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Sub-technology market share strongly affects critical material constraints in power system transitions

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Critical material constraints may limit and guide power system transitions towards net zero. Pathways to mitigate these constraints need to be evaluated and pursued to ensure successful transition. Here, we explore the material constraint mitigation pathways from the perspective of adjusting power generation sub-technology market shares, analysing nineteen critical materials that may cause material constraints. We find that the power generation system transition within China's carbon neutrality scenario results in 52.2 megatonnes of cumulative material demand by 2060, approximately 2.7 times that of the business-as-usual scenario. Solar photovoltaic and wind power sub-technology market shares have the greatest impact on critical material demand. As progressive thin-film solar photovoltaic sub-technologies gain market share, the demand for gallium from solar photovoltaic may increase 56-fold. Material constraints are likely to occur for gallium, terbium, germanium, tellurium, indium, uranium and copper. The importance value is determined by the ratio of power sector to all-sector material demand; the importance value of gallium will increase to 50% due to increases in gallium arsenide and permanent magnet sub-technologies. Our study findings show that sub-technology market shares need to be considered when evaluating future material constraints. Our results provide insights for future research investigating mitigation pathways.

The deployment of renewable energy and low-carbon technologies is necessary for mitigating anthropogenic contributions to global climate change[1,2]. Power systems are major contributors to climate change and are central to a carbon-neutral or net-zero societal transition. This deployment includes renewable electricity power generation from solar photovoltaics (PVs), wind power, and hydropower[3] and the utilization of carbon capture and storage (CCS) when more traditional sources are used[4]. However, greater non-fossil fuel power generation (such as PV and wind power) increases the demand for bulk materials such as iron, copper and aluminium[5,6]. The demand for precious and byproduct metals such as silver (Ag), gallium (Ga), and germanium (Ge) will also increase[7,8]. Many low-carbon transition materials are defined as critical materials. Critical materials are materials of high economic importance and high supply risk[9]. Copper is one such example since it is a material that is difficult to substitute in any power generation system. Future electrified and low-carbon power

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electricity systems are heavily dependent on these materials. Additional material demands from power systems can intensify material constraints that is already facing pressures from a growing population and technological and economic development[6,10]. These material constraints may greatly restrict the power system transition towards net zero[11].

In response to emerging material constraint challenges in a power system transition, existing studies have focused primarily on quantifying critical material demand for a specific renewable energy technology. This quantification has specifically targeted solar PV[8,12,13] and wind power[14–16]. Several studies have also considered various material demands during the global power generation system transition[17–19], as well as in major economies such as China[20–22], the U.S.[23] and the EU[24,25]. These studies identify multiple material constraints and significant supply risks by comparing the material demand from non-fossil fuel power deployment with its current production or reserves. For example, they reported that the global average annual demand for Ge and tellurium (Te) from 2015 to 2050 will be 1176% and 483% of their 2015 production, respectively, under an equal technology adoption scenario for crystalline silicon (c-Si) and thin-film solar cells in 2050[8]. The cumulative demand for Cu, Ga, Ag and Te from the power system transition to meet China's carbon neutrality goal by 2060 will exceed its national reserves[22].

Current studies provide a solid foundation for examining material demands and constraints but rarely investigate pathways to mitigate critical material constraints arising from the transition of power systems towards carbon neutrality. Understanding can be enhanced with a more detailed investigation into further sub-technology. Sub-technology refers to a collection of techniques within a broader technology that have more precise common goals, domains, or functional features. For example, solar PV technology includes sub-technologies such as c-Si solar cells and thin-film solar cells. There are distinct differences in material requirements among different power generation sub-technologies[26] (see *Sub-technologies and corresponding material intensity* of the *Methods* section). Examining the specific sub-technology market share (i.e., the percentage of each sub-technology) scenarios provides a more accurate portrayal allowing for additional and important insights to mitigate critical material constraints[27]. Using the critical material Te as an example, its annual demand can increase ninefold due to variations in the market share of CdTe (Cadmium Telluride) sub-technology[23]. The methodology has been introduced to investigate the impact of sub-technology roadmaps on material demand in power systems, with a focus on solar PV and wind power technologies[26,28,29]. Comparing with these studies, the main advancement in our study is to investigate additional technologies and consider a different scope rather than improvements in the methodology. Our study provides a systematic and holistic analysis of current sub-technologies across the entire power generation system. We also integrate analyses of emerging sub-technologies such as gallium arsenide solar cells (GaAs) and perovskite sub-technologies. These sub-technologies are disregarded by existing studies but will be critical in the future.

We extend our investigations by incorporating the external material demands incurred outside power systems since other non-power sectors can also compete for critical materials[18]. This broader perspective on material demand provides a more holistic evaluation of future critical material constraints. To exemplify this situation, the total neodymium production from 2011 to 2015 was 77.8 kilotonnes (kt) and was able to meet the global wind power technology demand from 2026 to 2030[16]. However, meeting the total neodymium demand across all end-use sectors will be challenging since it is projected to need double the production levels from 2011 to 2015[30]. This depiction is different from most existing studies that evaluate material constraints by comparing the ratio of material demand to material supply (reserve). Some studies have briefly discussed the material demand of low-carbon technologies to all-sector material demand[14,18,28], but they focus only on one or a few technologies or materials. The limited number of studies do not comprehensively evaluate all nineteen materials (Supplementary Table 9) relevant for power generation system transitions under a net-zero scenario. Additionally, the importance value indicator and the threshold of 10% are not proposed to comprehensively assess the level of material constraints.

Here in this study, we move forwards by predominantly (1) analysing the critical material constraint mitigation pathways that focus specifically on three power generation sub-technology market share scenarios; (2) evaluating the future demand for each of the nineteen critical materials that may pose material constraints using the dynamic material flow analysis (MFA) method; and (3) considering the material demand of nonpower generation sectors. We use three market share scenarios that assume low (conservative), moderate, and progressive penetration of future sub-technologies. Twenty-two major sub-technologies within the solar PV, wind power, hydropower, nuclear power and CCS technology categories (see the Methods section) are considered. These five electricity categories will dominate future power generation for a carbon-neutral future in China and potentially the rest of the world. We also introduce an importance value indicator, which is a ratio of the power generation system material demand to the total material demand across all sectors, to provide a holistic evaluation of the material constraints caused by power generation system transition. Sub-technology market share impact on this indicator is also evaluated to further elucidate the material constraints.

We find that solar PV and wind power sub-technologies will be the greatest future contributors to the material demand, especially for critical materials such as Te, Ge, Ga and indium (In). Adopting emergent sub-technologies such as GaAs intensifies the Ga material supply constraints. Alternatively, adopting existing mature c-Si solar cell sub-technology can avoid the potential material constraints of Ga and Te. Importantly, the progressive deployment of new and emerging sub-technologies will increase the importance values of Ga and terbium (Tb) and result in further material constraints. These findings provide new insights to inform industrial and policy strategies and pathways and can guide them in adjusting sub-technology market shares such that the material constraints arising from power system transitions under China's carbon neutrality goals can be mitigated.

Results

Material demand under various low-carbon transition pathways

Two pathways of power system transition are used to reflect power generation scenarios. The first pathway is a business-as-usual (BAU) scenario; here, the power generation system characteristics are projected using historical trends. The second is a carbon neutrality scenario (CNT); in this scenario, the transition pathway complies with China's carbon neutrality goal. Both power system transition pathways are integrated with a moderate market share scenario (MOD) (see the Methods section) to form two integrated scenarios: BAU_MOD and CNT_MOD. Figure 1a, b shows the cumulative demand for all nineteen materials from China's power generation system transition. These nineteen materials are categorized as either technology-specific materials or structural materials, according to the classification in Carrara et al.[25]. Technology-specific materials refer to materials that function in power conversion components and include PV modules, wind turbine generators, or fuel rod assemblies, and control rod assembly in nuclear reactors. Structural materials refer to materials that function as electric components or alloying elements in construction materials. Vanadium (V), nickel (Ni), copper (Cu), niobium (Nb) and molybdenum (Mo) are structural materials, and the remaining materials are technological materials.

We find that the cumulative demand for the nineteen materials will reach approximately 52.2 megatonnes (Mt) by 2060 under CNT_MOD; this value is more than double the 19.3 Mt of BAU_MOD. The material

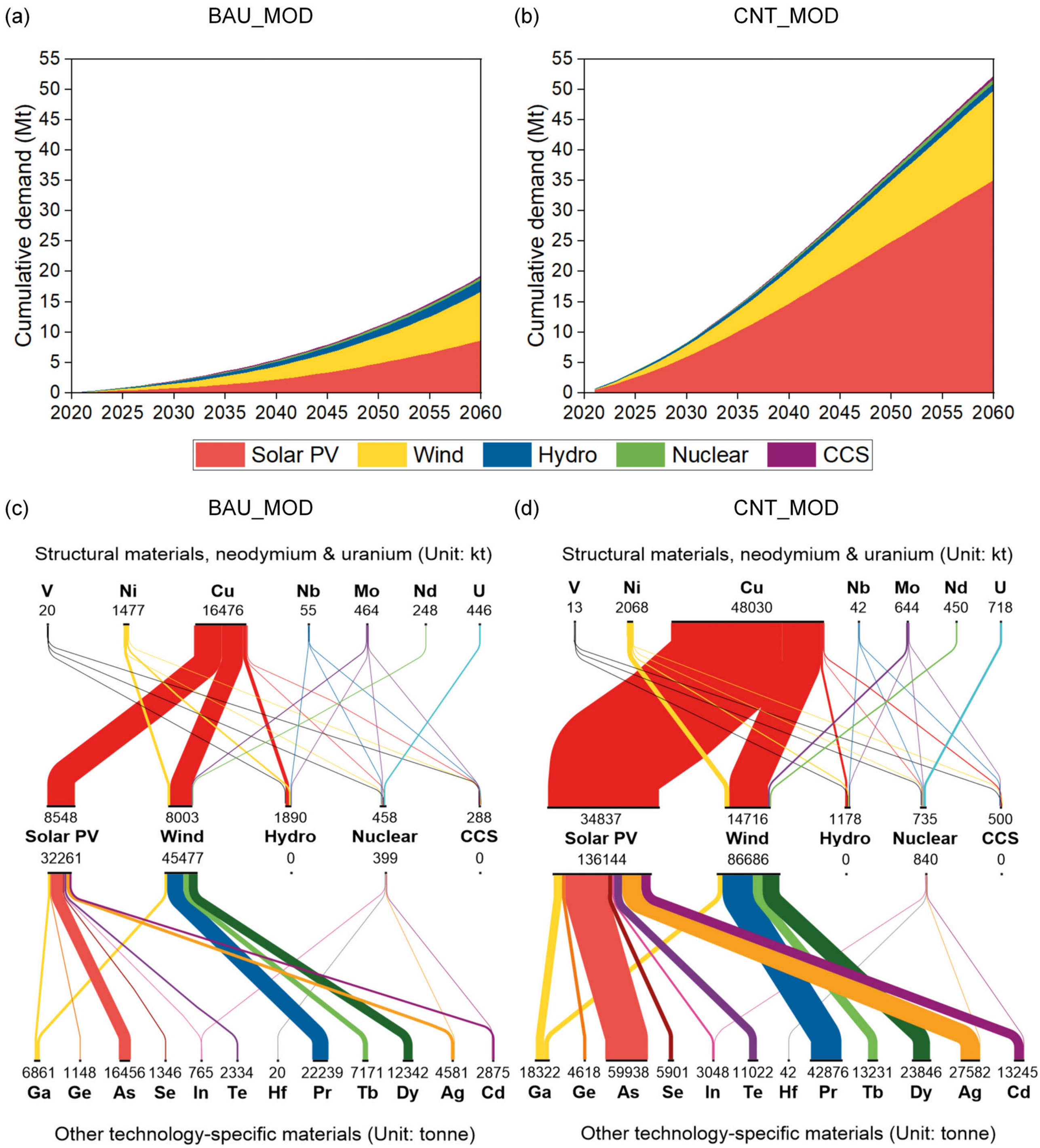

Fig. 1 | Cumulative material demand by 2060. a, **b** Cumulative demand by year and technology under the BAU_MOD and CNT_MOD scenarios, respectively. **c**, **d** Flow of materials to technologies under the two scenarios, respectively. BAU_MOD denotes the business-as-usual power system transition scenario integrated with the moderate sub-technology market share scenario. CNT_MOD denotes the carbon neutrality power system transition scenario integrated with the moderate sub-technology market share scenario. CCS denotes carbon capture and storage. PV denotes photovoltaic. Mt means megatonnes. Technology-specific materials refer to materials that function in power conversion components, such as PV modules and wind turbine generators. Structural materials refer to materials that function as electric components or alloying elements in construction materials. Nd and U are more aligned with structural materials; thus, they are listed under structural materials in **c** and **d**. Source data are provided as a Source Data file.

demand from solar PV technology shows the most significant increase and increases 3.1 times from 8.6 Mt under BAU_MOD to 35.0 Mt under CNT_MOD in 2060. The material demands from wind power, nuclear power and CCS by 2060 also increase by 84%, 61% and 73%, respectively. Solar PV and wind power both contribute to substantial shares in the cumulative demand by 2060 and add up to approximately 90%. Hydropower is the only technology showing decreasing material demand under CNT_MOD relative to BAU_MOD since the BAU_MOD scenario deploys hydropower to a much greater extent.

With respect to the demand for different materials (Fig. 1c, d), the cumulative material demands for Cu, Ga, Ge, arsenic (As), selenium (Se), In, Te, Ag, and cadmium (Cd) will more than double under CNT_MOD relative to BAU_MOD. This increase in material demand is mostly caused by solar PV expansion. The cumulative hafnium (Hf) demand also increases by 1.1-fold (increase to 42 tonnes) because of the nuclear power demand. Cu accounts for approximately 90% of the cumulative material demand under both scenarios because it is used as an alloying element in various construction materials and electric components. Ni, Mo and uranium (U) are also significant. The former two materials are important alloy elements in construction materials such as steel. U serves as fuel in nuclear power generation. The other thirteen technology-specific materials account for less than 2% of the cumulative demand under both scenarios.

Annual material demands of most materials under the CNT_MOD scenario are 11–125% greater than those under the BAU_MOD scenario for 2060 (Fig. 2). Furthermore, the annual material demand for most materials will peak before 2060, such as praseodymium (Pr), dysprosium (Dy) and Hf, will peak around year 2040 under CNT_MOD. This result indicates that the largest material challenges will occur earlier than the carbon neutrality year. Ge shows the largest increase in annual demand as the scenario shifts from BAU_MOD to CNT_MOD. This value will increase by 7.1 times in 2027, which is mainly due to the rapid increase in newly added solar PV capacity before 2040 under the CNT_MOD scenario (Fig. 2n, Supplementary Fig. 3d). The maximum annual demand for U occurs due to a market share increase in two Generation IV (Gen IV) nuclear reactor types (high-temperature gas-cooled reactors (HTGR) and fast breeder reactors (FBR)). These two sub-technologies require much less U per gigawatt (GW) of electrical generating capacity than traditional pressurized water reactors (PWR) (Fig. 2o). The maximum annual Hf demand (Fig. 2n) in 2035 is due to joint occurrences. The first is a peak in the newly added capacity of nuclear power under the CNT_MOD scenario (Supplementary Fig. 3d). The second occurrence is the declining PWR technology market share (Supplementary Fig. 2e), where Hf is needed in the PWR fuel cladding[31].

Interestingly, the annual demands for V and Nb are lower under the CNT_MOD scenario than under the BAU_MOD scenario for most years (Fig. 2a, d). This result occurs because these materials are required mainly by hydropower, whose annual newly added capacity under CNT_MOD is less than that under BAU_MOD after 2030 (Supplementary Fig. 3c). The annual Ag demand also decreases (Fig. 2r), although the newly added capacity for solar PV continues to increase (Supplementary Fig. 3a). This decreasing Ag trend is caused by a decreasing share of the crystalline c-Si sub-technology, the only solar PV sub-technology that needs Ag (Supplementary Fig. 2e).

Effects of the sub-technology market share on material demand

Three market share scenarios under the CNT scenario are formulated to evaluate the potential impact of adjusting the sub-technology market share. Each scenario reflects varying technological progress levels: conservative (CNT_CON), modest (CNT_MOD) and progressive (CNT_PRO) deployment of emerging new sub-technologies (see Supplementary Fig. 2 for detailed sub-technology settings). We find that solar PV sub-technology market shares play vital roles in determining the technology-specific material demand. More material demand is observed as more progressive scenarios are adopted (Fig. 3a). The cumulative material demand is only 44.5 kt under the CNT_CON scenario but significantly increases to 141.3 kt and 154.8 kt under the CNT_MOD and CNT_PRO scenarios, respectively. Uptake of the latest thin-film solar cells, especially the GaAs sub-technology, in the solar PV market is the main cause of this demand increase. The demand for Ag is the largest under CNT_CON (35.1 kt) and accounts for 79% of the technology-specific material demand of solar PV. This occurs because the c-Si sub-technology continues to expand its already dominant market share (Fig. 3a). Under scenario CNT_MOD, however, the demand for As, which does not exist under CNT_CON, accounts for 42% of solar PV technology-specific material demand and exceeds Ag demand by almost 1.2 times. The demand for Cd, Ga and Te also significantly increases. The demands for As and Ga are even greater under CNT_PRO (83.9 kt and 15.1 kt, respectively) because of rapid GaAs market share growth. This increase offsets and exceeds the reduction in material demand achieved by the radical deployment of perovskite solar cells envisioned in this scenario (Supplementary Fig. 2a). The Ga demand from solar PV under the CNT_PRO scenario is projected to be 56 times higher than that under the CNT_CON scenario.

The wind power also requires more technology-specific materials than other technologies (Fig. 3b). Similar to solar PV, the highest demand for technology-specific materials by wind power is also observed under the most progressive scenario CNT_PRO, but it is only 3% higher than the demand under CNT_MOD. The CNT_PRO scenario projects that the novel pseudo direct-drive wind turbine (PDD) sub-technology will capture 20% of the onshore market and 40% of the offshore market in 2060. The CNT_MOD scenario plays a dominant role in the commercialized direct-drive permanent magnet synchronous generator wind turbine (DD-PMSG) sub-technology in the wind power market. The two types of wind turbines are highly material intensive because of their substantial use of heavy permanent magnets[25,32,33]. Consequently, the demands for technology-specific materials under CNT_MOD and CNT_PRO are 29% and 31% greater than those under CNT_CON, respectively. Since the content of neodymium (Nd) is much higher than those of other materials in permanent magnets[32,33], more than 83% of technology-specific material demand from wind power is Nd.

Interestingly, nuclear technology material demand under more progressive scenarios leads to a reduction in material demand, particularly for the U demand (Fig. 3c). If U is excluded, the demand for other materials is marginal with respect to the demand for solar PV and wind power. Among the other materials, the demand for Ag accounts for nearly 76% of all scenarios, primarily because of its dominant use in the control rod absorber of PWR sub-technology[34].

Unlike solar, wind and nuclear technologies, hydropower and CCS require only structural materials. The hydropower sub-technology market share has the most significant effect on the structural material demand. The hydropower project scale also affects the material demand. Therefore, the lowest material demand for hydropower occurs under the CNT_MOD scenario (Fig. 3d) because it assumes greater use of less material-intensive large-scale hydropower and reservoir sub-technology (see Supplementary Method 9 for more information about the hydropower scale and sub-technologies). The market share has a limited effect on structural material demand for other technologies. Specifically, compared with other technologies, nuclear power has a marginal demand for structural materials (Fig. 3c).

Based on an annual perspective, we find that the annual demand for most technology-specific materials will increase with the shift from conservative scenarios (black lines) to progressive scenarios (red and blue lines, Fig. 4). For example, the annual demands for As, Te, and Cd rapidly increase under the MOD and PRO scenarios (Fig. 4g, i, s) because of the rapid deployment of the GaAs and CdTe sub-technologies. The annual demands for Pr, Nd, Tb, and Dy are the highest under CNT_PRO in almost every year (Fig. 4j–m). This result is caused by the greater use of a novel PDD wind turbine sub-technology. The annual demand for Ga quickly increases as the market share scenario becomes more progressive, and this is partially attributed to the demand from wind turbines with permanent magnets. Moreover, compared to that under the CNT_MOD scenario, the demand for Ge, Se, and In will decrease under the CNT_PRO scenario (Fig. 4f, h, q); this was primarily caused by the substitution of thin-film solar cells with more advanced perovskite sub-technology under the CNT_PRO scenario. The annual demands for Hf and U are also lower under CNT_MOD and CNT_PRO (Fig. 4n, o) because both Gen IV nuclear reactor sub-technologies that do not require Hf in their fuel cladding[31,35] will increase to 100% in 2060 under both scenarios.

For structural materials, the annual demands for V and Nb exhibit declining trends as the market share scenario becomes more progressive (Fig. 4a, d). This occurs because the more advanced PSH sub-technology requires less V and Nb than the reservoir and run-of-river

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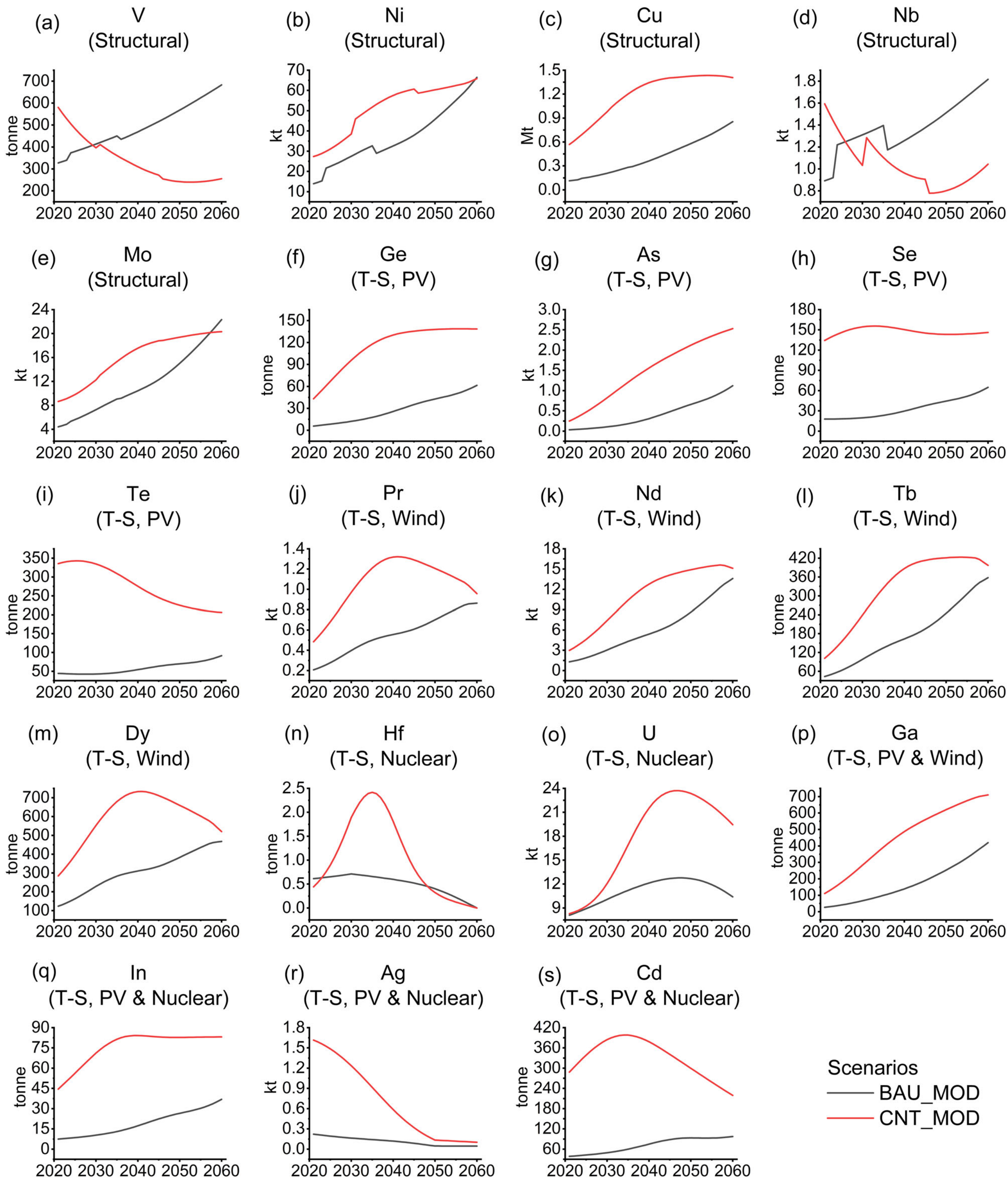

Fig. 2 | Annual material demand under the BAU_MOD and CNT_MOD scenarios. Materials are categorized into structural materials (**a**–**e**) and technology-specific (T-S) materials (**f**–**s**), with the latter further specified regarding the technology or technologies requiring them. Technology-specific materials refer to materials that function in power conversion components, such as PV modules and wind turbine generators. Structural materials refer to materials that function as electric components or alloying elements in construction materials. Note: BAU_MOD denotes the business-as-usual power system transition scenario integrated with the moderate market share scenario. CNT_MOD denotes the carbon neutrality power system transition scenario integrated with the moderate market share scenario. PV denotes photovoltaic. Source data are provided as a Source Data file.

(RoR) hydropower sub-technology. The variations in annual demand for Ni under different scenarios are due mainly to wind power sub-technologies (Fig. 4b). This occurs because direct drive (DD) wind turbine technology dominates the wind power market under CNT_MOD and requires fewer high-alloyed steels than gearbox parts[15,25,33]. The annual demands for Cu and Mo have minor variations as the scenario changes (Fig. 4c, e) because their material intensities have insignificant differences among the sub-technologies.

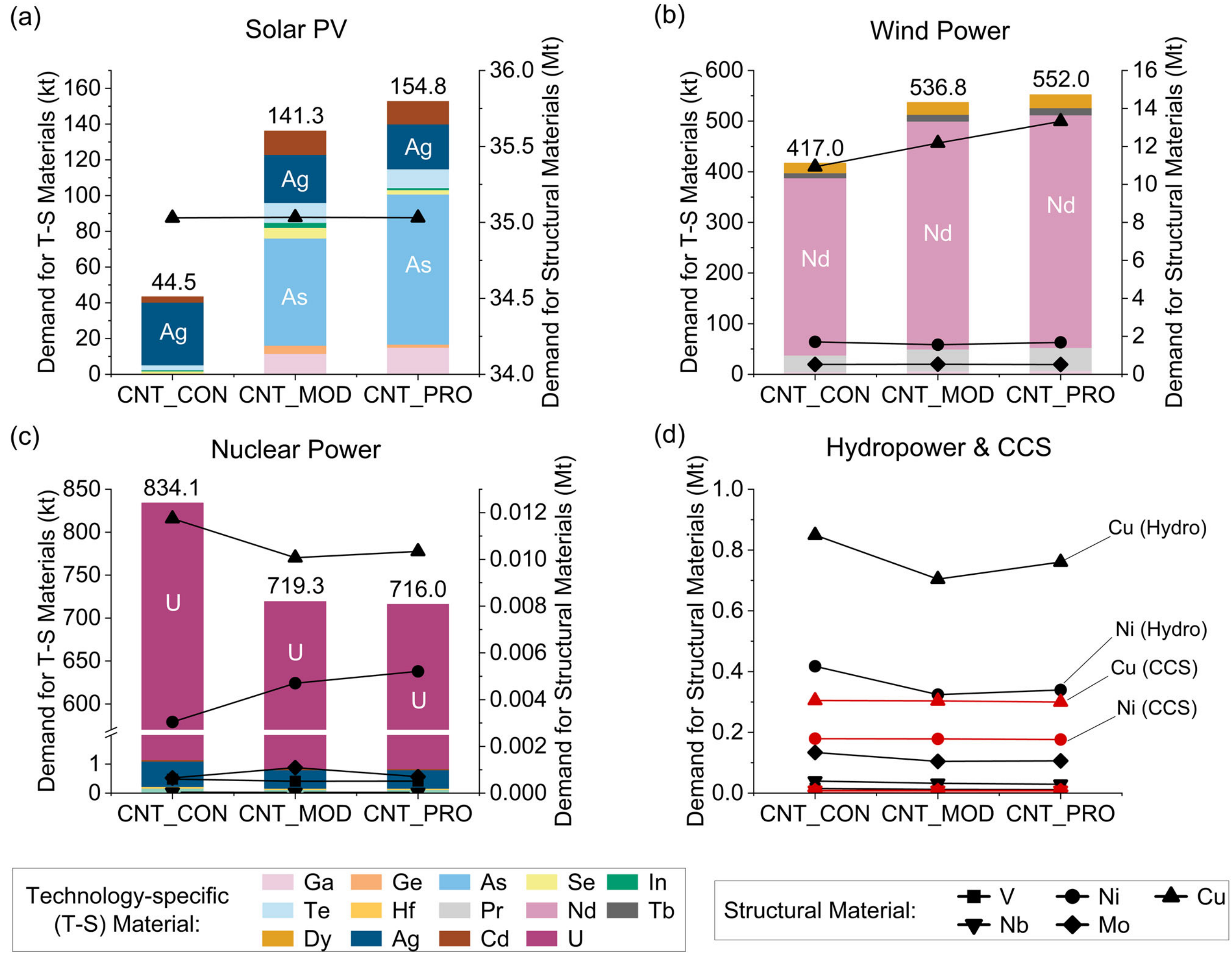

Fig. 3 | Cumulative material demand from 2021 to 2060 under the CNT_CON, CNT_MOD and CNT_PRO scenarios for different technologies. **a** Solar photovoltaic (PV), **b** wind power, **c** nuclear power, **d** hydropower and CCS (carbon capture and storage). The nineteen materials are categorized into technology-specific materials and structural materials. Technology-specific materials refer to materials that function in power conversion components, such as PV modules and wind turbine generators. Structural materials refer to materials that function as electric components or alloying elements in construction materials. Both hydropower and CCS require all five structural materials but no technology-specific (T-S) materials; thus, they are plotted together in **d**. To differentiate the material demand between CCS and hydropower in **d**, the structural material demand from CCS is plotted in red rather than black. CNT_CON denotes the carbon neutrality power system transition scenario (CNT) integrated with the conservative market share scenario (CON). CNT_MOD denotes the CNT scenario integrated with the moderate market share scenario (MOD). CNT_PRO denotes the CNT scenario integrated with the progressive market share scenario (PRO). Solar PV denotes solar photovoltaic. Source data are provided as a Source Data file.

Material constraints and importance values under the power system transition

We now compare the cumulative material demand through 2060 with the current reserves in China for each of the 19 materials. This comparison is for both the power generation sector and across all sectors. Here, current reserves of Cu and U in China will not even be able to meet the demand from power generation system transitions, not to mention other sectors. The cumulative U demand from the power generation system transition is 3.4 times China's current reserves under the CNT_CON scenario (Fig. 5a). Under the CNT_MOD scenario, Ge, Se and Te also exhibit material constraints, and the cumulative Te demand from the power generation system transition is 3.6 times its current reserves (Fig. 5d). Nevertheless, the material constraints under the CNT_PRO scenario are alleviated due to the rapid phase-in of the perovskite solar cells sub-technology, and only Cu, Te and U show material constraints (Fig. 5g). Fourteen of the nineteen materials will face material constraints by 2060 when other sectors are considered. The only exceptions are V, As, Hf, Nd and Dy. Notably, the cumulative demand for Ni and Se will be nearly 20 times their current reserves.

To further assess the impact of power generation system transition on material constraints, we introduce an importance value. This value is defined as the ratio of material demand from the power generation system transition to the overall material demand across all sectors (Fig. 5b, e, h). Viebahn et al. [32] assumed that 10% of the global reserves of every material would be available for power generation system transition. Therefore, we set a 10% threshold for the importance value to identify materials whose future demand could be seriously affected by the transition. We find that only Ga, Te, Nd and Tb have importance values of ≥10% (20%, 10%, 14% and 23%, respectively) by 2060 under CNT_CON because of the demand from wind power and solar PV. As the scenario changes from CNT_CON to CNT_MOD, the importance values of the four materials further increase. The demands for two additional materials, namely, Ge and In, also exceed 10% (30% and 20%, respectively) (Fig. 5e) because of the uptake of thin-film solar cells in the solar PV market. For Ga, the importance value even reaches 46%, with almost 2/3 contributed by solar PV and 1/3 contributed by wind power. The importance value for Ga further increases to 50% under CNT_PRO (Fig. 5h). In this scenario, compared with the

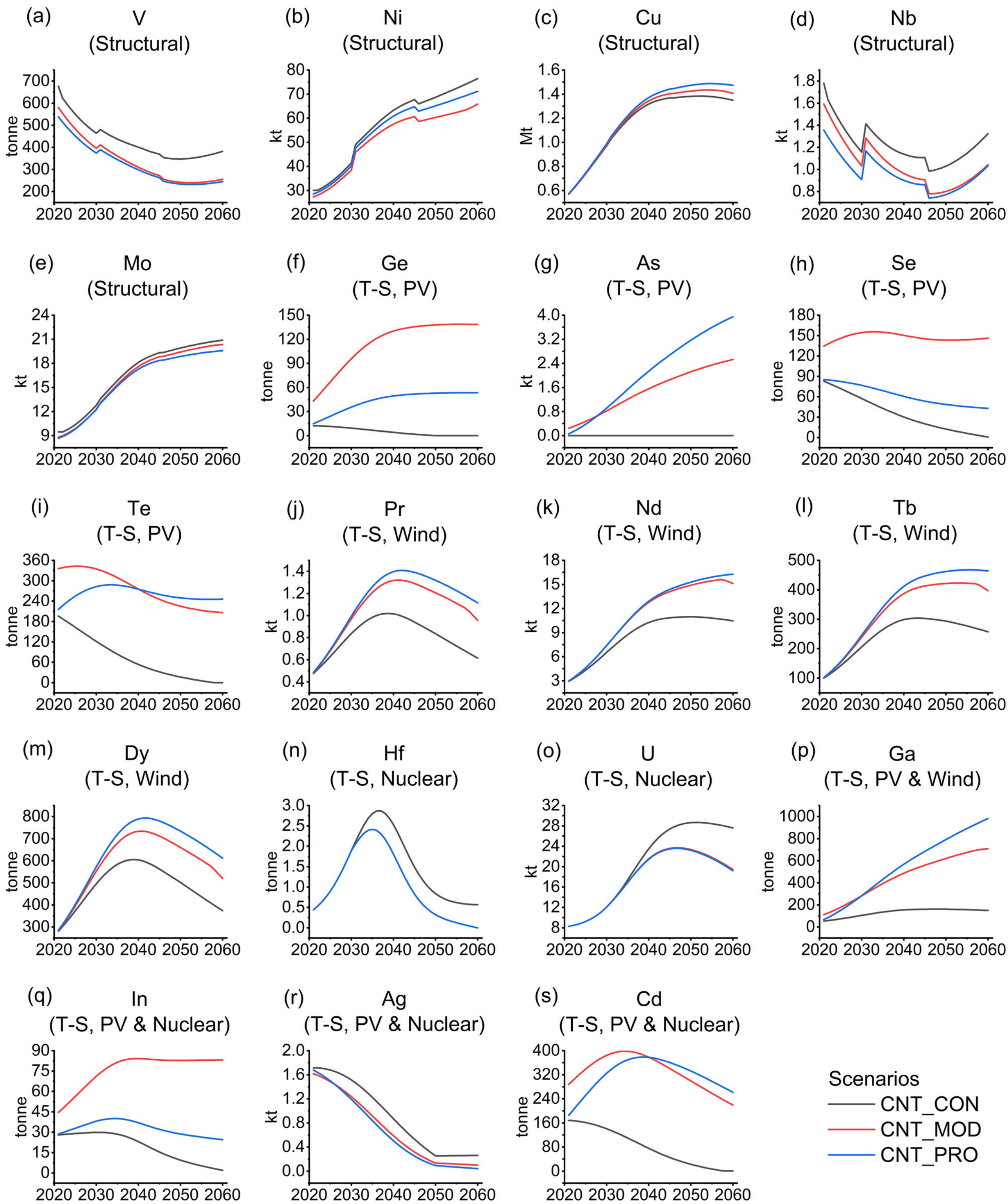

Fig. 4 | Annual material demand under the market share scenarios CNT_CON, CNT_MOD and CNT_PRO. Materials are categorized into structural materials (**a**–**e**) and technology-specific (T-S) materials (**f**–**s**), and the latter further specifies the technology or technologies requiring them. Technology-specific materials refer to materials that function in power conversion components, such as PV modules and wind turbine generators. Structural materials refer to materials that function as electric components or alloying elements in construction materials. Note: PV denotes photovoltaic. CNT_CON denotes the carbon neutrality power system transition scenario (CNT) integrated with the conservative market share scenario (CON). CNT_MOD denotes the CNT scenario integrated with the moderate market share scenario (MOD). CNT_PRO denotes the CNT scenario integrated with the progressive market share scenario (PRO). Source data are provided as a Source Data file.

hypothetical case where thin-film solar cells or wind turbines with permanent magnets are not used, the demand for Ga nearly doubles from the deployment of innovative solar PV and wind power sub-technologies. The radical deployment of perovskite solar cells under CNT_PRO can cause the corresponding importance values of Ge and In to be reduced by half relative to the CNT_MOD level, but they still have importance values of 14% and 10%, respectively. Although the demands for structural materials are much greater than those for

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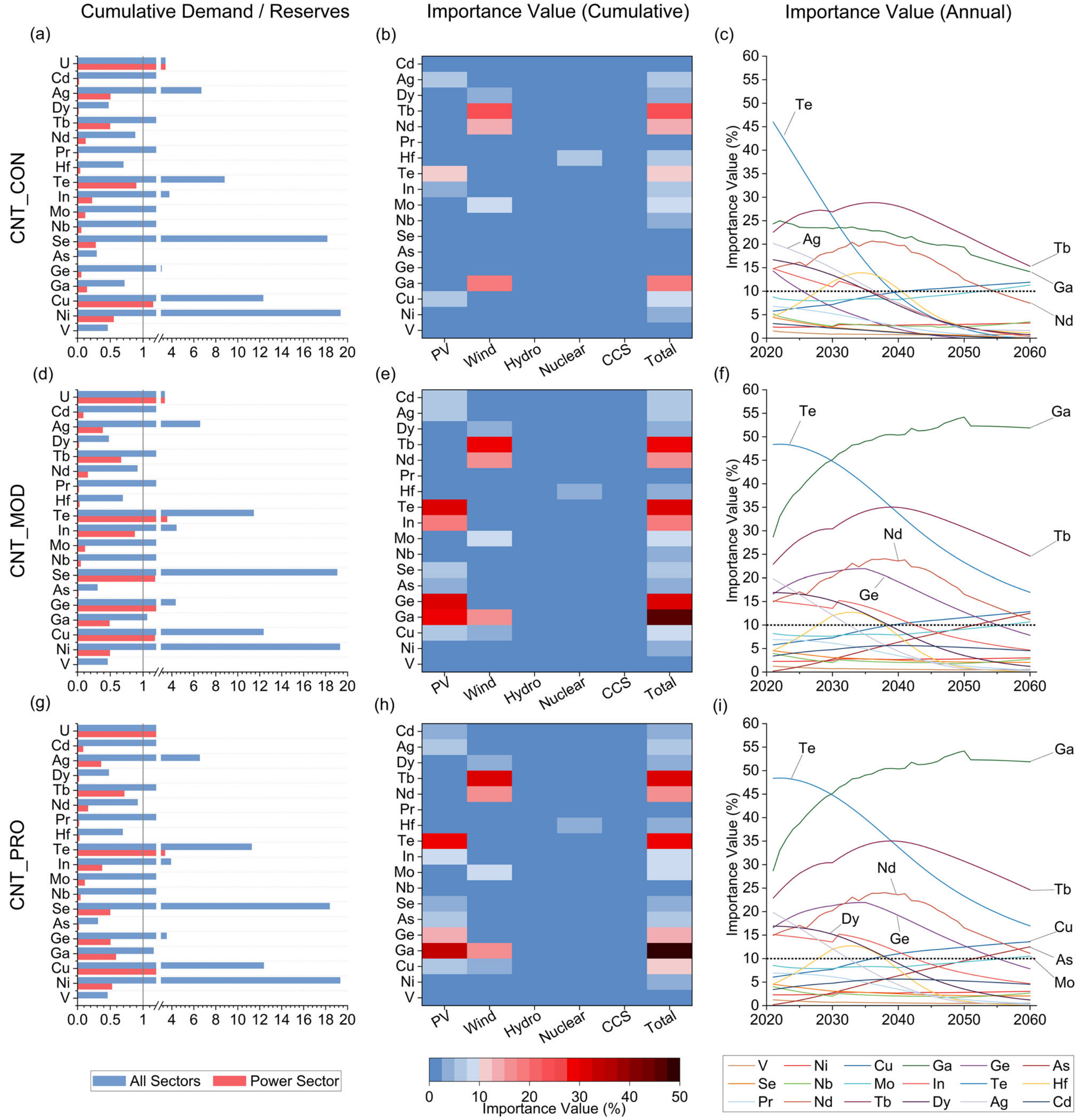

Fig. 5 | Ratio of the cumulative material demand to current reserves in China and the cumulative and annual importance values of the power system transition. a, **d**, **g** Ratios of the cumulative demand from the power system transition and from all sectors, respectively, by 2060 to current reserves by materials. **b**, **e**, **h** Importance values of cumulative demand by 2060 under the CNT_CON, CNT_MOD and CNT_PRO scenarios, respectively. **c**, **f**, **i** Importance values of the annual demand under the three scenarios from 2021–2060. Since the importance value of none of the materials exceeds 50%, the scale ends at 50% in **b**, **e**, and **h**. The black short dotted lines in **g**, **h**, and **i** mark the 10% importance value threshold. Note: CCS denotes carbon capture and storage. CNT_CON denotes the carbon neutrality power system transition scenario (CNT) integrated with the conservative market share scenario (CON). CNT_MOD denotes the (CNT) scenario integrated with the moderate market share scenario (MOD). CNT_PRO denotes the CNT scenario integrated with the progressive market share scenario (PRO). PV denotes photovoltaic. Source data are provided as a Source Data file.

technology-specific materials, the five structural materials have importance values of no more than 10% under each of the three scenarios. Even as the c-Si market share steadily expands to 100% in 2060 under the CNT_CON scenario, the importance value of Ag is still 7% (Fig. 5b). However, concern still exists for Cu, Ni and Ag since their reserves cannot meet the immense material demand for all sectors by 2060 (Fig. 5a, d, g).

The importance value trends for annual material demand (Fig. 5c, f, i) show that the most significant material constraints, if any, will likely appear around the period of 2040–2050 under each scenario. Notably, the importance value of Tb peaks at 29% in 2036 under CNT_CON (Fig. 5c), Ge peaks at 43% in 2034 under CNT_MOD (Fig. 5f), and Ga peaks at 54% in 2050 under CNT_PRO (Fig. 5i). After the maximum values are reached, the importance values decline because of a decrease in the power generation system material demand (Fig. 4) jointly with increases in other sector demands. The importance value of Te ranges from 46% to 59% among the three scenarios in 2021 but significantly decreases to 0–17% in 2060. This decrease arises from much greater demand increases in other sectors. A similar pattern and reason exist for Dy (Fig. 5c, f, i). The decrease in the importance value of Ag can be attributed to the reduction in material intensity and the market share of the c-Si sub-technology. The importance values of the structural materials Cu, As, and Mo increase to more than 10% as they approach 2060. This result is caused by an increase in the transition demand coupled with decreased demand in other sectors. This result indicates a moderate but growing challenge.

Sensitivity analysis of key parameters

The impacts of key parameters on our main results are assessed by increasing and decreasing each material intensity and average lifetime by 30%; this is regarded as the largest range[19,36]. We perform this sensitivity analysis under the CNT_PRO scenario, where the cumulative material demand from the power generation system is the highest among all scenarios. The sensitivity results are illustrated in Supplementary Fig. 4. Here, the cumulative material demand changes in the same proportion as the material intensity estimates change (Supplementary Fig. 4a). When all material intensity estimates increase by 30%, the cumulative material demand increases by 16.1 Mt (30%) to 69.6 Mt. Conversely, when the material intensity estimates each decrease by 30%, the cumulative material demand also decreases by 16.1 Mt to 37.5 Mt. The average lifetime is less sensitive than the material intensity. The cumulative material demand decreases by only 14% to 46.0 Mt when the average lifetime estimate increases by 30%, and it increases by 26% to 67.4 Mt when the average lifetime estimate decreases by 30%.

For the importance value sensitivity, a higher importance value correlates to a greater sensitivity to the changes in the material intensity and lifetime (Fig. 5c and Supplementary Fig. 4b, c). More specifically, when the two parameters change by 30%, the importance values of Ga, Te, and Tb, which are greater than 20% in the main results, vary by at least 2%. In contrast, the importance values of V and Pr, which are less than 2% in the main results, vary marginally. Similar to the impacts on the cumulative material demand, the importance value is more sensitive to the material intensity than to lifetime. For example, when the material intensity changes by 30%, the importance value of Ga increases by 7% or decreases by 9%. In response to the 30% change in the average lifetime, however, it increases by 6% or decreases by 5%. These sensitivity analyses indicate that accelerating material intensity reduction can be a better approach to reduce the material demand from the power generation system transition than extending the lifetime of materials.

Discussion

It is necessary to consider material constraints when designing low-carbon power system transition policies. We build and expand upon previous studies that focused on quantifying material demands and gaps during renewable power generation system transitions. We investigate potential pathways to mitigate these material constraints by adjusting the market share for each sub-technology within its main technology category. We also evaluate the demand for nineteen materials from power generation system transitions seeking to achieve China's carbon neutrality goals. Moreover, we propose an importance value by jointly considering the power system sector and all-sector material demands. We find that solar PV and wind power sub-technology market shares can greatly affect demand for technology-specific materials and their importance values as proportions of all sector demands. Both Ga and Te demonstrate the highest importance values because of their high demand for the CdTe and CIGS sub-technologies. The demand from GaAs and wind turbines with permanent magnets further intensifies the material constraint for Ga. Changing the sub-technology market share can increase the technology-specific material demand from solar PV by 2.2–2.5 times and from wind power by approximately 30%.

Compared with the existing related literature, the overlap in the material demand from solar PV, wind, hydropower and nuclear power generation under a carbon neutrality goal in our study is 1.5 times that of Wei et al.[22]. This difference occurs because our cumulative installed capacity is relatively high. Our wind power material demands tend to be lower for similar sub-technology market share scenarios of Elshkaki and Shen[20] and Wang et al.[21]; these results are caused by the relatively higher material intensity assumption of their studies with respect to our study. Our results for solar PV material demand are substantially lower than those in previous studies because previous studies have not considered emergent GaAs and perovskite sub-technologies[20,21]. Alternatively, the demand for Ga is higher in our study because GaAs requires more Ga than CIGS. Some existing studies have also identified material constraints on renewable electricity generation technologies at both the global level and the Chinese level (Supplementary Table 8). Although constraint materials such as Cu, Ga, and Te align with those identified in our study, significant discrepancies remain. For example, Ag is projected to face material constraints when the material intensity in a c-Si solar cell is set as a constant, according to the existing literature[20,22]. However, due to the exclusion of GaAs solar cells, Ga is less likely to be constrained[20,37]. A more detailed comparison between our study and existing relevant studies is provided in Supplementary Table 8. These comparisons further reinforce our findings that material demands can vary significantly across different sub-technologies.

Our findings can help mitigate material constraints by adjusting sub-technology market shares. First, sub-technology market shares for both solar PV and wind power development need to be considered during the power generation system transition. In the solar PV market, conventional c-Si solar cell sub-technologies consume relatively fewer critical materials than progressive thin-film solar cell sub-technologies, such as CdTe and CIGS. Conventional c-Si technology also has the advantage of higher energy conversion efficiency than thin-film solar cells[38]. However, thin-film solar cells have economic and environmental advantages over c-Si since expensive and energy-intensive solar-grade silicon is not needed[13]. Thin-film solar cells have gained increasing market shares since 2000[39], although the high balance-of-system cost may prevent a-Si market share from increasing[40]. Both CdTe and CIGS are cost-competitive in terms of their module costs, minimum sustainable prices (MSPs) and levelized costs of electricity (LCOE)[41–43]. Due to this complex array of factors, the most appropriate sub-technology for solar power development is difficult to select from only a single perspective. In this context, perovskite, an emergent sub-technology, may be a potential candidate. The scarcest material required by this sub-technology is lead (Pb), but its massive deployment will not result in Pb supply constraints[27,44]. The manufacturing cost, energy payback time (EPBT), MSP and LCOE of this sub-technology are more competitive than those of c-Si, CdTe and CIGS solar cells[45,46]. Major challenges faced by this sub-technology include stability, scalability and bankability[47–49], which may restrict its large-scale and commercial application.

Second, in the wind power market, conventional onshore wind turbines without permanent magnets, primarily DD-EESG (direct-drive electrically excited synchronous generator) and DFIG (doubly-fed induction generator) sub-technologies, are preferable to other sub-technologies from a material constraint perspective. Economically, DFIG also has advantages of lower capital cost due to the use of much cheaper generators and converters[50]. Thus, DFIG is recommended for incumbent commercialized wind turbines considering the material, environmental, and economic aspects of the onshore wind market. In the offshore wind market, operation and maintenance (O&M) costs have become more important. The cost advantage of DFIG over

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permanent magnet sub-technologies is reduced because the permanent magnet use in generators can reduce the O&M cost requirements for wind turbines[51]. SCIG (Squirrel cage induction generator) sub-technology has been recently favoured in Europe because of its flexibility and robustness[33,52] and is likely more appropriate in the offshore wind market. Furthermore, similar to DFIG, SCIG minimally relies on rare earth elements. The two emergent sub-technologies, PDD and SDD (superconducting direct-drive), provide a contrasting situation. PDD should not be considered for massive deployment because of its heavy permanent magnets and consequently substantial rare earth element demands. The SDD sub-technology has reduced the turbine weight and volume, increased efficiency and has a relatively minimal rare earth element demand[27,53,54]; this sub-technology can be an option for the future offshore wind power market when it is commercialized. As superconducting generators are more compatible with larger wind turbines (>10 MW)[54], the scale effects of turbines can also reduce greenhouse gas emissions[55]. SDD has attracted significant research community attention, and installations are already planned[33]. However, the very low working temperature, complex cryogenic cooling system and high LCOE requirements hinder its commercialization[53,56]. This example shows that even though sub-technology material constraints can be used to inform decisions, many other dimensions of concern need to be considered, including economics, supporting technology, and even political acceptance.

Third, in addition to careful planning for solar PV and wind power sub-technologies, nuclear power technology is a promising candidate in response to material constraints, especially those related to Ga, Te, Nd and Tb. However, the nuclear power sub-technologies do have U constraints since China has limited U reserves; thus, they are more reliant on international trade. However, more important issues and difficulties are related to politics and safety. Nuclear power deployment requires serious radiation security for workers, nuclear accidents and spent fuel waste. Although countries such as France and Sweden are successful examples of nuclear power generation, approximately 70% and 50% of electricity is from nuclear technology, respectively[57]. However, the success of the two countries in terms of nuclear power occurred mainly because of their target for oil independence in imports and the cheap nuclear costs during the 1970s[58]. There are significant political voices to abandon nuclear power in both countries, particularly after multiple nuclear disasters, including Three Mile Island, Chernobyl, and Fukushima; these incidents have been permanently cemented in sociopolitical psyches for decades. Once again, due to these broader issues, even with the many materials and climate benefits, some sub-technologies will not be feasible in some regions.

Appropriate policies are also needed to support the implementation of mitigation pathways that adjust the sub-technologies adoption during the carbon neutrality transition. For example, targeting and strengthening R&D support are needed to address technological barriers for commercializing potential emergent sub-technologies, such as perovskite solar cells and SDD wind sub-technology. Reducing the economic cost of potential sub-technologies is essential since the demand for technologies is directly influenced by their cost. Regulatory market mechanisms can enhance subsidies, guiding the adoption of specific technologies. At the same time, restrictions on the exploitation of scarce critical materials, such as mining rights reduction, production quota tightening and illegal mining crackdown[59,60], increase material prices. Subsequently, this will facilitate the phase out of critical material-intensive technologies, such as permanent magnet turbine sub-technologies. However, care should be taken when legal restrictions are imposed. The increase in cost and scarcity may encourage illegal practices, resulting in short-term damage, as grey and black markets may emerge to meet unmet demand. More broadly, before introducing and enforcing policies, a careful examination of technology choice and transition consequences should be completed.

It is also recommended to prioritize targeted strategies and policies for reducing material use and enhancing the supply of materials with higher importance values (such as Ga, Te, Se and In) to mitigate material constraints. For example, reducing the absorber layer thickness, enhancing the material utilization rate, and improving the cell and module yields should be pursued in the design, fabrication and manufacturing stages[12,13,40]. Savings can be made in materials and process designs, not just in technological designs. Unconventional sources, such as coal fly ash for Ga[61,62], sulfidic copper ores for In[63,64], marine geo-resources such as sedimentary bedrock for Se[65], and increasing Te yield from copper anode slime[66,67], should be encouraged. Regulatory mechanisms and economic incentives should be in place to utilize these sourcing alternatives[64,68]. Furthermore, policies to facilitate secondary production of critical materials from end-of-life (EoL) products are crucial. Recovery methods such as nitrogen pyrolysis and vacuum decomposition, leaching and solvent extraction need further policy support to increase the efficiency of the recycling of Ga, Ge, In or Te from electronic wastes[69–71]. A prioritization scheme for these practices and materials can be obtained from the results of this study.

This study also provides implications for subsequent research focusing on pathways to respond to material constraints in achieving climate agendas throughout the world. Many developing countries need to facilitate their own clean energy transitions and may face similar critical material constraints. The main findings and implications of this study can assist them in adjusting sub-technology market shares on the basis of their own resource endowments. Material constraints mean that emerging economies face further pressures to compete with China and other more developed countries to find new sources. These sources can be in developing country regions. The countries that supply materials may be under greater pressure to provide resources, further amplifying the resource curse faced by developing nations. Therefore, developing nations need to use this information carefully to develop and prioritize their own material supply strategies and plan for greater demands. They may also desire to trade technology for resources to help them achieve their carbon neutrality goals. We realize that many complexities remain in regard to trade in critical materials, and international bodies need to monitor these activities such that underdeveloped and vulnerable regions are not victims of the rush for critical materials.

We need to moderate any conclusions and recommendations we make because certain study limitations exist. First, future material demands from other sectors are forecast by combining the extrapolation of previous forecasts, exponential models and intensity-based methods; these methods have already been much improved over existing simple extrapolation methods. However, these methods still result in uncertainty and can be further improved. Second, future material supply projections are outside the scope of our study, which prevents the further presentation of the potential supply–demand gap adjustments likely to emerge in the future. Third, we demonstrate the significant impacts of sub-technology market share on material demand. However, we did not consider or develop an optimal sub-technology market share mix that could minimize or even avoid material constraints. More studies can be further explored to address these limitations in the future as more relevant data and knowledge becomes available.

Methods

Electricity generation under different low-carbon scenarios

Solar PV, wind power, hydropower, nuclear power, and carbon capture & storage (CCS) applied to fossil fuel and bioenergy power plants are used low-carbon electricity technologies. These technologies represent significant shares in future power systems for both China and the world. Technologies including CSP, geothermal, ocean, and bioenergy without CCS are excluded owing to their minor future forecast shares[72–74]. Although battery energy storage may also be an important element of future renewable energy-dominated power systems, the focus of this study is only on power generation systems. The three reasons for omitting battery energy storage in our study are as follows. First, the aim of this study is to reveal how different power generation sub-technologies affect the material demand. Battery energy storage will likely not affect renewable power generation sub-technology development since different sub-technologies of solar PV or wind power can use the same type of batteries as the energy storage option[75–77]. Inclusion of transmission and battery technology may even cause complexities that confound the core analysis of sub-technology development. Second, material demands from battery storage sub-technologies have already been widely investigated in the literature. They reported that battery storage will cause material constraints for lithium, cobalt, nickel, and manganese, even if they are used only for electric vehicles[78–80]. Thus, power system battery storage sub-technologies do not need to be further investigated. Third, hydrogen energy storage and dispatchable hydropower sub-technologies such as PSH and reservoir hydropower will dominate future power storage systems[4,81] because it is not feasible to use battery storage to support these large future power systems. In addition, a significant percentage of battery energy storage relies on recycled electric vehicle batteries. Approximately 30% of the vehicle-to-grid participation rate is predicted to meet China's entire power storage requirement in 2050[82].

Two scenarios are designed to project the transition of China's power system: the business-as-usual scenario (BAU) and the carbon neutrality scenario (CNT). The BAU scenario projects the future power system on historical trends using the computational general equilibrium (CGE) model developed by our coauthor[83,84]. It is a widely used model for assessing long-term policy impacts, such as taxes, subsidies, quotas and renewable energy application. The modelling framework covers 33 sectors (including 5 energy-related and 28 nonenergy sectors) and includes four integral modules (production, income generation, expenditure allocation, and trade interactions). It outlines the trajectories of economic growth, demographic shifts, energy demand and supply dynamics, investment patterns, and carbon emissions. Its input data include population, GDP, energy consumption and structure, and labour employment. This BAU scenario assumes that the cumulative capacity of the five low-carbon electricity technologies will reach 4.9 TW by 2060 (Table 1).

No detailed power system projection for the CNT scenario exists in official documents. However, the five low-carbon electricity technologies, especially solar PV and wind power, are each considered to be necessary future power systems and will be strongly promoted[85–87]. The CN60 scenario designed in Zhang et al.[74] is selected as the basis of our CNT scenario because it provides comprehensive coverage of climate and energy policies, energy resources, sectors, costs, and socioeconomic factors[74]. Their projection aligns with China's low-carbon targets and closely reflects China's future planning. The five low-carbon electricity technologies focus on solar PV and wind power. The cumulative capacity of these five low-carbon electricity technologies is predicted to reach 10.5 TW by 2060, and carbon emissions from the power sector are expected to be negative at −0.8 gigatonnes in 2060.

Zhang et al.[74] provide future forecasts in five-year intervals. The annual installed capacities of these five technologies are thus determined by interpolating data points from the original projections (Supplementary Note 1). The original projections for both the BAU and CNT scenarios are listed in Table 1. The annual evolution of the cumulative installed capacity of the five technologies under the BAU and CNT scenarios from 2020 to 2060 is shown in Supplementary Fig. 1.

Sub-technologies and corresponding material intensity

In this study, the sub-technologies that are currently in commercial use and the sub-technologies that are still under development and not widely utilized are considered. For example, solar PV sub-technologies such as gallium arsenide (GaAs) and perovskite solar cells and wind power sub-technologies such as PDD and SDD are included because of their promising future prospects[8,26,33].

Sixteen of the nineteen materials used in this study are categorized as critical materials by at least China, the United States, and the European Union. The remaining three materials are Ag, Se, and Cd. Table 2 lists these sub-technologies and their corresponding material demands. The values of the material intensity for the sub-technologies are obtained from either existing literature or from our calculations. The material intensities of solar PV and wind power sub-technologies appear in many studies because of the relative sub-technologies. We

Table 1 | Projected installed capacity under the BAU and CNT scenarios

Scenarios	Year	Solar PV (GW)	Wind Power (GW)	Hydro power (GW)	Nuclear power (GW)	Coal CCS (GW)	Natural gas CCS (GW)	Biomass CCS (GW)
BAU[a]	2025	323	360	409	58	12	1	0
	2030	413	460	451	67	42	3	1
	2035	527	586	498	78	73	5	2
	2040	672	749	550	90	76	5	2
	2045	858	955	607	104	80	5	2
	2050	1095	1219	671	121	84	6	2
	2055	1398	1556	741	140	89	6	2
	2060	1784	1986	818	163	93	6	2
CNT[34]	2025	899	560	432	60	0	0	0
	2030	1549	800	499	88	0	0	0
	2035	2541	1310	525	116	18	0	18
	2040	3431	1682	549	161	30	0	30
	2045	4374	2106	574	214	47	0	47
	2050	5267	2572	598	223	47	0	71
	2055	5990	3065	607	224	47	0	104
	2060	6509	3132	615	225	47	0	150

CNT denotes the carbon neutrality power system transition scenario integrated with the moderate market share scenario. PV denotes photovoltaic. CCS denotes carbon capture and storage. GW is the abbreviation of the power unit gigawatt.

[a]BAU denotes the business-as-usual power system transition scenario integrated with the moderate market share scenario.

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Table 2 | Sub-technologies and their corresponding considered materials

Technology	Sub-technology	Technology abbreviation	Technology-specific materials	Structural material
Solar PV	Crystalline silicon T.[a]	c-Si	Ag	Cu
	Amorphous silicon T.	a-Si	Ge	
	Copper indium gallium diselenide T.	CIGS	Cu, Ga, Se, In	
	Cadmium telluride T.	CdTe	Te, Cd	
	Gallium arsenide T.	GaAs[b]	Ga, As	
	Perovskite T.	Perovskite[b]	/	
Wind power	Squirrel cage induction generator T.	SCIG	Ga, Pr, Nd, Tb, Dy	Ni, Cu, Mo
	Direct-drive electrically excited synchronous generator T.	DD-EESG		
	Doubly-fed induction generator T.	DFIG		
	Gearbox permanent magnet synchronous generator T.	GB-PMSG		
	Direct-drive permanent magnet synchronous generator T.	DD-PMSG		
	Pseudo direct-drive T.	PDD[b]		
	Superconducting direct-drive T.	SDD[b]		
Hydropower	Reservoir T.	Reservoir	None	V, Ni, Cu, Nb, Mo
	Run-of-river T.	RoR		
	Pumped storage hydro T.	PSH		
Nuclear power	Pressurized water reactor T.	PWR	In, Hf, Ag, Cd, U	V, Ni, Cu, Nb, Mo
	High-temperature gas-cooled reactor T.	HTGR	U	
	Fast breeder reactor T.	FBR	U	
CCS	Pre-combustion capture T.	Pre	None	V, Ni, Cu, Nb, Mo
	Post-combustion capture T.	Post		
	Oxyfuel capture T.	Oxy		

[a]T. means sub-technology. The technologies listed are ranked in descending order based on the length of their commercialization history. CCS denotes carbon capture and storage.
[b]These sub-technologies have not been commercialized on a large scale or are still in the laboratory. CCS denotes carbon capture and storage. PV denotes photovoltaic.

select studies that provide more comprehensive material intensity estimations or those that consider more impact factors when the material intensity is supplied for a given sub-technology.

The solar PV material intensity is determined by using existing literature such as those of Kavlak et al.[7], Viebahn et al.[32] and Nassar et al.[23]. The material intensity estimations for commercialized wind turbine types are obtained from Carrara et al.[25]. The wind turbine types covered by this study are comprehensive. Material intensities are calculated using the evolution of the rated power, rotor diameter, hub height, foundation type, and glass fibre and carbon fibre usage; these are based on the life cycle assessments by leading wind turbine manufacturers such as Vestas.

Material intensity data for hydropower, nuclear power, and CCS technologies are limited. We integrated the corresponding technical data, life cycle inventory data and chemical composition data using the material intensity calculation for these technologies. Sub-technology material intensity estimates and projection details are presented in Supplementary Methods 1–5. The material intensities in sub-technologies tend to decrease over time because of technological progress and optimization. Therefore, the material intensities in this study are set to decrease over time according to the different trends, as defined in the existing literature[8,23,25]. Supplementary Tables 2–5 list the material intensity values and annual reduction rates of all the sub-technologies from the status quo to 2060.

Market share scenario setting

We set market share scenarios by referring to forecasts in official documents, institutional reports, academic studies, and expert consultation. These multiple sources enable the identification of a consensus future technology development pathway. The three sub-technology market share scenarios are designed to reflect distinct levels of technological progress in electricity generation technologies. These three scenarios cover the broad spectrum of technological development and market sub-technology preference possibilities, from very conservative to very progressive forecasts.

The CON scenario is a conservative projection. CON assumes that the current market share is maintained in the future with more mature sub-technologies, such as crystalline silicon solar cell (c-Si), preferred over emerging new sub-technologies. As an example, in the CON scenario, the c-Si sub-technology is set to represent approximately 97% of the global solar PV market in 2023 referring to the Fraunhofer Institute, which is the largest solar research institute in Europe[39]. Its market share is set to increase to 100% in 2060 based on the conservative EU long-term strategy forecast plans for the solar PV market[25].

The PRO scenario is a radical projection and assumes rapid deployment of emerging new sub-technologies, such as gallium arsenide (GaAs) and perovskite solar cells and pseudo direct-drive (PDD) and superconducting direct-drive (SDD) wind turbines. In the PRO scenario, these sub-technologies may gain significant market shares or even displace currently mature sub-technologies. As an example, the International Energy Agency (IEA)'s[88] progressive sub-technology projections show that GaAs and perovskite market shares are set to increase from 0% in 2021 to 70% in 2060 in the solar PV market. For wind power, the IEA shows that the collective market share of PDD and SDD—each of which has not yet been commercialized—will increase to 40% in onshore markets and 80% in offshore markets by 2060[15,33].

The MOD scenario provides a more moderate projection, assuming no drastic market share changes. Emerging new sub-technologies, such as thin-film solar cells and permanent magnet wind turbines, are assumed to gradually expand their market share. This assumption means that permanent magnet wind turbines currently in use likely control both onshore and offshore wind power markets before 2060. This assumption aligns with the wind power market projections for both China and the U.S[16,89]. More details regarding the procedure for setting these scenarios are presented in Supplementary

Methods 6–11. The market share evolution under the three market share scenarios is shown in Supplementary Fig. 2.

To demonstrate the differences in material demand under different climate targets, the market share scenario MOD is integrated with two power system transition scenarios, BAU and CNT. The two integrated scenarios are denoted as BAU_MOD and CNT_MOD. As the carbon neutrality goal is China's incumbent climate policy, the effects of market share under BAU are irrelevant. Thus, in this study, the BAU scenario is not integrated with the CON and PRO scenarios. The CNT scenario is further integrated with the two market share scenarios to formulate scenarios of CNT_CON and CNT_PRO. These two integrated scenarios, along with CNT_MOD, are used to analyse the effects of market share on material demand and the importance of the power system transition in all-sector material demand.

Material demand calculation using dynamic material flow analysis

The power system transition material demand is determined using dynamic material flow analysis. The calculation procedure starts by quantifying the annual decommissioning capacity ($F_{out,i,t}$) of technology i in year t, as shown in Eq. (1).

$$F_{out,i,t} = \sum_{t'=t_0}^{t'=t-1} L_i(t, t') \times F_{in,i,t'} \tag{1}$$

where $F_{in,i,t'}$ denotes the newly added capacity of technology i in a previous year t' and $L_i(t,t')$ represents the lifetime distribution of technology i. The distribution functions and parameters of low-carbon technologies are listed in Supplementary Table 1, and the references are provided in Supplementary Note 2.

The calculations for the newly added capacity of a specific sub-technology j of technology i in year t ($F_{in,j,t}$) are shown in Eqs. (2) and (3).

$$F_{in,i,t} = S_{i,t} - S_{i,t-1} + F_{out,i,t} \tag{2}$$

$$F_{in,j,t} = F_{in,i,t} \times P_{j,i,t} \tag{3}$$

where the cumulative installed capacity of technology i in two consecutive years t and t-1 are denoted by $S_{i,t}$ and $S_{i,t-1}$, respectively. $F_{in,i,t}$ and $F_{in,j,t}$ represent the newly added capacity of technology i and sub-technology j of technology i, respectively, in year t. $P_{j,i,t}$ denotes the market share of sub-technology j in the market of technology i in year t.

Finally, the annual demand for material k from sub-technology j in year t ($D_{k,j,t}$) and the cumulative demand for material k (D_k) by 2060 can be calculated by using Eqs. (4) and (5).

$$D_{k,j,t} = F_{in,j,t} \times I_{k,j,t} \tag{4}$$

$$D_k = \sum_{j,t} D_{k,j,t} \tag{5}$$

where $I_{k,j,t}$ denotes the material intensity of material k in sub-technology j in year t.

Estimation of material demand from other sectors

A holistic low-carbon power system transition impact analysis of resource security requires forecasting future material demands across sectors. Some studies have forecast material demand in other sectors via simple extrapolation methods (e.g., scaling with GDP development). We advance this basic method by using three approaches to estimate different material demands. In our study, data is used from published literature, an exponential growth model, and an intensity-based method.

We use existing study forecast data for some materials, such as Ni, Cu, Ga, and Nd, when this information exists. An exponential growth model is used to forecast future demands for materials that have only historical data. We use an intensity-based method when materials have limited historical data. The total demands of the five structural materials of V, Ni, Cu, Nb, and Mo are currently available across the end-use sectors or can be directly calculated. Thus, the material demands for these five materials in other sectors are calculated as the difference between the forecast all-sector demand and the demand calculated under the scenario BAU_MOD.

U is the only material used entirely by nuclear power technology[90,91]. Thus, its demand does not need to be calculate in the other sectors. Detailed procedures for estimating material demands using the three methods are provided in Supplementary Method 12 and Supplementary Tables 6 and 7, respectively. Notably, although material demand in other sectors change under different development pathways, we assume an MOD pathway. We assumed the sub-technology market share scenario as MOD when the material demand from business-as-usual (BAU) is compared with that from carbon neutrality (CNT) transition pathways. Estimating material demand in other sectors under different pathways is difficult and complex.

Sensitivity analysis method

Two crucial parameters, the material intensity and average lifetime, are examined to determine the sensitivity of our results. Sensitivity analysis is needed since the material intensity estimates are obtained from various sources and, in some cases, contradict other. Any future evolution is inevitably uncertain.

The scale lifetime parameters in the Weibull distribution for solar PV and wind power, or the arithmetic means in the normal distribution for hydropower, nuclear power and CCS, are also evaluated by referring to relevant studies[19,36]. The impacts of changes in the average lifetime on newly added capacity and material demand are also considered. Although some studies include sub-technology market share in their sensitivity analyses[19], its impacts are more precisely evaluated via the three sub-technology market share scenarios. Hence, it is excluded here. We conduct our sensitivity analysis under the CNT_PRO scenario, which has the highest cumulative material demand. The values of all material intensities and average lifetimes are assumed to increase and decrease by 30%; this is the largest sensitivity range used by other relevant studies[19,36].

Data availability

All data supporting the findings of this study are provided in the main text, the Supplementary Information file, and the Source Data file. Source data are provided with this paper.

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H.D. designed the research; H.D. and T.Z. conducted the research; H.D., T.Z., P.W., and S.Z. performed the analysis; H.D., T.Z., J.S. and Y.G. led the writing of the manuscript.

Competing interests
The authors declare no competing interests.

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