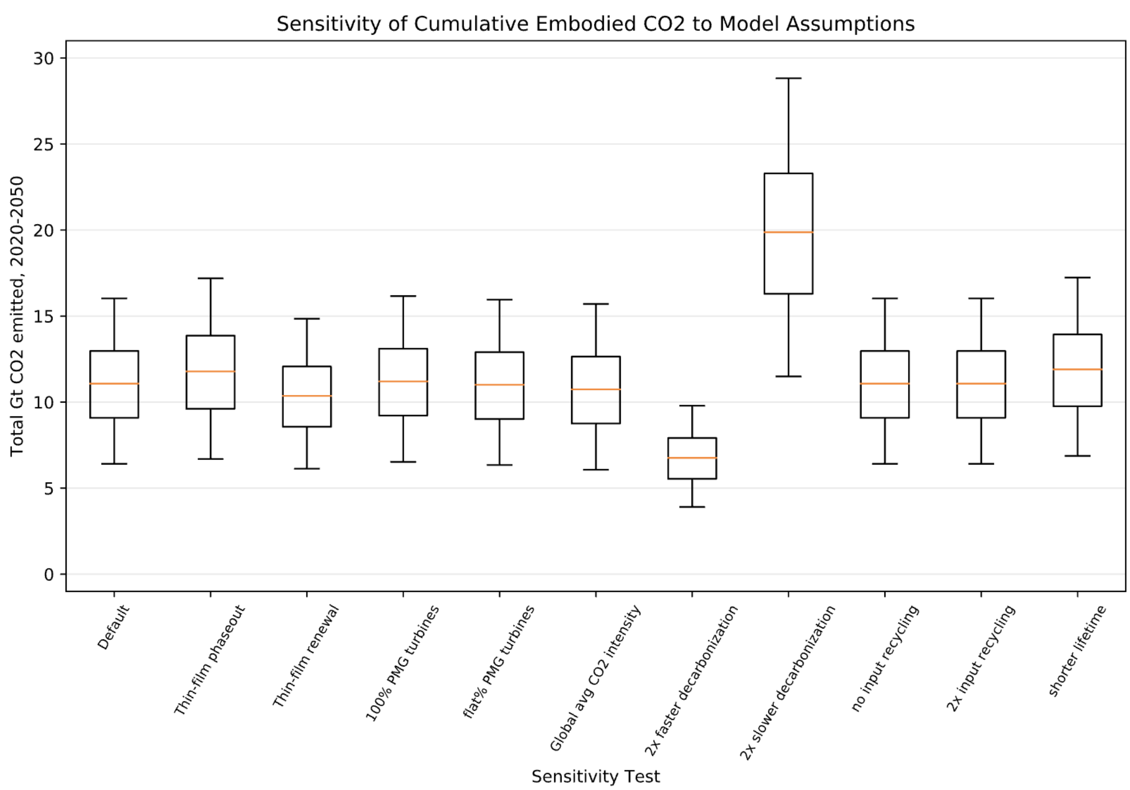
Supplementary Figure 2: Schematic diagram showing model framework and organization.

	Al	Cement	Cu	Steel
median LED consumption	279.0 (56.8)	1033.3 (136.6)	88.0 (6.0)	1606.1 (68.2)
grand median of all scenarios besides LED	109.2 (76.2)	905.4 (323.8)	37.8 (24.3)	1026.2 (758)
grand median of all 1.5C scenarios besides LED	203.7 (82.5)	1303.7 (379.7)	69.0 (25.0)	1849.3 (642.9)
grand median of all other 1.5C scenarios w W+S >40%	247.8 (68.6)	1326.1 (332.2)	79.7 (21.4)	1996.3 (584.3)
grand median of all other MESSAGE-GLOBIOM 1.0 scenarios	101.0 (58.6)	1111.9 (400.8)	33.6 (17.8)	1148.0 (364.9)
units	Mt	Mt	Mt	Mt

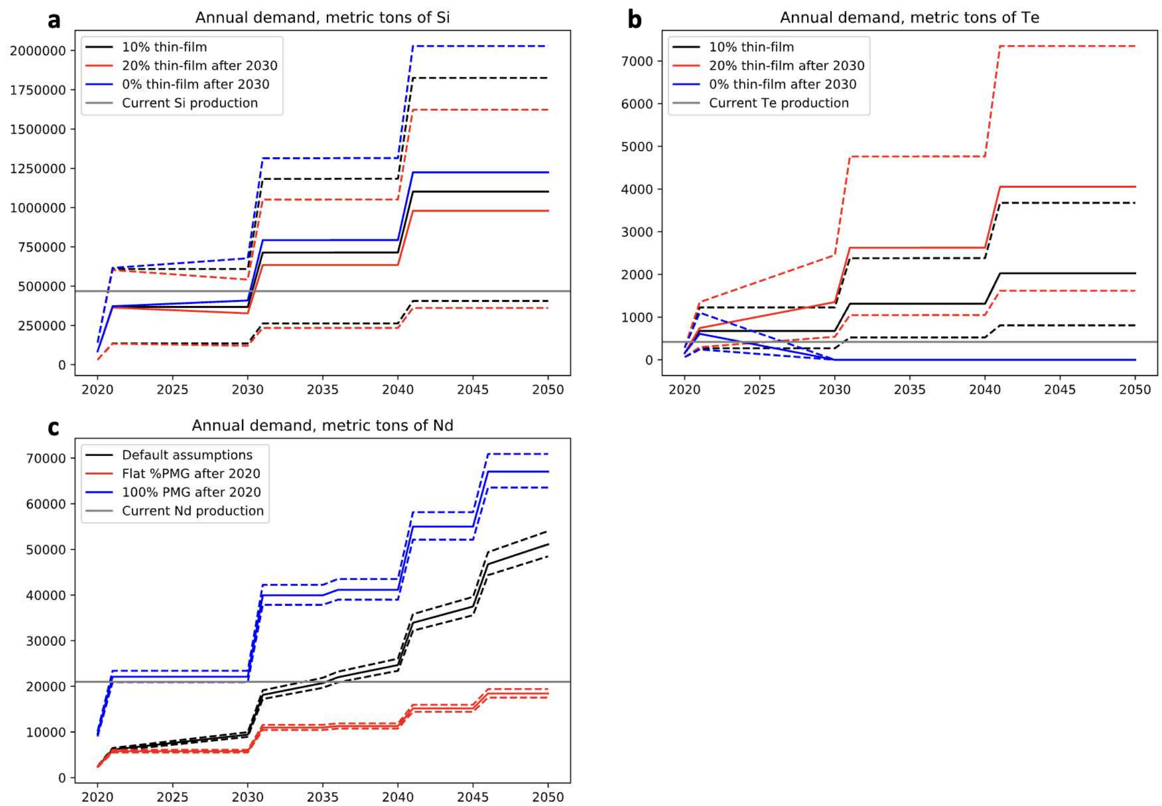
Supplementary Table 2: Comparison of cumulative 2020-2050 material demand for aluminum (Al), cement, copper (Cu), and steel under the Low Energy Demand (LED) scenario relative to other groups of scenarios tested.



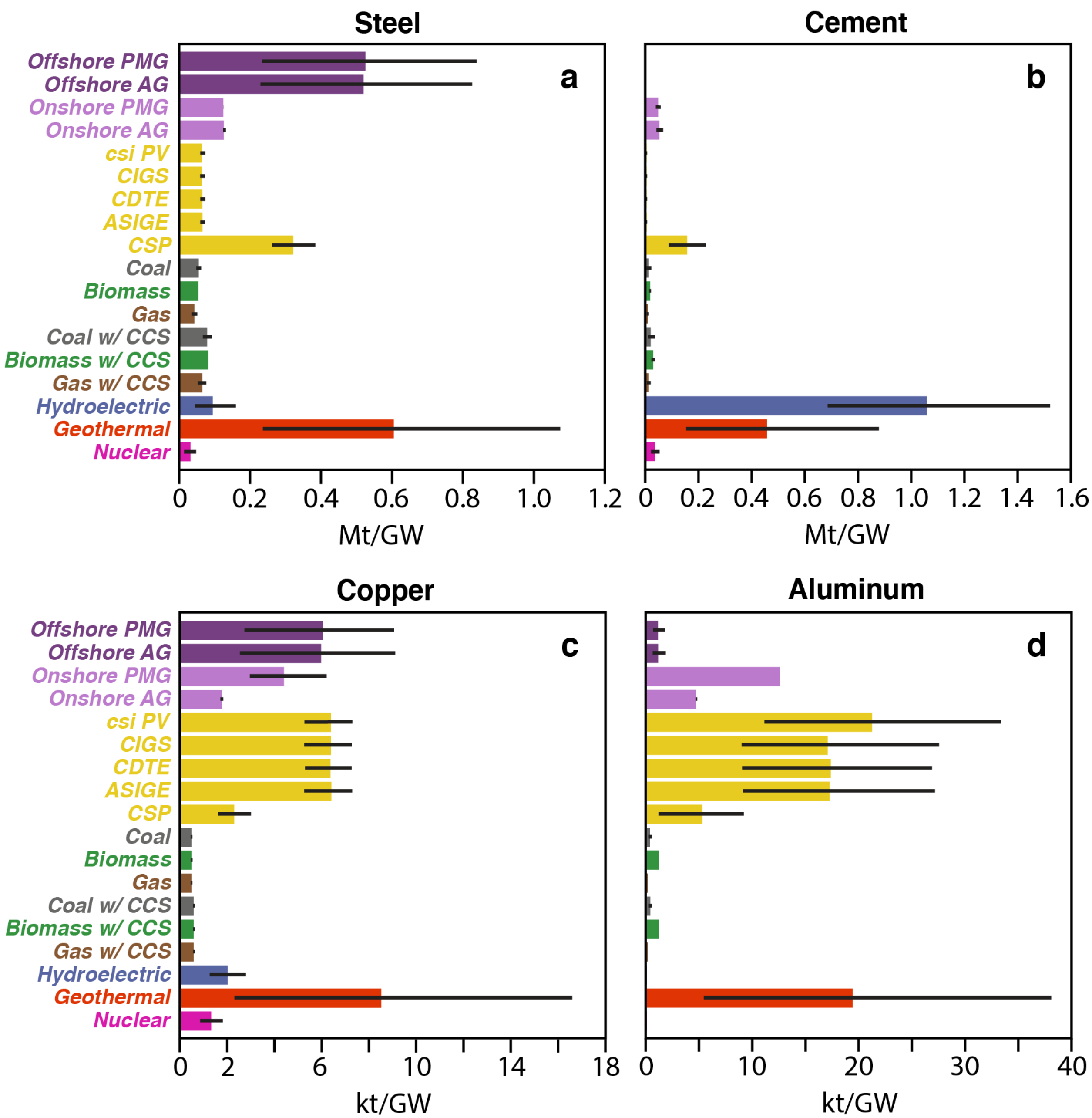
Supplementary Figure 3: Time series plots of annual power sector demand for **a,** steel, and **b,** neodymium under modeling runs with different numbers of Monte Carlo simulations (100, 1000, and 5000). Solid lines show median annual demand values, while dashed lines show extent of 2.5th percentile and 97.5th percentile annual demand values.



Supplementary Figure 4: Box-and-whisker plots of cumulative 2020-2050 power generation materials-associated CO2 emissions under varying model assumptions using the MESSAGE-GLOBIOM SSP1 1.9 scenario. Gold lines show median values. Boxes are drawn between the upper and lower quartiles. Whiskers denote extent of 2.5th percentile and 97.5th percentile values. See Methods for detailed description of assumptions employed for the sensitivity tests shown.



Supplementary Figure 5: Time series plots of annual power sector demand for **a,** solar-grade polysilicon, **b,** tellurium, and **c,** neodymium under different technology assumptions for **a, b** thin-film solar PV technologies and for **c,** wind turbine drive technologies. Horizontal grey lines represent current global annual production rates for each material. Solid lines show median annual demand values, while dashed lines show extent of 2.5th percentile and 97.5th percentile annual demand values.



Supplementary Figure 6: Barplots of material intensity for four selected bulk materials. **a,** steel **b,** cement **c,** copper **d,** aluminum for each generation technology, expressed in tons per GW of electricity generation capacity. Black whiskers denote extent of 2.5th percentile and 97.5th percentile values.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryFile2CO2intensityspreadsheet.xlsx
- SupplementaryFiguresandTables.docx
- SupplementaryFile1Materialintensities.xlsx