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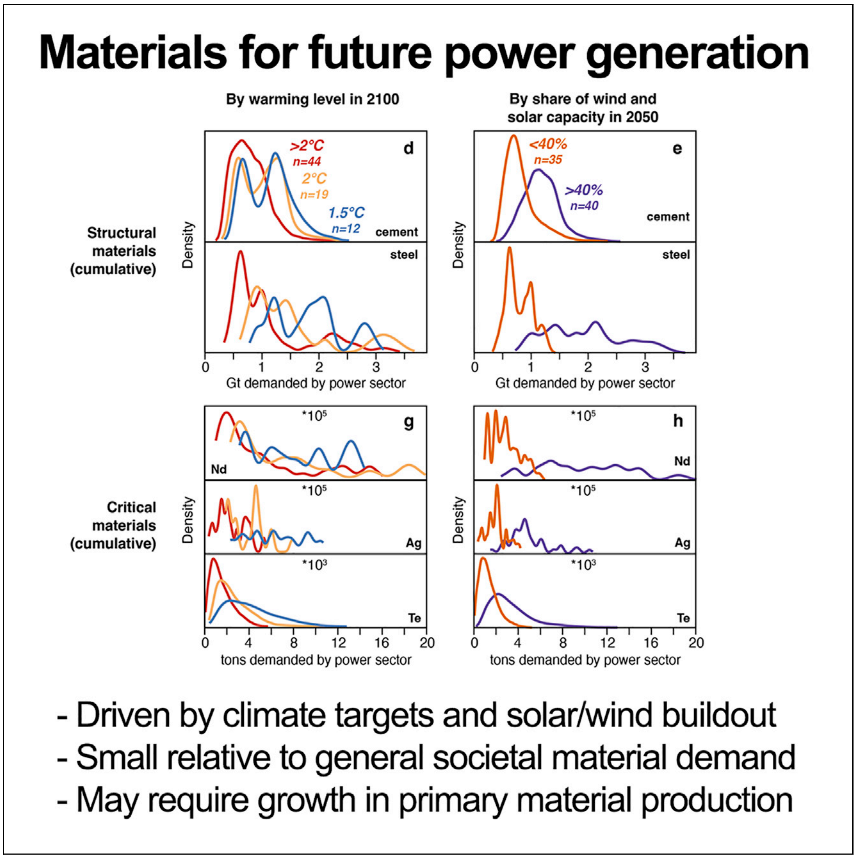

How many tons of steel, copper, silver, rare earth metals, and other materials are needed to build power generation facilities over the next 30 years? This study estimated future global material needs for electricity-producing infrastructure across a wide range of scenarios. While wind and solar energy require materials in high quantities, we find these technologies will not be limited by the availability of key metals and materials. However, increasing material demand may require more material production to meet estimated needs.

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Highlights

Material production must expand to meet future power generation material needs

Geologic reserves of materials are sufficient to meet all projected future demand

The magnitude of material needs scales directly with wind and solar deployment

Emissions impacts of material production are non-negligible, but limited in magnitude

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Future demand for electricity generation materials under different climate mitigation scenarios

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SUMMARY

Achieving global climate goals will require prodigious increases in low-carbon electricity generation, raising concerns about the scale of materials needed and associated environmental impacts. Here, we estimate power generation infrastructure demand for materials and related carbon-dioxide-equivalent (CO_2eq) emissions from 2020 to 2050 across 75 different climate-energy scenarios and explore the impact of climate and technology choices upon material demand and carbon emitted. Material demands increase but cumulatively do not exceed geological reserves. However, annual production of 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 consume only a minor share of global carbon budgets (1%–9% of a 320 Gt CO_2eq 1.5°C 66% avoidance budget). Our results highlight how technology choices and mitigation scenarios influence the large quantities of materials mobilized during a future power sector decarbonization.

CONTEXT & SCALE

Global decarbonization of the electricity generation sector over the next three decades will necessitate the construction of substantial new infrastructure such as wind and solar farms, hydroelectric generating stations, and nuclear power plants. Such infrastructure contains substantial quantities of materials, from bulk commodities like steel and cement to specialty metals like silver and rare earth metals. Our estimates of future power sector generation material requirements across a wide range of climate-energy scenarios highlight the need for greatly expanded production of certain commodities. However, we find that geological reserves should suffice to meet anticipated needs, and we also project climate impacts associated with the extraction and processing of these commodities to be marginal. Due to varying material intensity of different power generation technologies, technological choices strongly influence the spectrum of future material requirements.

INTRODUCTION

In the coming decades, human societies must make deep reductions in greenhouse gas (GHG) emissions to meet international climate goals. As the largest source of current emissions,[1] fossil fuel electricity generation will require replacement by non-emitting technologies, with further clean generating capacity added to meet expected growth in global electricity demand. Decarbonization will drive electrification of transportation, buildings, and industry, with most climate mitigation scenarios produced by global integrated assessment models (IAMs) and energy system models predicting considerable growth in global electricity demand by 2050.[2–5] The required pace for installing new non-emitting power generation infrastructure accelerates with progressively more ambitious climate targets. In scenarios that limit global mean warming to 1.5°C above pre-industrial temperatures, future growth of non-emitting generation capacity substantially exceeds historical growth rates in electricity generation capacity.[6]

Sweeping transformation and growth of the power sector will require considerable inputs of emission-intensive raw materials, from critical materials such as rare earth (in particular neodymium [Nd], dysprosium [Dy]) and semi-/precious metals to structural materials such as cement, steel, and fiberglass. Because extraction and processing of some critical materials remains highly concentrated in just one or a handful of countries,[7–10] they possess 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 pose concerns. 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 fugitive methane emissions from coal mines account for much of this carbon, energy consumption for mine activities is estimated to contribute 1% of global fossil emissions (0.4 Gt CO_2e). Process emissions from cement and steel production account for 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 thus raise challenges for policymakers, industry, and environmental activists, potentially impacting 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 required to deploy specific technologies at large scale in specific regions[17–25] or to deploy a wider range of technologies globally.[7,26–37] However, most papers estimate future potential material requirements for just a handful of power sector decarbonization scenarios or pathways.[7,26,28,29,31–33,35–37] One recent study does evaluate power sector material demand and associated emissions for hundreds of IAM scenarios but does this only for four bulk materials (iron [Fe]/steel, aluminum [Al], copper [Cu], and concrete).[38] Generally, the existing literature has not taken this additional step to quantify the emissions associated with the materials used to build non-emitting power generation infrastructure at global scales.

Here, we estimate requirements for 15 critical, structural, and bulk materials needed to build new electricity-generating infrastructure between 2020 and 2050 in 75 different IAM mitigation scenarios taken from the SR15 database (Data S1), which aim to limit the increase in global mean temperatures to ~2°C above pre-industrial temperature or less. We use deployment projections for different energy technologies from the IAM scenarios and ranges of material intensities from the literature to estimate future material demands. Evaluating such a wide range of scenarios can provide insight into the sensitivity of future material demands to differences in technology choices, climate targets, and modeling group assumptions.

We also estimate CO_2 emissions associated with calculated material demands in these scenarios. We then compare future material demand patterns to current raw material production rates, historic production growth rates, and estimates of present-day global reserves and resource potential. Similarly, we compare cumulative CO_2 emissions associated with material needs—using 100-year global-warming-equivalent values—with the estimated carbon budgets linked to different temperature targets.

RESULTS AND DISCUSSION

Patterns of material demand and material-associated emissions across scenarios

More ambitious climate scenarios show higher demand for materials in new power sector generation infrastructure from 2020 to 2050, leading to higher cumulative material-associated GHG emissions (Figure 1). However, these added material-associated emissions are more than offset in aggressive mitigation scenarios by accelerated rates of decarbonization that result in lower overall warming.

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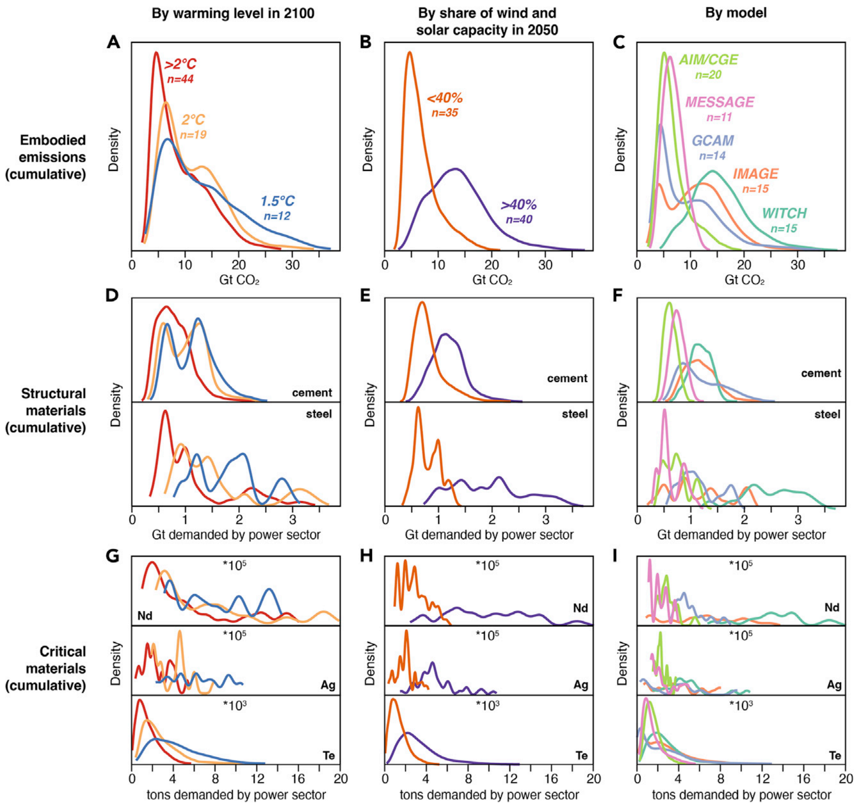

Figure 1. Probability distributions of materials used for power sector generation infrastructure in global mitigation scenarios

(A–C) Probability density functions showing probability distributions of (A)–(C) cumulative 2020–2050 materials-associated CO_2eq emissions.

(D–F) Cumulative 2020–2050 power generation steel and cement requirements.

(G–I) Cumulative 2020–2050 power generation 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.

In nearly all cases (84th percentile and below), cumulative material-associated emissions in 1.5°C mitigation scenarios amount to <20 Gt CO_2eq, or half a year's global GHG emissions at current rates. The 1.5°C mitigation scenario with the highest cumulative material-associated emissions yields 37 Gt CO_2eq, about 1 year's current global GHG emissions, while the 2.5th–97.5th percentile range of estimates for 1.5°C scenarios spans 4–30 Gt CO_2eq (median of 12 Gt). This is comparable to a range of estimates in Kalt et al. for cumulative 2021–2050 emissions associated with bulk use of steel/Fe, concrete, Al, and Cu in the electricity system (5–55 Gt CO_2eq).[38]

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 CO_2, respectively.[39,40] Cumulative emissions associated with deployment of new power sector generation infrastructure 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. We do note that carbon emissions required to achieve full societal decarbonization will be larger when considering equipment and infrastructure needed to decarbonize other sectors such as transportation, buildings, industry, and agriculture.

IAM scenarios only coarsely account for industrial sector emissions, without explicitly considering the material requirements of deployed clean technologies or their associated emissions footprint. If current modeling approaches are consequently underestimating future industrial sector emissions, this may marginally reduce carbon budgets in practice. For instance, a materials-related carbon footprint of 30 Gt CO_2eq would represent 14% of cumulative 2020–2050 industry-related CO_2 emissions in the MESSAGE-GLOBIOM SSP1-1.9 scenario (219 Gt CO_2eq), or 46% of cumulative industry-related emissions in the AIM/CGE 2.0 ADVANCE_2020 1.5C-2100 scenario (66 Gt CO_2eq), but to a first order, the emissions embodied in materials for electricity-generating infrastructure under mitigation scenarios (4–30 Gt CO_2eq) do not pose a major threat to remaining 1.5°C carbon budgets (320–420 Gt CO_2eq).

Overall raw material demand and material-associated emissions are heavily driven by wind and solar technology trends. In Figure 1, differences in Nd, silver (Ag), and tellurium (Te) demand across groups of scenarios reflect varying deployment of wind turbines, silicon-based solar photovoltaic (PV) technology, and thin-film solar PV technology, respectively. 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 such specialty materials but also for structural bulk materials like cement and steel (Figure 1) and Cu and Al (Figure S1). Scenarios with higher wind and solar generation in 2050 also produce greater material-related emissions (Figure 1), due to the higher material requirements of these technologies per unit capacity and in particular due to the considerable carbon footprint of solar-grade polysilicon.

In 1.5°C scenarios, most material-related emissions are associated with solar-grade polysilicon (median: 7.2 Gt CO_2eq, 2.5th percentile to 97.5th percentile: 1.8 Gt CO_2eq to 23.8 CO_2eq), steel (1.6, 0.8–2.8 Gt), Al (1.2, 0.4–2.4 Gt), and cement (0.6, 0.3–1.1 Gt). The combined sum of emissions associated with nickel (Ni), Nd, Ag, Dy, manganese (Mn), Te, indium (In), gallium (Ga), cadmium (Cd), and selenium (Se) over the modeled period amounts to <1 Gt CO_2eq in essentially all scenarios.

Patterns of material demand and material-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 much higher wind deployment between 2020 and 2050 compared with other models, increasing both power sector demand for materials and material-associated carbon emissions. We note that the low energy demand (LED) scenario,[3] which assumes markedly reduced global final energy demand, excludes carbon capture and carbon dioxide removal (CDR) technologies from deployment, and undertakes mitigation efforts consistent with a 1.5°C target, does not produce lower material demand than other scenarios (Table S3). The LED scenario actually shows high demand for Al and Cu 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, high assumed wind and solar deployment, and avoidance of negative emission technologies. Note however that this comparison is somewhat incomplete, as we do not assess material requirements for CDR technologies in this study, which would increase the material demand associated with non-LED scenarios in practice.

Proactive policies and technology shifts to decarbonize the heavy industrial sector will reduce the climate footprint of electricity-sector decarbonization. Materials for power sector infrastructure in some 1.5°C scenarios produce the bulk of cumulative

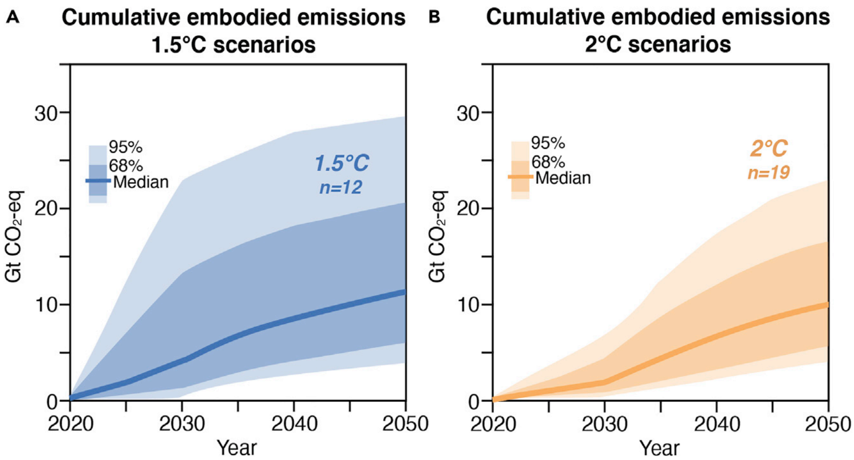

Figure 2. Time series of cumulative power-generation-material-associated CO_2 emissions
(A and B) Cumulative material-associated CO_2 emissions from 2020 to 2050 in metric tons for (A), 1.5°C end-of-century warming scenarios and (B), 2°C end-of-century warming scenarios. The solid lines denote the median. The dark shaded areas show the one-sigma range (16th–84th percentile), while the light shaded areas show the two-sigma range (2.5th–97.5th percentile) across scenarios.

embodied emissions by 2030 (Figure 2). Even modest progress toward industrial decarbonization in the next several years could yield compounded benefits in terms of avoided GHG emissions as global heavy industry mobilizes to build clean generation infrastructure and other clean technologies.

Potential material constraints due to production challenges

For many of the materials investigated, demand from new clean power generation infrastructure will consume a considerable proportion of total global production. At the peak pace of a 1.5°C-consistent scenario, for instance, Ag demand for solar panels might require ~10% of current world production. Future Al and Cu demand for power sector infrastructure could require ~18% of current production. CuInGaSe (CIGS) thin-film solar could strain supply chains for In and Se even if CIGS thin-film is installed at a relatively low percentage of overall future solar PV capacity (2%).

Yearly demand for solar-grade cover glass and for fiberglass composites used in wind turbine blades could require over a fifth of current global flat glass manufacturing capacity and most of glass fiber production. This is an imprecise assessment, as 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 heavily influence these supply chains is intriguing.

For some materials (Dy, Nd, solar-grade polysilicon, or Te), 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 Te 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 International Energy Agency (IEA), which projects a 3- to 7-fold increase in demand for the rare earth metals (the IEA scenario also includes rare earth demand from electric vehicles) and a 2-fold increase in polysilicon demand between 2020 and 2040.[7]

Table 1. Maximum annual demand for each material in power sector generation infrastructure during the 2020-2050 period across scenarios, compared to current annual production rates

	Units	1.5°C max annual demand	2°C max annual demand	Current annual production	Median 1.5°C max annual demand as % of current production
Aluminum	Mt	11.4 (5.62–20.7)	7.21 (3.23–21.8)	68	16.8%
Cement	Mt	71.4 (30.7–105)	52.8 (22.9–137)	4,400	1.6%
Copper	Mt	3.64 (2.07–6.25)	2.30 (1.24–6.55)	26	14.0%
Fiberglass	Mt	3.16 (1.32–6.63)	2.03 (0.904–6.70)	4.76	66.4%
Glass	Mt	20 (13.2–55)	12.4 (6.16–35)	100	20.0%
Manganese	Mt	0.0372 (0.00989–0.848)	0.0563 (0.0103–0.385)	20	0.2%
Nickel	Mt	0.167 (0.0648–0.292)	0.112 (0.0433–0.301)	2.7	6.2%
Solar-grade polysilicon	Mt	1.14 (0.379–3.15)	0.620 (0.193–2.40)	0.750	152%
Steel	Mt	87.2 (54.6–251)	63 (32.2–220)	1,870	4.7%
Cadmium	t	1,910 (715–5,240)	1,040 (365–3,940)	24,000	8.0%
Dysprosium	t	5,570 (2,090–13,700)	3,640 (1,410–13,300)	1,800	309.4%
Gallium	t	38 (16–97)	21 (8–75)	555	6.8%
Indium	t	113 (52–288)	62 (26–224)	920	12.3%
Neodymium	t	57,000 (23,100–121,000)	38,300 (16,100–123,000)	21,000	271.4%
Selenium	t	520 (171–1,500)	282 (88–1,130)	3,300	15.8%
Silver	t	2,970 (2,100–7,560)	1,840 (1,050–5,100)	25,000	11.9%
Tellurium	t	2,160 (756–6,110)	1,170 (386–4,610)	580	372.4%

Variability in maximum yearly demand (median, then 2.5th percentile value to 97.5th percentile value) for each material due to deployment of new power generation infrastructure, under 1.5°C end-of-century warming scenarios and 2°C end-of-century warming scenarios, relative to current global annual production of each material. t, metric tons; Mt, million metric tons.

Our overall results align well with other studies.[27,32,34,36,38,41] Our values for cumulative power sector generation infrastructure demand for steel, Al, and Cu are around half the magnitude of estimates obtained in a similar study by Kalt et al.,[38] a difference likely resulting from our commensurately lower estimated material intensities for solar, wind, and nuclear generation and differences in study boundaries. Our range of maximum annual power sector demand for bulk and specialty materials is comparable to estimates in other studies (60–80 Mt/year of steel; 15 Mt/year of Al; 5–7 Mt/year of Cu; 80,000 t/year of Nd; 4,000 t/year of Ag; 3,000 t/year of Te).[32,36] Such similarities likely result from similar material intensity estimates and assumed clean power infrastructure deployment rates.

Whether society can meet future material demands for new power sector generation infrastructure also depends on whether projected growth in material requirements outpaces historical growth in raw material production. We estimate that median future 10-year growth rates for Cu, solar-grade polysilicon, Ga, In, Se, Ag, and Te demand will exceed their respective average historical (1946–2018) 10-year growth (Table S1). In particular, growth in solar-grade polysilicon, Ga, In, and Te demand might considerably outpace historical precedent.

Importantly, Cd, Ga, In, Se, and Te are not mined directly but extracted as byproducts of mining that primarily targets other minerals. As such, the future availability of these byproducts partly depends on production of the primary resource. Te and Se are mostly produced as byproducts of Cu mining and processing,[42,43] Cd and In are byproducts of zinc (Zn) processing, and Ga is produced from bauxite mined primarily for Al.[43]

We find that byproduct production via anticipated growth in demand for primary metals should meet power sector generation infrastructure demands for Cd, Ga, In, and Se, but not Te (Table S2). This result may be pessimistic, as higher future demand for byproducts could incentivize unprecedented improvements in extraction technology and investment in byproduct production.

Overall, these results highlight how limited Te availability could restrict CdTe thin-film deployment. Assuming continued growth in Cu production based on historical trends, then adding projected power generation infrastructure needs, today's rates of byproduct production of Te from Cu ore processing imply annual production of up to 958 tons/year by 2050 (Table S2). This would support an upper-end deployment rate of 50.4 GW/year of CdTe thin-film solar, about 9–10 times the total production of CdTe modules in 2020.[44] With some scenarios implying solar PV deployment rates of 700 GW/year in the 2030s and 2040s, this suggests that Te production limits CdTe thin-film solar to ~7% of future solar deployment. This would be insufficient to meet this study's assumption of CdTe solar making up 8% of future solar deployment, which is admittedly larger than its share in recent years.[20,45–47] In practice, this share could remain low, or future CdTe arrays might utilize less Te.

Sufficiency of geologic reserves

Current global reserves of critical materials are likely adequate, as future demand from electricity generation infrastructure does not exceed existing resources over the next 30 years, with the possible exception of Te (Table 2). In 1.5°C scenarios, median cumulative Te demand consumes ~88% of estimated Te resources. Although we do not explicitly assess availability of bulk materials, raw materials are not likely to limit steel, concrete, fiberglass, glass, or polysilicon availability.

Cumulative demand for some critical materials does require a non-negligible share of current reserves. Median 2020–2050 total Cu demand is 81.8 million tons, >10% of estimated reserves of 790 million tons. Similarly, electricity generation infrastructure under 1.5°C scenarios could consume >10% of current global Ag reserves, ~7.5% of Cd reserves, ~7.9% of Dy reserves, >15% of In reserves, >7% of Nd reserves, ~5% of Ni reserves, and ~10% of Se reserves. As many materials, such as rare earth metals, are employed across numerous technologies from electric vehicles to drones to aircraft, increasing demand from the power sector over coming decades could strain economy-wide supply chains and impact commodity and energy project costs. For instance, the IEA projects annual Cu demand in the electric vehicle and battery storage sectors to reach 1.1–3.3 million tons per year by 2040.[7]

Ultimately, growth rates in mineral production and changing estimates of economically recoverable mineral reserves depend on not just geology, but also commodity prices, demand, and extraction techniques. For byproduct commodities, production and reserves depend on demand for the primary mineral and other co-products in addition to the byproduct in question.

Historically, mineral markets have adjusted to accommodate growing demand over time. For instance, the ratio between reserves and production for both Cu and Ni has remained relatively stable from 1980 to 2010.[48] Increases in raw material prices may

Table 2. Comparison of cumulative 2020–2050 power sector generation infrastructure material demand to current estimates of existing reserves and resources for each material of interest

	Units	1.5°C cumulative demand, 2020–2050	2°C cumulative demand, 2020–2050	Estimated reserves	Estimated resources
Aluminum	Mt	241 (110–380)	141 (58.4–310)	30,000	75,000
Cement	Mt	1,300 (683–2,050)	1,120 (562–1,820)	N/A	N/A
Copper	Mt	81.8 (40.8–109)	49.5 (23.7–100)	880	3,500
Fiberglass	Mt	69.5 (22.5–99.6)	37.7 (15.4–135)	N/A	N/A
Glass	Mt	446 (234–756)	280 (113–525)	N/A	N/A
Manganese	Mt	0.892 (0.167–7.60)	1.26 (0.155–44.9)	150	1,730
Nickel	Mt	3.80 (1.11–4.70)	2.13 (0.901–6.28)	95	300
Solar-grade polysilicon	Mt	22.5 (7.21–48.9)	11.8 (3.45–33.2)	N/A	N/A
Steel	Mt	1,960 (1,100–2,950)	1,330 (724–3,360)	N/A	N/A
Cadmium	T	37,700 (13,700–82,300)	20,000 (6,410–55,000)	500,000	6,000,000
Dysprosium	T	87,200 (32,900–159,000)	53,400 (22,000–203,000)	1,100,000	1,980,000
Gallium	T	771 (312–1,470)	414 (146–1,060)	110,000	1,000,000
Indium	T	2,280 (976–4,430)	1,230 (454–3,090)	15,000	47,000
Neodymium	T	929,000 (360,000–1,390,000)	546,000 (251,000–1,890,000)	12,800,000	23,000,000
Selenium	T	10,100 (3,310–23,800)	5,350 (1,570–15,600)	100,000	171,000
Silver	T	67,600 (36,900–106,000)	45,100 (19,300–79,100)	530,000	1,310,000
Tellurium	T	42,300 (14,600–95,900)	22,300 (6,730–63,700)	31,000	48,000

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 2°C end-of-century warming scenarios. t, metric tons; Mt, million metric tons.

disincentivize adoption of certain technologies or encourage raw materials substitution, decreasing long-term demand. Alternatively, rising material prices might incentivize new exploration and technical advances, expanding production to support increases in demand.

Materials intensity and material-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 Al (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 (Nd and Dy), critical minerals for thin-film solar (Cd, In, Se, and Te), common metals for electronics applications (Cu and Ni), and other bulk commodities (flat glass in solar modules and fiberglass composites in wind turbine blades) account for a small to negligible quantity of the carbon emissions associated with materials used in power generation infrastructure.

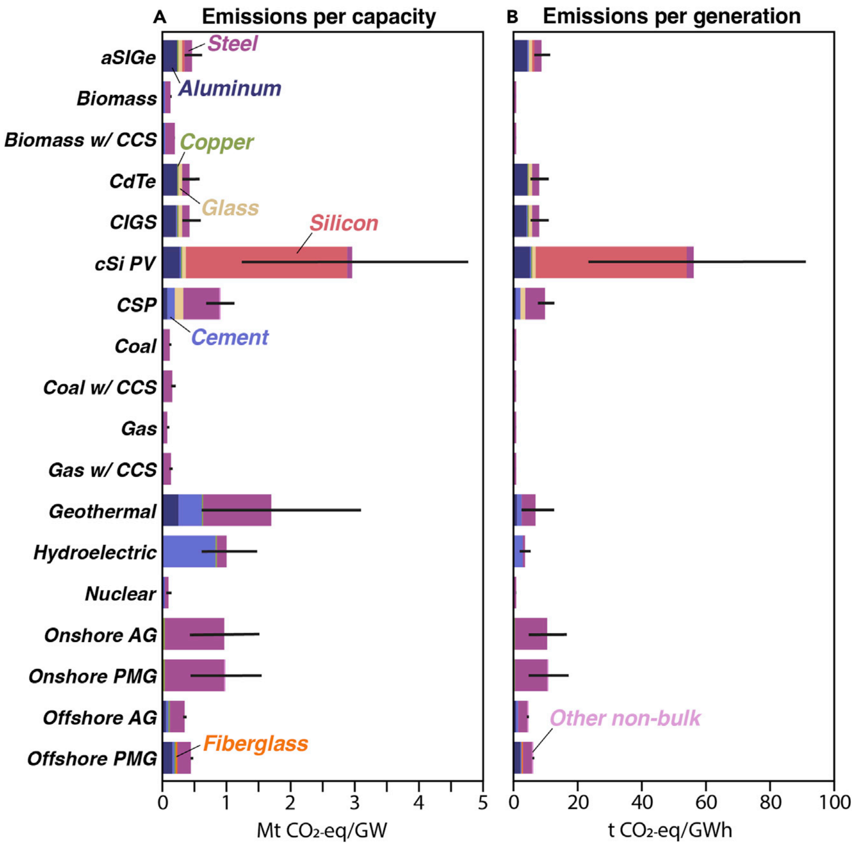

Figure 3. Material-related carbon intensity of electricity generation infrastructure

(A and B) For each electricity-generating technology, bars show CO_2eq emissions per unit of (A) generating capacity (B) and electricity generated, colored by material. Black whiskers reflect the range of total carbon intensities spanning the 2.5th–97.5th percentiles. aSiGe, amorphous silicon germanium thin-film solar; CdTe, cadmium telluride thin-film solar; CIGS, copper indium gallium selenide thin-film solar; cSi PV, crystalline silicon solar photovoltaic; CSP, concentrating solar power; AG, asynchronous gearbox wind turbine drive; PMG, permanent magnet gearbox wind turbine drive.

The higher material requirements of solar, wind, hydro, and geothermal generation (Figure 4), result in higher material-associated carbon emissions for these technologies (Figure 3), due to greater steel and concrete needs and the high carbon intensity of solar-grade polysilicon. 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 material-associated carbon emissions of solar and wind generation relative to other technologies due to their lower capacity factors.

These findings reemphasize the importance of decarbonization of the global steel and cement sectors, given that these industries make up much of the material-associated carbon cost of new electricity generation infrastructure. The high carbon footprint of solar-grade polysilicon, caused by the dominance of 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. Developing alternative, less energy-intensive industrial pathways for raw material production can reduce the climate and environmental impacts associated with these supply chains.

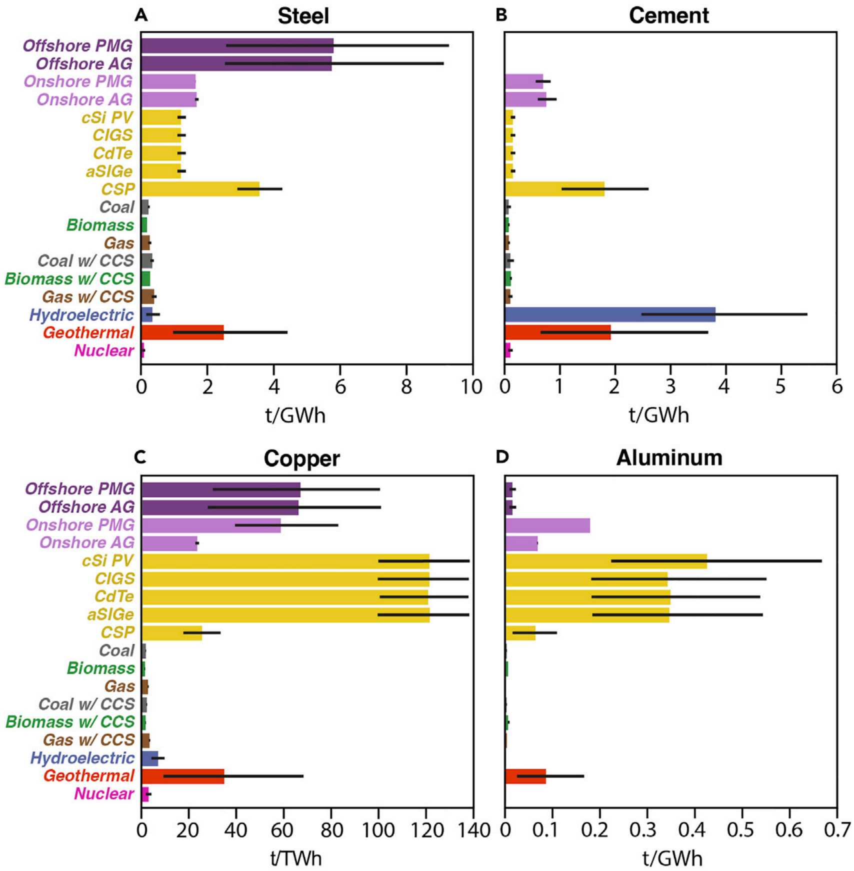

Figure 4. Material intensity of four selected bulk materials

(A–D) (A) Steel, (B) cement, (C) Cu, and (D) Al in each generation technology, expressed in tons per unit of electricity generation (t/GWh or t/TWh). Black whiskers reflect the range of total intensities spanning the 2.5th–97.5th percentiles. PMG, permanent magnet gearbox wind turbine drive; AG, asynchronous gearbox wind turbine drive; cSi PV, crystalline silicon solar photovoltaic; CIGS, copper indium gallium selenide thin-film solar; CdTe, cadmium telluride thin-film solar; aSiGe, amorphous silicon germanium thin-film solar; CSP, concentrating solar power.

Transmission and distribution infrastructure

Transmission and distribution networks will drive added demand for bulk materials over coming decades but do not meaningfully affect demand for critical materials. Transmission lines, transformers, and substations require significant Al, cement, Cu, and steel, but these requirements are smaller than electricity generation infrastructure needs.

From 2020 to 2050, we estimate that transmission infrastructure drives cumulative demand for Al and Cu that is less than half of that needed for generation infrastructure (Table 3). For cement and steel, cumulative demand in 1.5°C scenarios is around a sixth and a quarter of generation infrastructure needs, respectively. Annually, Al and Cu consumption in transmission networks is less than half of corresponding requirements in power sector generation infrastructure.

These are idealized estimates that do not account for several potentially important sources of error, in particular the varying transmission requirements of different electricity generation technologies. This method likely underestimates transmission material demand for scenarios with a high proportion of wind and solar generation, given

Table 3. Cumulative and max annual 2020–2050 demand for aluminum, cement, copper, and steel in the transmission and distribution network

		1.5°C scenarios		2°C scenarios			
	Units	Cumulative demand, 2020–2050	Max annual demand (Mt/year)	Cumulative demand, 2020–2050	Max annual demand (Mt/year)	Current production rate	Median 1.5°C max annual demand as % of current production
Aluminum	Mt	97.6 (42.5–204)	4.10 (1.88–10.5)	70.0 (27.2–216)	3.13 (1.46–15.6)	68	6.0%
Cement	Mt	208 (90.3–434)	8.72 (3.99–22.4)	149 (57.9–461)	6.65 (3.11–33.2)	4,400	0.2%
Copper	Mt	29.9 (13.0–62.4)	1.26 (0.57–3.22)	21.4 (8.33–66.3)	0.96 (0.45–4.78)	26	4.8%
Steel	Mt	495 (215–1,033)	20.8 (9.50–53.3)	355 (138–1,100)	15.8 (7.42–79.2)	1,870	1.1%

Values are 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 2°C end-of-century warming scenarios. Mt, million metric tons.

the more geographically distributed nature of solar and wind parks relative to current systems built around central power stations. As such, this component of our analysis merely seeks to provide an approximate sense of the scale of transmission network material demand relative to power generation infrastructure material demand.

Key limitations

Our model calculates material demand and material-associated emissions for new generation infrastructure but does not include material requirements and emissions associated with fuel production, parts manufacturing, construction, fuel combustion, operations, and decommissioning and end-of-life processes (Figure S2). Similarly, the embodied emissions per ton of material reflect a cradle-to-factory-gate scope that incorporates emissions associated with mining, ore processing, and refining, but not the manufacturing of finished parts or the end-of-life phase.

Our study's results may consequently underestimate true raw material requirements, while our selected materials of interest is also not comprehensive. Our simplistic separate estimate of material requirements associated with off-site transmission and distribution, which may require sizable quantities of Cu, steel, cement, and Al,[36,49] omits much of the transmission grid's real-world complexity. Nor does this analysis account for the widespread future deployment of grid-scale battery storage, which may in turn leverage distributed battery capacity from electric vehicles.[36]

We note that requirements for Mn and Ni in power generation infrastructure are inconsistently reported in the literature, partially because these are often constituents of alloyed steels of varying compositions. As such, our projections of Mn and Ni requirements are relatively tenuous. We largely refrain from discussing estimated Mn and Ni demand in detail. The related results are included in the supplemental information.

Sensitivity tests

We conducted sensitivity analyses upon a 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 of raw material requirements, changing deployment assumptions for 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 experimental procedures).

No discernable differences were observed when the model was run using 100, 1,000, or 5,000 Monte Carlo iterations (Figure S3).

Overall, sensitivity testing suggests that our material-associated emissions estimates are relatively insensitive to technology-specific assumptions. Altering the share of thin-film solar deployments did not substantially affect cumulative emissions (Figure S4). Changing the proportion of permanent magnet drive wind turbines deployed, assuming a global versus regional material CO_2 intensity for certain materials and modifying input recycling assumptions similarly produced little effect. Shortening the modeled lifespan of installed wind and solar by 25% also yielded 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 directly affect the material-associated CO_2 footprint of new power sector infrastructure.

Predictably, thin-film and permanent magnet assumptions do significantly affect estimates of demand for specialty materials associated with those technologies (Figure S5). While we have endeavored to make reasonable assumptions regarding the share of thin-film solar types and permanent magnet drive wind turbines in future infrastructure 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.

Conclusions

The large future buildout of new electricity generation infrastructure will require significant raw materials. However, while the minerals and heavy industrial sectors remain relatively carbon intensive, the emissions associated with sourcing raw materials for power sector generation infrastructure represent a small fraction of remaining carbon budgets across all scenarios tested.

Global mineral reserves should adequately meet needs posed by power sector material demand. However, estimated future demand could consume a meaningful fraction of current annual production for many raw materials and may necessitate expansion of global production by severalfold for certain inputs like Nd, fiberglass, Dy, solar-grade polysilicon, and Te. Energy system design affects future material demand, with scenarios that deploy higher shares of wind and solar generation requiring larger quantities of material. Projected needs highlight the importance of proactive efforts to develop new mineral production, particularly considering the long lead times required to establish new supply chains.[7] Public climate policies should support new mineral resource development for clean technologies while enforcing accountability, promoting community and labor engagement, and requiring responsible technical practices to prevent inequitable economic, health, or environmental impacts.[8,10,50,51]

Most material-associated emissions result from the high demand for solar-grade polysilicon, as well as bulk materials such as steel, cement, and Cu that are commonly required across most generation technologies. Proactive industrial sector decarbonization efforts alongside the process of power sector decarbonization can help avoid some of these material-associated emissions.

Recycling and innovation to reduce material demand could play meaningful roles in cutting future requirements for individual raw materials[50] but will not change the overall anticipated increase in material demand. With the power 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. Nevertheless, researchers, policymakers, and industry stakeholders should endeavor to improve material efficiency and recycling practices to marginally reduce future mineral needs.

As this modeling analysis illustrates, estimates of future material demands from clean energy technologies may vary widely across scenarios due to differing assumptions and technology selections. While an increasing number of studies have begun to examine material requirements associated not just with power generation infrastructure but also transmission and distribution networks, energy storage systems, and clean vehicles,[26,35–37,52] approaches that assess material needs for a range of scenarios can help constrain the key drivers and upper and lower bounds of future material demand. With the research community's understanding of the magnitude of future material demand for clean technologies coalescing, a shift in focus to explore the effect of technological improvements, material substitution, recycling, and alternative technological choices can help identify promising solutions.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Information and requests for resources and code can be directed to and will be fulfilled by the lead contact, Seaver Wang (seaver@thebreakthrough.org).

Materials availability

This study did not generate new unique materials.

Data and code availability

Scripts, input files, and output data files are available at Zenodo: https://doi.org/10.5281/zenodo.7023703.

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

We selected electricity generation technologies commonly included in the Integrated Assessment Modeling Consortium (IAMC) 1.5°C Scenario Explorer.[53–55] The IAMC 1.5°C Global time series data snapshot release 2.0 was downloaded from https://data.ene.iiasa.ac.at/iamc-1.5C-explorer/#/downloads. These technologies are 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, as it accounts for a negligible quantity of current and future generation capacity.

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 (PMGs). We broke down the conventional solar PV category into crystalline silicon PV as well as three thin-film solar technologies: Cu In Ga diselenide (CIGS), Cd telluride (CdTe), and amorphous silicon germanium (aSiGe).

Our primary study boundary for material requirements is limited to generation and transformer infrastructure only. We conducted a separate, simplistic estimate of material demand for grid transmission beyond the plant boundaries. This importantly excludes upstream materials associated with fuel extraction and processing and also excludes downstream infrastructure, such as CO_2 pipelines in the case of carbon capture and sequestration (CCS) facilities. Such a study scope imposes some 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 drilling, onshore versus offshore), while the assumed extent of CCS or carbon capture utilization and storage (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 material demand from battery or other energy storage facilities co-located with electricity generation, as IAMC scenarios do not explicitly specify outputs or assumptions corresponding to such storage.

Finally, we selected 17 metals and raw materials for which to estimate global demand and associated carbon emissions over the next 30 years: Ag, Al, Cd, cement, Cu, Dy, fiberglass, Ga, solar cover glass (glass), In, Mn, Nd, Ni, Se, solar-grade polysilicon (denoted as Si), steel, and Te. We qualitatively divide these 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, Cu, fiberglass (a major component of wind turbine blade composites), glass (a major input for solar technologies), solar-grade polysilicon, and steel. The remaining materials (Ag, Cd, Dy, Ga, In, Mn, Nd, Ni, Se, and Te) we designate as "specialty metals."

This is not an exhaustive list of raw materials used in electricity generation technologies. Nevertheless, this selection of materials can provide an illustrative assessment of how expanding 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 published literature. The referenced studies and data values are detailed in (Data S2). 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 factors, although the use of values derived from per-unit-generation figures was minimal and generally avoided. The details of such calculations are provided in Data S2.

Life cycle assessments (LCAs) and calculations for wind and solar technologies were generally only included if published in or after 2010, 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. To use these values, we applied a conversion 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 an assumed range of cement content per cubic meter of concrete. Based on Data S6 of Xi et al.,[56] 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 165–400 kg of cement per cubic meter. We further assume a range of concrete densities of 1,600–2,500 kg/m^3 for concrete of strengths <15–35 MPa.[57]

Thus, to convert from tons of concrete to tons of cement, we calculated a range of concrete volume based on a density range of 1,600–2,500 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 165–400 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 some technology-specific assumptions to resolve uncertainties regarding future technology choices and gaps in material demand estimates. We considered materials estimates for both monocrystalline silicon and polycrystalline silicon PV installations within the broader cSi PV category. For Cu, 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 Bödeker et al.,[58] 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 Cu, Ni, and Mn.

For some technologies, different plant types are considered within the same broader category. Given high uncertainties in the future outlook for CSP solar generation, 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 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. Based on the findings reported in Singh et al.,[59] 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 Cu intensity of a fossil plant with CCS would be 1.2 times that of a plant without CCS. Carbon capture capabilities may be more integrated within some emerging designs such as Allam cycle gas turbines,[60] which could reduce mineral requirements. However, in the case of add-on retrofits, which require lowering a plant's effective net power output or additional off-site power generation to operate add-on carbon capture equipment, our assumptions may underestimate the true extent of material requirements associated with CCS technology.

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

To project future power generation capacity by technology type, we leveraged scenarios from the IAMC 1.5°C Scenario Explorer.[53–55] From this database, we curated a list of 75 models and scenarios for which to calculate future electricity-sector material demand and material-associated emissions, based on several criteria. First, we selected models that projected 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 Shared Socioeconomic Pathway (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 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 (Data S1). 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.7023703.

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 values for 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 fraction of coal (or gas) electricity generated with carbon capture relative to total coal (or gas) electricity generation.

Many scenarios, most notably the SSPs, do not separately break down 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 fractions of solar CSP and offshore wind within all solar and wind deployed in all ADVANCE scenarios from a given modeling group (IMAGE, MESSAGE-GLOBIOM, POLES ADVANCE, and WITCH-GLOBIOM) and assume those same proportions of offshore wind and solar CSP for SSPs produced by that modeling group. For the AIM/CGE 2.0 model, for instance, ADVANCE scenario outputs report zero offshore and zero CSP capacity, so we assume for AIM/CGE 2.0 SSPs that zero wind capacity is offshore wind and that zero solar capacity is solar CSP.

We subsequently adopted 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.[45,61–64] We assume that non-PMG wind turbine capacity is comprised of AG designs.

For PV solar, we assume that c-Si solar stays at a constant 90% of all new capacity added from 2000 to 2050. The remaining 10% is comprised 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,[65] assuming that the future market landscape retains some fraction of thin-film solar PV deployment comparable to patterns observed over the past decade.

Generation capacity for each technology type in each year was linearly interpolated across gaps in the scenario data. While we experimented with cubic and quadratic piecewise polynomial fits, which might produce more realistic deployment patterns compared with the uniform installation rates implied using linear interpolation, we found that nonlinear approaches led to poor fits in many common cases. We calculated the total change in capacity from year to year, additionally implementing a calculation to account for end-of-life retirement of both existing capacity at the start of the model run and new 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:

$$Retirement\ year\ =\ Lifetime\ (years) + year\ of\ installation \qquad \text{(Equation 1)}$$

As the IAM scenario data do not provide capacity data for many generation types prior to 2005, we assume that the 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 follow:

$$Capacity\ retired\ (GW)\ =\ \frac{Capacity\ in\ 2005\ (GW)}{Lifetime\ (years)} \qquad \text{(Equation 2)}$$

This simplifying assumption for the retirement of existing capacity in 2005 has a minimal impact upon the model results, as installed global solar and wind capacity in 2005 is relatively small and requires few mineral inputs to replace. Meanwhile, most retiring fossil infrastructure is not replaced with new fossil infrastructure under these climate-constrained model scenarios.

Not all 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 replaced capacity plus any positive change in total capacity from the prior year.

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 zero retirement for both hydroelectric power and nuclear power, given that these technologies enjoy long service lives with the strong possibility of lifetime extension, such that replacement of existing capacity over the 2020–2050 study period is minimal. In any event, all technology lifetimes are sufficiently long that replacement of new generation capacity of any kind installed after 2020 is relatively minimal during the model period.

Calculation of material demand

Annual material demand for new power generation infrastructure was calculated by multiplying the total new capacity installed that year (new capacity added + replaced capacity) by the material intensities per unit capacity for each generation technology. Calculated material requirements for all newly installed capacity thus account for both replacement of retired capacity and newly installed capacity. Annual material demand for the years 2020–2050 was then summed to calculate cumulative 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 using 1,000 simulations. A triangular distribution of material intensities was created based on the mean, minimum, and maximum of material intensity estimates for a given material and technology. In rare cases, where only a single material estimate was available for a particular material and technology, that estimate was used without assuming a distribution. In each Monte Carlo simulation, one material intensity value for each material of interest was selected from the triangular distribution constructed for that material.

Global raw material production and input recycling rates

Recent global annual production values, current reserves, and global resource potentials for each material were drawn from recent sources, largely from figures presented in Månberger and Stenqvist,[32] Dominish et al.,[41] and from values reported by the US Geological Survey[43] (Data S3). 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 (Data S3).

For projecting utilization of recycled inputs over the study period, we assume that current input recycling rates remain constant between 2020 and 2050. Input recycling of Cd, Dy, fiberglass, Ga, In, Nd, Se, solar-grade polysilicon, and Te is assumed to be zero, 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.

Analysis of material production growth rates and byproduct production

To assess whether projected growth rates in demand for key materials lie within historical precedent, we calculated a simple estimate of future global demand over time for each material. We took current global production of each material and subtracted the total modeled power sector generation infrastructure demand in 2020 to estimate current demand for each material outside the power generation sector. For the years 2030, 2040, and 2050, this 2020 base demand value was scaled into the future using to the average 10-year growth rate in global production of that material over the past 30 years, based on historical global production data from the US Geological Survey.[66] Future modeled power generation sector demand was then added to these values to estimate total global demand in 2030, 2040, and 2050.

We then calculated the resulting 10-year growth rate in demand for each material for each decade (2020–2030, 2030–2040, and 2040–2050). We compared future growth rates for each material against historical average and maximum 10-year growth rates from 1946 to 2018.

We omitted fiberglass and glass from this growth rate analysis due to the scarcity of reliable data regarding historical production of fiberglass and flat glass. In addition, fiberglass for wind turbine blades and solar cover glass are specialty products with a short modern history of industrial-scale production, complicating meaningful comparison against historical production rates. Similarly, solar-grade polysilicon has only achieved mass production within the last two decades. However, historical production figures are readily available for this commodity.[67] As such, we compare future demand for solar-grade polysilicon against the 2010–2020 growth rate in global production, which is approximately 300%. For Dy and Nd, whose individual production rates are not tracked by the US Geological Survey, we compare future growth rates against the historical growth rate for rare earth oxide production as a category.

A number of materials (Cd, Ga, In, Se, and Te) are not mined as primary products but rather produced as byproducts from mines that primarily target commodities such as Cu or Zn. We therefore performed a simple assessment of whether future projected demand for primary metals would drive sufficient byproduct production of these specialty metals. For these five metals, we calculated an average ratio of primary to byproduct production over the past 20 years using historical data.[66] Using this ratio, we estimated future byproduct production from the primary metal, assuming future demand for the primary metal based on its average 10-year production growth rate over the past 30 years, as described above. This is a highly simplified analysis, as a more technically accurate calculation that considers mineral byproduct curves and economics of extraction is beyond the scope of this study.

While a significant fraction of current Ag production occurs as a byproduct of other mineral production, we opted not to analyze Ag as a byproduct mineral. Ag can be mined as a primary metal and is produced as a byproduct from several different ore sources.[43]

Carbon intensity calculations

We compiled cradle-to-gate figures for the per-ton CO_2 intensity of the materials of interest via a literature review (Data S3). For most materials, we assumed a single average CO_2 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 that region's characteristics were assumed for all global production). For many materials, we relied upon global warming potential estimates published in Nuss and Eckelman.[68] Meanwhile, we adopted a region-specific approach for Ag, aluminum, cement, Cu, and steel, as LCAs of production from each major region were more readily available.

All carbon and GHG emissions were converted to kg CO_2eq per ton of material on a GWP100 basis. Note that while comparisons of CO_2eq 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 we assessed is from CO_2 rather than other GHGs.

To calculate material-associated carbon emissions, we multiplied estimated demand for each material by its carbon intensity. For materials where some demand is met with 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 account for changing industrial sector CO_2 intensity, which affects the embodied carbon intensity of each material, we leveraged industrial process emissions reported as an output by 40 models in the IAMC 1.5°C Scenario Explorer. Each of these models is categorized based on the magnitude of global mean warming observed in the year 2100 (1.5°C low overshoot, 1.5°C high overshoot, lower 2°C, higher 2°C, and above 2°C). 1.5°C low overshoot and 1.5°C high overshoot pathways limit median warming to 1.5°C in 2100 with a 50%–67% probability and a >67% probability of temporarily overshooting 1.5°C of warming prior to 2100, respectively. Lower 2°C and higher 2°C scenarios limit 21st century peak warming to below 2°C with >66% and 50%–66% probability.[69] For each category of scenarios based on their end-of-century warming level, we created a time series of the ratio of industrial process emissions in each year relative to a reference year of 2010 (industrial process emissions in 2010 = 1). This ratio generally increases and peaks midway through the 2020–2050 modeling period (with a max value of 1.08 across all scenarios), then declines as the global economy decarbonizes. In each year for each model/scenario, based on that scenario's end-of-century warming category, we scaled material-associated CO_2 emissions using its respective ratio.

Sensitivity analysis

To test the sensitivity of our results to modeling assumptions, we performed sensitivity tests by varying input parameters and assessing the impact of these changes. We performed these tests for a single model, MESSAGE-GLOBIOM 1.0 SSP1 1.9, 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 good assessment of the importance of assumptions around wind and solar technologies and lifetimes in particular.

First, we changed the number of Monte Carlo simulations used to sample material intensity from a distribution for each material and technology, comparing differences when the model was run using 100, 1,000, and 5,000 Monte Carlo simulations.

We also altered assumptions regarding the future share of various solar PV and wind technologies. For solar, we considered a "thin-film phaseout" scenario where 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 where the proportions of CdTe and CIGS solar in new solar PV capacity doubles to 16% and 4% between 2020 and 2030, while c-Si PV declines to 80% of installed solar PV. In both scenarios, these shares are then held constant from 2030 to 2050.

For wind, we modified the proportion of onshore and offshore wind turbines employing permanent magnet drives. In a "100% PMG" scenario, all onshore and offshore wind turbines use permanent rare earth magnet drives after 2020. In contrast, the "flat% PMG" scenario envisions a future where the proportion of onshore and offshore wind turbines using permanent magnets remains constant at 2020 values.

We also varied the CO_2 intensity and decarbonization rate of the raw materials sector, evaluating the effect of assuming a uniform global average CO_2 intensity for each material instead of considering regional CO_2 footprints of materials. We also assessed the impact of doubling and halving the pace of industrial sector decarbonization. We also ran scenarios in which rates of input recycling were either doubled or assumed to be zero.

Finally, we considered the impact of 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.

Transmission and distribution infrastructure material demand

While power transmission and distribution networks are not a primary focus of this study, these systems also require substantial bulk materials. We conducted a simplistic analysis of Cu, aluminum, steel, and cement demand in the future high-voltage transmission system for the 75 models and scenarios we examined, following the approach of Deetman et al..[36] This calculation scales the approximate global high-voltage transmission grid length in 2016 by the ratio of global generation capacity in each year relative to its 2016 value:

$$\textit{Grid length in year } x\ (km) = \textit{Grid length in } 2016\ (km) \times \frac{\textit{Capacity in year } x\ (GW)}{\textit{Capacity in } 2016\ (GW)} \quad \text{(Equation 3)}$$

To estimate material demand of the transmission and distribution network, we multiplied this length estimate by the material intensity per km for high-voltage transmission lines. We also assumed a frequency of transformers and substations per km along with a material requirement for each transformer and substation, and multiplied these factors by the same length estimate.[36]

To convert tons of concrete to tons of cement, we assumed that transmission networks primarily employ concrete with a cement content of 280 kg of cement per m^3 concrete, and a density of 2,400 kg of concrete per m^3 concrete.

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AUTHOR CONTRIBUTIONS

S.W., Z.H., and S.D. designed the study methodology, scope, and approach. S.W., J.L., E.B.O., L.L., and J.M. conducted the detailed background literature review.

S.W. conducted the scenario-based modeling of power sector generation material demand and associated emissions, ensured reproducibility, and led the writing of the main text. J.L. and G.D.N.-M. conducted the scenario-based modeling of transmission infrastructure material demand and associated emissions and ensured reproducibility. S.W., S.D., Z.H., and J.L. produced figures, tables, and graphs for the manuscript. All authors reviewed and edited the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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