Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Energy policy could curb Europe's overconsumption of critical material supply

Jonathan Peel

jonathan.n.peel@gmail.com

ETH Zurich

Aysha Cotterill

ETH Zurich

Cyril Chelle-Michou

ETH Zurich

Anthony Patt

ETH Zurich

Tim Tröndle

ETH Zurich https://orcid.org/0000-0002-3734-8284

Article

Keywords:

Posted Date: October 14th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11332632/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: There is **NO** Competing Interest.

Title:

Energy policy could curb Europe's overconsumption of critical material supply

Authors:

Jonathan N. Peel[1,4]✉, Aysha Cotterill[1,4], Cyril Chelle-Michou[3], Anthony Patt[1] & Tim Tröndle[1]

[1]Institute of Environmental Decisions, ETH Zurich, Zurich, Switzerland.

[3]Institute for Geochemistry and Petrology, ETH Zurich, Zurich, Switzerland

[4]These authors contributed equally: Jonathan N. Peel, Aysha Cotterill

✉email: jopeel@ethz.ch

Abstract

Demand from the global net-zero transition threatens to exceed the supply of critical materials. Europe's transition is well underway, yet European policy focuses on expanding supply, which is slow to scale. Here, we analyse how energy-system designs and sub-technology choices could keep Europe's material demand within benchmark shares of global supply to 2050. In a reference scenario, demand for 23 of 24 critical materials exceeds Europe's per-capita share. Non- and low-permanent-magnet drivetrains in wind turbines and electric vehicles most effectively relieve rare earth overconsumption, yet industry is moving towards more magnets. Sodium-ion or low-cobalt batteries and iridium-free electrolysers also substantially reduce overconsumption. Aluminium grids relieve copper demand and expanded nuclear power relieves most materials, though with non-material trade-offs. Nickel and copper demand remains high even under extreme mitigation, as do five other materials dominated by non-energy demand. Avoiding overconsumption therefore requires technology-specific energy policy alongside economy-wide demand reduction.

[main; 2,852 words]

As part of its energy transition, Europe is rapidly building infrastructure for low-carbon electricity generation[1], the electrification of heat and transport, sector coupling, and electricity transmission[2]. Due to the scale and pace of the transition globally, the International Energy Agency and others project that supply chains will fall short of demand for many materials critical to the transition[2–4]. The EU Critical Raw Materials Act tackles this by changing permitting policy to increase supply[5,6]; however, mine lead times are 17 years on average[2] and investment in exploration is falling[3]. Therefore, European policy should also consider how to reduce the material consumption of the transition[6].

A fast-growing body of literature examines how to mitigate material overconsumption in net-zero energy systems. However, no study has yet asked how design and technology choices across Europe's whole energy system could keep its material demand within supply capacities. Most focus on the transition globally[4,7–9], in China[10,11], or in other individual countries[12,13]. The few with a European scope cover only individual sectors: power system demand[1,14], transport[15], or a subset of sectors[16]. Meanwhile, broader European energy system studies do not account for material needs, as shown by an ex-post analysis of 59 studies[17].

Assessments of material demand against reserves or supply share a common methodological structure. They apply material intensities ex-post to pre-published capacity projections[4,7,8,14,17–19], most often from integrated assessment models[4,7,8,19], and mitigate material demand either via a shrink factor applied to material intensity[15,20] or with optimised sub-technology market shares[4,11,17]. Neither approach changes the mix of installed technology capacities such that the system is still technically feasible. Energy system optimisation, by contrast, produces systems that are feasible by construction. By varying explicit model assumptions, or by extending the solution space to near-optimal systems using modelling to generate alternatives[21–23], we can explore alternative technology mixes that remain feasible.

Here, we ask which technology choices let Europe stay within different shares of global critical material supply until 2050, and which materials warrant the most concern. We analyse demand against supply for 24 materials across 35 European countries under a net-zero sector-coupled energy system. We model the energy system's material demand by multiplying built capacities by material intensities. We obtain built capacities by augmenting the energy system model, PyPSA-Eur[24], with an electric vehicle (EV) stock turnover and grid expansion models. We calculate the material intensities of energy infrastructure by solving a prospective life cycle inventory in 2030 using the tool *premise*[25]. We also calculate Europe's non-energy demand, including the embodied demand from imported goods. We project global supply from 2025 to 2050 and allocate it to Europe using three methods adapted from the literature: *GDP-supply*, *per-capita-supply*, and *per-capita-reduced-supply*, the last of which considers less developed regions as more entitled to global resources[16] (Methods; Supplementary Fig. 4).

We test both (1) *system scenarios,* which change the optimisation problem of the energy model by varying modelling assumptions and applying modelling to generate alternatives, and (2) *market-share scenarios*, which shift sub-technology market shares (Table 1). These scenarios are deliberately extreme and bound what is technically possible. We group materials into two broad categories, *primary/co-product* and *by-product/synthetic option*, the former having less elastic supply (Methods). We find that a cost-optimal European energy system exceeds its per-capita supply allocation for 23 of 24 critical materials, but that technological levers, especially non-magnetic drivetrains and alternative batteries, substantially relieve this overconsumption.

Reference demand exceeds per-capita supply for 23 materials

We generate a reference scenario by combining the capacities of the cost-optimal European energy system with estimates of today's sub-technology market shares (Table 1). Combined energy-system and non-energy demand exceeds a per-capita share of global supply for every material except indium (Fig. 1). In particular, demands for cobalt and iridium exceed 50% of global supply in this scenario. Both have high energy-system demand, from batteries and electrolysers respectively, and high non-energy demand. Sixteen materials have greater non-energy than energy-system demand, and non-energy demand alone exceeds GDP-supply for five materials: cadmium, germanium, silver, iridium, and platinum. This is particularly concerning for platinum, a primary metal with high-confidence non-energy demand, even though we exclude the 55% of that demand from autocatalysts, which the transition retires (Supplementary Fig. 29). Copper and nickel, also primary metals, exceed GDP-supply through combined energy and non-energy demand across many sectors.

Reference energy-system demand overconsumes rare earths, battery materials, and iridium

In the reference scenario, the energy system contributes enough demand on its own to exceed GDP-supply for the battery materials cobalt and graphite, the magnet rare earths dysprosium and terbium, and the catalyst metal iridium (Fig. 1). We consider this overconsumption most critical for the rare earths, since these are co-products, making their supply less responsive to price signals (Methods). Dysprosium and terbium are the most critical of these, as they have less than 1% recycling and "extreme geopolitical production concentration"[26]. We consider this least critical for iridium, whose energy demand comes solely from today's electrolysers, which are expected to fall in iridium consumption (Discussion) and are readily substituted (Fig. 2); furthermore, iridium's non-energy demand was not directly available in the literature[27–30] , so it is assigned a low confidence.

The high energy-system demand for rare earths stems from permanent magnets in EV motors and in onshore and offshore wind turbine generators. Energy-system demand for cobalt and graphite exceeds GDP-supply, driven by stationary (grid) and, above all, EV batteries. The reference scenario calculates a far greater capacity of EV batteries (21.6 TWh) than stationary batteries (3.1 TWh). In Europe, 73% of EV batteries are cobalt-intensive nickel manganese cobalt (NMC) lithium-ion (Li-ion) batteries, compared with only 20% of stationary batteries. Finally,

iridium overconsumption stems from electrolysers supplying low-carbon hydrogen to industry and for energy storage (in the *H2 and V2G* scenario only; Table 1).

Non-magnetic drivetrains relieve rare earth overconsumption

To explore how to mitigate the energy system's critical material demand (Fig. 1), we apply 12 alternative scenarios with varying technology mixes and market shares (Table 1). Fig. 2 and Supplementary Fig. 1 show the effect of each scenario in isolation, for the energy-system and total demand, respectively.

As we consider rare earth overconsumption most critical (Fig. 1), a key scenario is *EV magnet pull*, which replaces permanent magnet motors with induction motors. Over 90% of EVs currently use permanent magnet motors, which are more rare-earth-intensive and costly than induction motors but offer superior efficiency and power density[2]. This scenario provides the greatest benefit for dysprosium, which has a particularly inelastic supply[26], bringing its energy system demand to less than GDP-supply (Fig. 2). The increase in copper caused by the rotor cage and stator of the induction motors is minimal relative to GDP-supply.

Scenarios that target wind turbines reduce magnet rare earth demand, but reducing installed wind capacity has significant trade-offs. *Wind magnet pull* replaces permanent magnet generators with induction-based generators in onshore wind. However, induction-based generators require more maintenance, so they are feasible for only about 5% of offshore turbines near the shore[2]. *Wind magnet pull* shifts offshore wind demand from direct-drive to gearbox turbines, trading efficiency and reliability for lower rare earth consumption. This especially relieves terbium overconsumption, and the increase in copper is negligible (Fig. 2). *Wind pull* reduces dysprosium and terbium demand most dramatically, but by cutting installed wind capacity it increases battery and semiconductor material demand, as more batteries and solar are needed to compensate (Supplementary Figs. 18–20). Combining all three scenarios practically eliminates the energy system's critical material demand for terbium, dysprosium, neodymium, and praseodymium (Fig. 3).

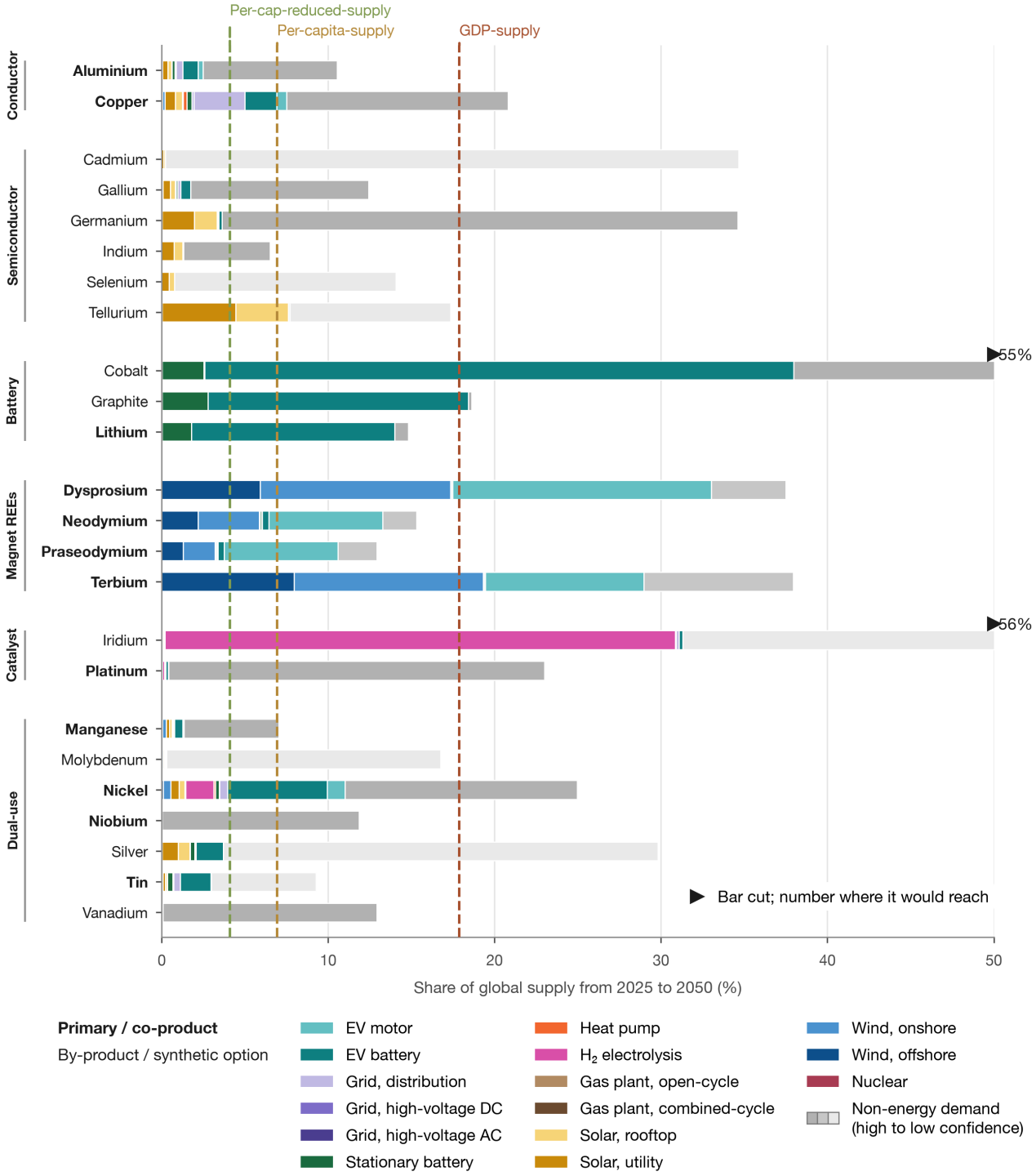


Fig. 1 | Critical material demands against supply from 2025 to 2050 for Europe in the reference scenario. The reference scenario uses capacities from a cost-optimal energy system with current estimates of market shares. Dotted lines show different allocations of global supply, where per-capita-reduced-supply is a per-capita weighting that also reflects Europe's lower entitlement to global supplies, as it is already more developed. For each material, non-energy-based demand is calculated using either a dedicated source (high confidence), a combined source (medium confidence), or a GDP-weighting of global non-energy demand (low confidence). Typeface indicates supply elasticity: *primary materials / co-products* (more inelastic) versus *by-products / synthetic option* (more elastic). Graphite refers to battery-grade graphite. EV, electric vehicle; REEs, rare earth elements.

Table 1 | System and market share scenarios.

Scenario name	Scenario type	Material focus	Implementation	Rationale
Reference	System	-	Unconstrained cost-optimal solution from PyPSA-Eur.	Provides baseline demand and point of comparison for later scenarios.
Solar pull	System	Semiconductor	Use modelling to generate alternatives to decrease solar investment with 15% slack.	Decrease solar demand for semiconductor materials, while maintaining energy system feasibility.
Wind pull	System	Magnet REEs	Use modelling to generate alternatives to decrease wind investment with 15% slack.	Decrease wind demand for copper and magnet rare earths, while maintaining energy system feasibility.
Nuclear push	System	General	Use modelling to generate alternatives to increase nuclear investment with 15% slack.	Nuclear has a low demand for critical materials, so increasing it reduces the energy system's dependence on wind, solar, and batteries.
H2 and V2G	System	General	Enable seasonal hydrogen storage and vehicle-to-grid charging technology.	Hydrogen storage and vehicle-to-grid charging help balance electricity supply and demand; enabling them reduces the required grid-scale battery storage and its material demand.
Reference	Market share	-	Estimates for present-day market shares in Europe.	Serves as a reference point against other scenarios.
EV NMC-811 push	Market share	Battery	100% of EV battery demand from Li-ion NMC-811.	Shift to lowest-cobalt batteries, while staying within the dominant Li-ion NMC chemistry.
EV LFP push	Market share	Battery	100% of EV battery demand from Li-ion LFP.	Shift to the dominant Li-ion chemistry in China, eliminating nickel, manganese, and cobalt.
EV Na-ion push	Market share	Battery	100% of EV battery demand from Na-ion.	Shift to Na-ion, reducing lithium, graphite, and cobalt.
EV magnet pull	Market share	Magnet REEs	Share of EV motors that are induction motors increases from 10% to 100%.	Shift EV permanent magnet motors from 90% market share to 0% to reduce demand for magnet rare earths.
Wind magnet pull	Market share	Magnet REEs	100% of onshore wind turbines become GB-DFIG; offshore, 95% become GB-PMSG and 5% remain GB-DFIG (current market share).	Shift demand away from permanent magnet-based generators; GB-DFIG has the lowest REE demand and already dominates onshore wind; GB-DFIG is not suitable for offshore wind, except for very nearshore applications (5% of market share), so the remaining market must be from PMSG. We choose the gearbox variant of PMSG, which has approximately a third of the rare earth demand of its direct-drive counterpart[1].
Silicon PV push	Market share	Semiconductor	Reduce market share of all thin-film solar technologies to 0%; crystalline silicon increases from 95% to 100%.	Reduce demand for limited semiconductor materials in thin-film solar panels.
Grid aluminium push	Market share	Conductor	Replace the grid's copper content with the equivalent aluminium for the same conductance.	Shift demand from copper to a metal with greater supply.
Electrolyser PEM pull	Market share	Catalyst	Proton exchange membrane market share decreases from 22% to 0%. Other technologies grow proportionally to compensate.	Reduce excess demand for iridium that stems from PEM electrolysers.

Slack is the maximum permitted increase in total system cost above the cost optimum (Methods). DD, direct drive; DFIG, doubly fed induction generator; EV, electric vehicle; GB, gearbox; H2, hydrogen; LFP, lithium iron phosphate; Na-ion, sodium-ion; NMC, lithium nickel manganese cobalt oxide; PEM, proton exchange membrane; PMSG, permanent magnet synchronous generator; PV, photovoltaic; REE, rare earth element; V2G, vehicle-to-grid.

EV battery and electrolyser sub-technologies matter

All EV battery scenarios reduce cobalt demand, with varying effects on graphite and lithium, and sodium-ion (Na-ion) batteries achieve the greatest reductions with the fewest side effects on other materials. Cobalt-containing NMC and nickel cobalt aluminium oxide (NCA) batteries hold 85% of the European market (Supplementary Table 4). We test three alternatives, each taking the whole market: low-cobalt NMC-811, cobalt-free lithium iron phosphate (LFP), and Na-ion, which is less widespread than Li-ion owing to its lower energy density[31]. We find all scenarios reduce cobalt significantly, with *EV NMC-811 push* having the most modest effect. The *EV Na-ion push* scenario also significantly reduces graphite and lithium demand, bringing their total critical material demand below GDP-supply (Supplementary Fig. 1). Each scenario has trade-offs: *EV LFP push*, *EV NMC-811 push*, and *EV Na-ion push* increase graphite, nickel, and manganese, respectively. The largest is from *EV LFP push*, which raises the energy system's graphite demand above GDP-supply (Fig. 2). Overall, *EV Na-ion push* reduces all three battery materials the most, bringing each under either per-capita-reduced-supply or a 10% energy-system contribution (Fig. 3, Supplementary Table 10).

Switching to alternative electrolyser technologies practically eliminates the energy system's iridium demand (Fig. 2). Proton-exchange-membrane (PEM) electrolysers, about a fifth of today's electrolyser capacity[32], depend heavily on iridium and platinum catalysts, while alkaline and solid-oxide electrolysers use neither[33]. *Electrolyser PEM pull* replaces PEM with alkaline and solid-oxide electrolysers, eliminating this iridium demand. Although PEM electrolysers account for a third of platinum's energy-system demand (Supplementary Fig. 3), removing them shifts platinum energy-system and total demand by less than 1 percentage point of GDP-supply (Fig. 2, Supplementary Fig. 1).

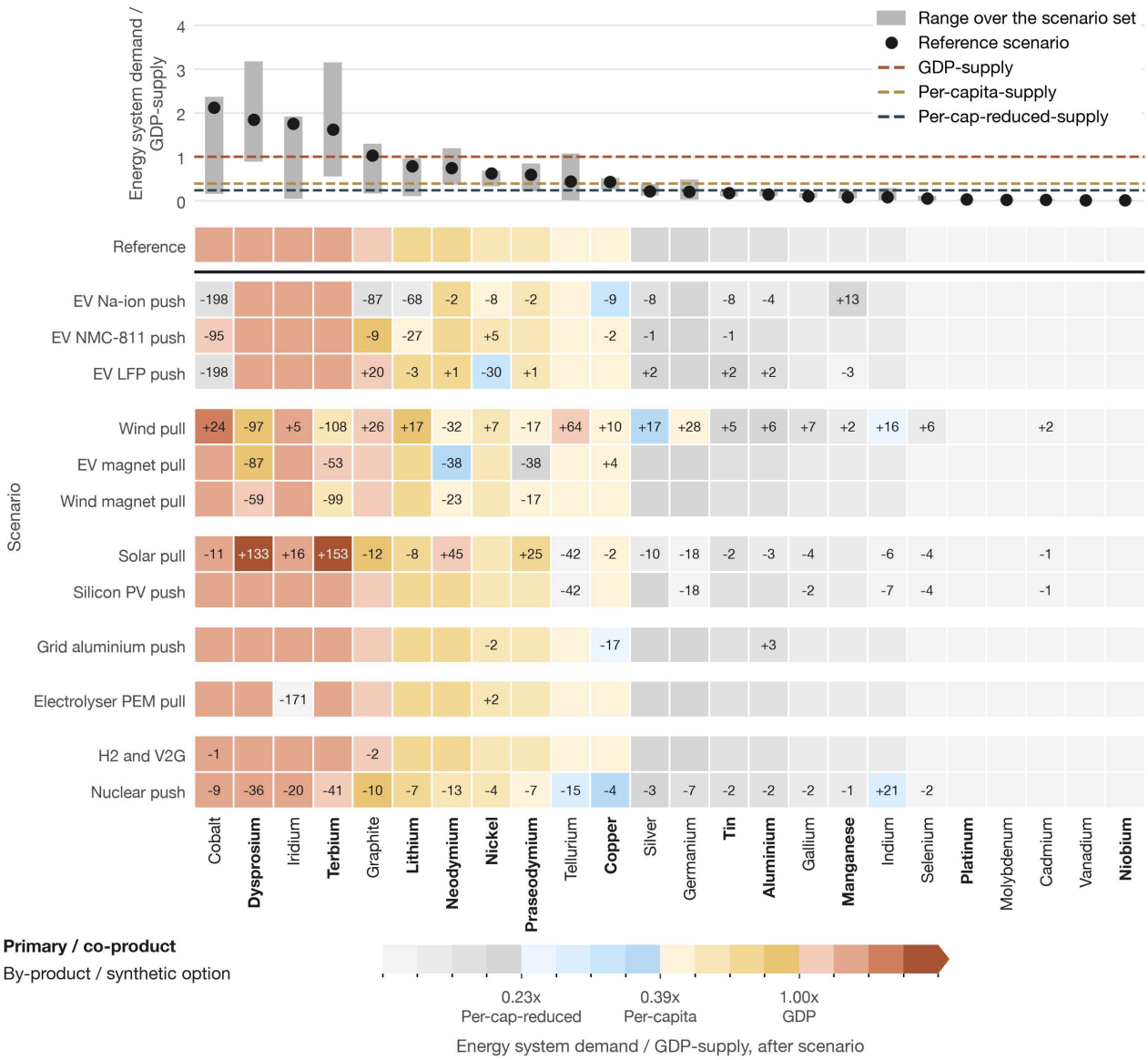


Fig. 2 | The effect of each scenario on the energy-system demand of each critical material. Above the matrix, for each material, we show the *relative demand* (i.e., the demand from the energy system divided by GDP-supply). We display the value of this fraction for the reference scenario as a point and the range across scenarios as a grey band. The matrix itself has a row for each scenario and a column for each material. Each cell of the matrix is coloured to again show the relative demand after a scenario is applied. The number in each cell displays by how many percentage points the relative demand changes as a result of each scenario. To isolate the effect of each lever, we combine each system scenario with the reference market share and each market-share scenario with the reference system. This figure does not include non-energy demand; see Supplementary Fig. 1 for the equivalent figure including non-energy demand. Typeface indicates supply elasticity: *primary materials / co-products* (more inelastic) versus *by-products / synthetic option* (more elastic). *Graphite* refers to battery-grade graphite. EV, electric vehicle; Na-ion, sodium-ion; NMC, nickel manganese cobalt; LFP, lithium iron phosphate; PEM, proton-exchange membrane; H2, hydrogen; V2G, vehicle-to-grid.

Grid aluminium, nuclear, and solar scenarios moderately relieve overconsumption

Substituting copper with aluminium in the electricity grid greatly reduces the energy system's copper demand with only a small increase in aluminium (Fig. 2). The decarbonised European energy system will require a large volume of additional electricity lines and cables (Methods),

which demand large quantities of conductive copper. *Grid aluminium push* brings total copper demand to just within GDP-supply (Supplementary Fig. 1), with insignificant effects on aluminium or nickel demand relative to their GDP-supplies.

Increasing installed nuclear capacity reduces critical material demands across all categories, most notably dysprosium and terbium (Fig. 2). *Nuclear push* uses modelling to generate alternatives to more than triple nuclear capacity, from 113 GW (the 2025 level, which caps all other scenarios) to 386 GW (Methods). Nuclear power has a mild material footprint, and increased nuclear capacity relieves the system of solar, wind, and stationary battery storage, along with their material demands. As well as relieving most other materials, *Nuclear push* increases total indium demand to exceed per-capita supply (Supplementary Fig. 1).

Installing less solar (*Solar pull*) has overwhelmingly negative consequences (Fig. 2), and increasing the share of silicon photovoltaic (PV) panels from 95% to 100% (*Silicon PV push*) reduces demand for semiconductor materials, but only tellurium moves significantly. *H2 and V2H*, which adds seasonal hydrogen storage and vehicle-to-grid (V2G) charging to balance electricity supply and demand, reduces grid storage requirements and uses the existing EV stock more efficiently, but barely changes battery material demand.

Energy system demands of copper and nickel are the most difficult to reduce

For each critical material, we model its lowest feasible demand by combining *system scenarios* and *market share scenarios* to minimise energy-system demand (Fig. 3). The scenario combinations that yield the minimum demand are in Supplementary Table 1. Under these extreme combinations, almost all materials end up with total demand within per-capita-reduced-supply or with less than 10% of total demand coming from the energy system. The most notable exceptions are nickel and copper (Fig. 3), two primary materials, as both are used extensively across the energy transition and cannot easily be substituted.

Discussion

We investigate how varying the design and sub-technology choices in Europe's energy transition can reduce its consumption of the global supply of critical materials to 2050, while still achieving net-zero. We find that a cost-optimal energy system with current market shares of technologies would consume more than Europe's per-capita allocation in 23 of 24 materials. We also find that many technological levers, especially non-magnetic drivetrains and alternative batteries, could significantly reduce overconsumption, but that overconsumption is unavoidable for nickel and copper.

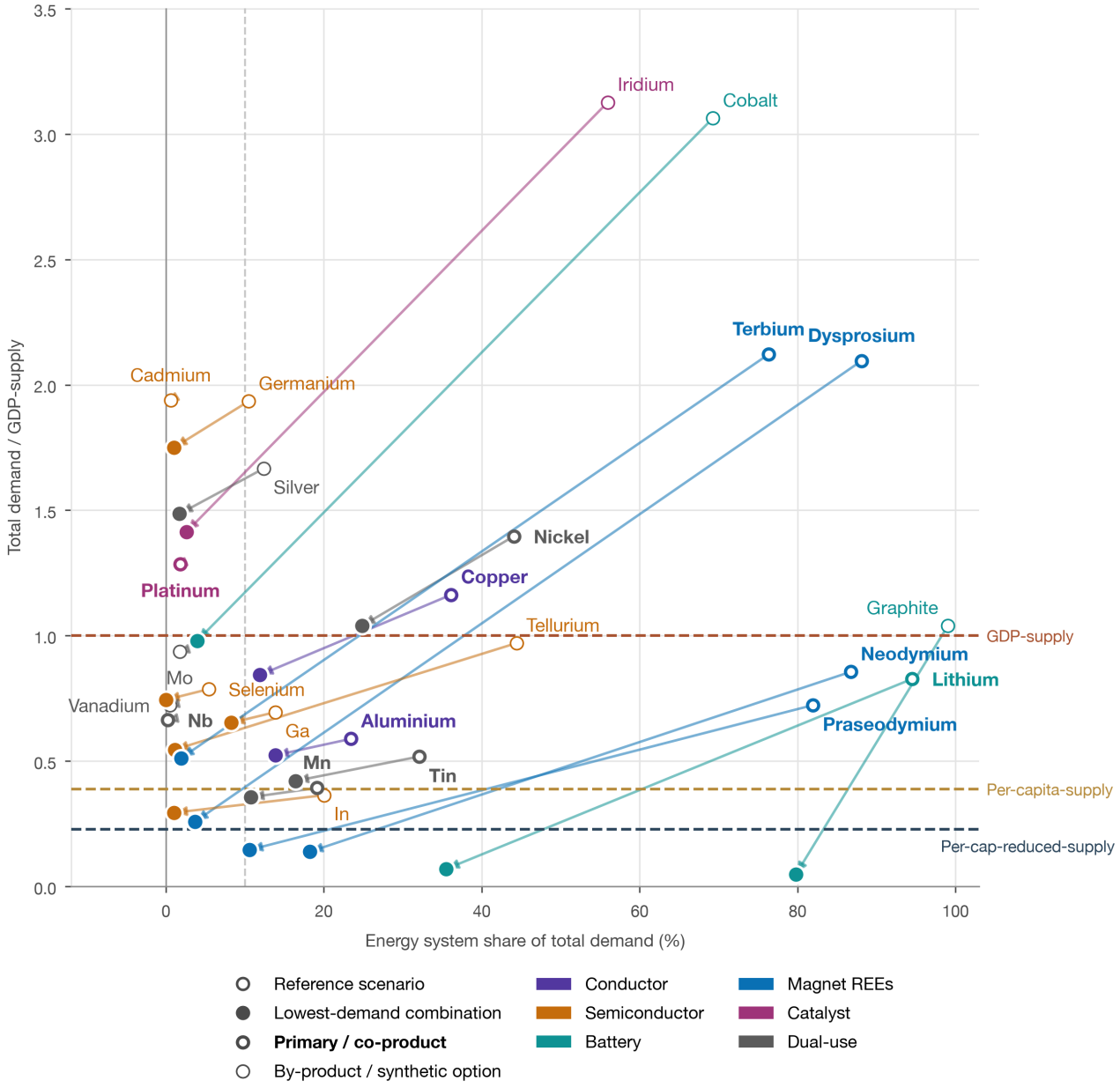


Fig. 3 | Energy system share and total demand from the reference scenario to the lowest feasible demand. For each material, we show the reference demand as a starting point and the lowest-demand combination as a destination point. The lowest-demand combination is the minimum that can be achieved through any feasible combination of the modelled scenarios; it combines exactly one system scenario with one or more market share scenarios. The scenarios resulting in the lowest demand are given in Supplementary Table 1. An additional dashed line marks 10% on the x-axis. Typeface indicates supply elasticity: *primary materials / co-products* (more inelastic) versus *by-products / synthetic option* (more elastic). *Graphite* refers to battery-grade graphite. Note that these reductions are the maximum possible for each material and could not necessarily be produced simultaneously. Some metals were abbreviated for display: Ga, gallium; In, indium; Mn, manganese; Mo, molybdenum; Nb, niobium.

We find that non-magnetic drivetrains for wind turbines and electric vehicles are essential for reducing magnet rare earths, corroborating previous findings[4,11,14]; however, industry is trending towards higher rare-earth demand to improve efficiency and reduce maintenance. For onshore wind, the share of permanent magnet turbines doubled from 2010 to 2020 and is projected to reach 40% by 2040[2]. For offshore wind, turbines are already 95% permanent magnet-based, but

systems with a gearbox have reduced rare earth demand; however, patents for direct drive drivetrains for offshore wind have increased from 67% in 2002 to 80% in 2018[34] due to the reduced maintenance needs of direct drive systems. Similarly, the market share of permanent magnet-based EV motors is over 90% and has risen in recent years. Induction motors draw energy from the battery to create a magnetic field that a permanent magnet provides naturally, so automakers have transitioned to permanent magnet motors to enable longer range. For example, Tesla's *Model Y Standard Range* (2022) used an induction motor, and the *Model Y Long Range RWD* (2024) uses a permanent magnet. Turbine manufacturers and automakers may benefit from keeping competitive non- or low-magnet turbines and vehicles in production as a hedge against rare earth shortages. Moreover, after the 2010 rare earth supply shock, the Japanese government supported research and development to redesign motors and other components, bringing Japan's rare earth demand to 30% below 2010 levels[3]; European policymakers could follow suit to keep rare earth consumption within a given share of global supply.

We find that Europe's battery material overconsumption would fall with a near-term shift to lower-cobalt Li-ion and a longer-term shift to Na-ion batteries, as supported by transport-focused studies[15]; however, European adoption is slow, especially compared with China. In 2025, high-cobalt NMC batteries had already fallen to ~0% of EVs sold in China, while LFP had reached 80%; in the EU, these figures were 81% and 13%, respectively[3]. Na-ion technologies currently have no market share in Europe or China, but Chinese manufacturers CATL and BYD now offer commercial options[3]. Policymakers could accelerate the shift to lower-critical-material batteries with industrial policy, such as subsidies or procurement criteria, that rewards lower material footprints.

PEM electrolysers and copper grids have effective alternatives with minimal trade-offs. We find that PEM electrolysers demand high quantities of iridium and platinum, which, at only 22% market share, push the energy system's iridium demand above GDP-supply, echoing global findings[35]. Mature alternatives such as alkaline electrolysers and research and development to improve the iridium efficiency of PEM electrolysers are likely effective levers. Substituting the grid's conductive copper with aluminium is already supported on a global level[2,4], and we find it brings total copper use under GDP-supply with negligible side effects for aluminium. Aluminium already dominates overhead lines, where weight and cost are the primary objectives, whereas copper dominates underground cables, where minimising the cross-section of cables is paramount. Given the extensive new transmission infrastructure required, we recommend that projects actively pursue aluminium conductors.

Increasing installed nuclear capacity relieves demands for many materials, in exchange for increased indium demand; however, this comes with non-material trade-offs. Our *Nuclear push* scenario more than triples installed nuclear capacity to 386 GW, an unprecedented rise: official high-nuclear scenarios total only ~168 GW by 2050 (EU with 144 GW[36]; UK with 24 GW[37]). Building significantly more nuclear power by 2050 would also face rising costs, long build times,

and political opposition[38]. The critical material co-benefits of nuclear power are therefore real but must be weighed against these challenges.

Finally, despite global studies recommending it[4,8,11], we do not believe minimising thin-film solar is an important lever to reduce Europe's critical material overconsumption. We find this lever only significantly moves tellurium, which is a by-product with more elastic supply. Moreover, thin-film solar has a small market share, and engineers use it for its thinness and flexibility in bespoke applications[39].

To mitigate Europe's critical material demand until 2050, policymakers need to consider levers beyond the energy system. Non-energy demand exceeds GDP-supply for five materials, most critically platinum. Moreover, even under extreme scenarios, nickel and copper retain high energy-system and total demand, as each has diverse uses across the energy transition and the broader economy. The result for copper is corroborated by global[4] and Chinese[11] studies, whereas the nickel result is new. As both are primary metals, their supply will be constrained by lengthy mine lead times (Methods). Following global studies[4], we recommend economy-wide efforts to reduce Europe's critical material consumption so that shortages do not impede the necessary energy transition.

A limitation of our work is that we collapse the time dimension to study only total supply and demand to 2050. This reveals shortages but not bottlenecks, which further work could investigate with an energy system pathway model. Our results are also sensitive to prospective material intensities, which may change. For instance, material efficiency for neodymium and praseodymium in permanent magnets may improve by up to 30% between 2015 and 2030[2]. Additionally, material supply to 2050 remains highly uncertain. Supplementary Section 2.6 details all supply estimation methods, and we call for greater availability of mining and refining data and projections.

Overall, we contribute the first assessment of how design and technology choices across Europe's sector-coupled energy system affect its critical material demand relative to its share of global supply. By developing a bespoke model based on energy system optimisation and prospective life cycle inventory, we show which technology levers relieve shortages and which materials require action beyond the energy system.

Methods

Supplementary Figure 4 shows a diagram of our methodology, which is self-contained and fully reproducible from source data using the workflow management tool, Snakemake, along with Python at github.com/jonathan-peel/material-balance. We divide our model into four main parts: material intensity, energy system model, supply, and other-sector consumption. These are subject to our chosen system and market share scenarios for the geographical and materials scope of our study.

Geographical scope and material selection

Our study is based largely on the open-source energy system model, PyPSA-Eur[24]. Therefore, we scope our study to this model's default 34 geographically European countries (Supplementary Fig. 5).

We select 24 materials that are critical to the energy transition, termed "critical materials" throughout, from the union of a policy screen and a literature screen. This deliberately generous selection avoids omitting any material that could be important. Our final list of materials is mostly metals, with some metalloids (germanium and tellurium) and non-metals (graphite and selenium).

The policy screen is based on the EU's strategic raw materials list (Annex I)[5]. The EU designates strategic materials based on a material's relevance in technologies "for the green and digital transition as well as defence and aerospace applications" and accounts for forecasted demand growth and difficulty in increasing global production. We filter to select materials that are foreground in the technologies we model.

The policy screen omits some materials important to the energy transition, especially those relevant to solar sub-technologies. Therefore, we also apply a screen based on the literature. For each material in a global study on material bottlenecks in the energy transition[4], we calculate the ratio of the transition-led demand (the total demand minus the authors' "Rest-of-Economy" demand) to the projected primary production capacity in 2050. We select all materials above 5%; Supplementary Fig. 7 shows the sensitivity to this threshold. This results in the addition of vanadium, tellurium, tin, molybdenum, silver, selenium, indium, cadmium, and niobium. We exclude two materials: silicon, because its binding constraint is polysilicon refining capacity, for which no robust projection exists (unlike graphite, for which the IEA provides a forward-looking supply projection); and boron, because its energy-system demand is orders of magnitude below that of any other material considered.

For graphite, we consider only battery-grade spherical purified graphite, from either natural or synthetic sources; embodied non-battery-grade graphite is out of scope. We make this choice because the IEA provides a robust projection for anode graphite[3], which is matched by a life cycle inventory for the same type of graphite (Material intensities). A supply-demand comparison for other forms of graphite is not currently available.

Material categorisation

We place materials into two broad categories according to how readily their supply would respond to price signals when demand exceeds supply: *primary/co-product* and *by-product/synthetic option*. We consider the primary/co-product category harder to scale due to how the economics of mining impact the availability of their ore. The availability of mined ore for primary materials is determined by the market for the material itself; for co-products, it is determined by the market for this material in balance with other co-products; and for by-products, it is determined by the market for another material, termed the host material[40]. To scale the supply of primary and co-product materials, new mines must be built, since the

354 quantity of ore mined is already set to match demand for the final materials. Conversely, the
355 recovery rate for by-products is generally low, meaning there is by-product in the ore that is never
356 extracted. Therefore, by-product supply can be scaled by recovering more of the material from
357 ore that is already mined, rather than discarding it[41,42]. In summary, after an increase in demand,
358 the supply of a primary or co-product material will scale at the rate new mines are built, which
359 takes 17 years on average[2], and the supply of a by-product can scale more immediately, provided
360 the large recovery headroom is not exhausted[41]. Similarly, some materials, such as graphite, can
361 be produced synthetically, so their production is not limited by long mine lead times[3]. We give
362 the classifications of materials in Supplementary Table 3.

363 **Scenarios**

364 We use two types of scenarios: system scenarios and market share scenarios (Table 1). We
365 design these (1) to be simple and therefore interpretable and (2) to explore the extrema of
366 different technologies and thereby bound the material demands of feasible energy systems.

367 System scenarios vary the assumptions of the energy system model, yielding different built
368 capacities. We do this in two ways: for *H2 and V2G*, we change the model assumptions to enable
369 energy storage via hydrogen and vehicle-to-grid charging, and for *wind pull*, *solar pull*, and
370 *nuclear push*, we use modelling to generate alternatives (MGA), i.e., we minimise or maximise
371 investment in the focus technology while allowing total system cost to rise to at most 15% above
372 the cost optimum (see Sector-coupled energy system modelling). In the reference scenario, we
373 use the cost-optimal energy system under standard assumptions (Sector-coupled energy
374 system modelling).

375 Market share scenarios vary the sub-technology market shares used to calculate the material
376 demand of each technology. Except for the reference scenario, all market share scenarios apply
377 extreme, arbitrary shifts towards particular sub-technologies. In the reference scenario, we
378 estimate Europe's current market shares, using global values for technologies where Europe-
379 specific data is not available (Supplementary Table 5). These scenarios are listed and visualised
380 in Supplementary Table 4 and Supplementary Fig. 8, respectively.

381 To make a full scenario, we combine a system scenario with a market share scenario. Fig. 1
382 shows the reference scenario, with a cost-optimal energy system with current sub-technology
383 market shares. Fig. 2 and Supplementary Fig. 1 show the effect of each scenario in isolation.
384 That is, we combine the reference market share scenario with each system scenario, and the
385 reference system scenario with each market share scenario. The results shown in Fig. 3 iterate
386 through all combinations of system and market share scenarios to find the greatest decrease in
387 demand for each material.

388 **Technologies and sub-technologies**

389 Supplementary Table 4 shows all the technologies and sub-technologies we select for the
390 energy system, as well as their market shares in the reference scenario.

Battery sub-technologies differ mainly in cathode chemistry. All except sodium-ion (Na-ion) batteries are lithium-ion (Li-ion) batteries with graphite anodes. Nickel manganese cobalt (NMC) cathodes are shifting towards lower cobalt content to increase energy density and reduce reliance on controversial cobalt supply chains; NMC-811 is the lowest-cobalt variant that we model. Lithium iron phosphate (LFP) cathodes contain no nickel, manganese, or cobalt and offer longer lifetimes and better thermal stability, but lower energy density; they already account for most EV sales in China[3]. Nickel cobalt aluminium (NCA) cathodes offer high energy and power density but lower thermal stability[2,13]. Na-ion batteries replace lithium with sodium and graphite with a hard-carbon anode, avoiding both materials, but have lower energy density and are the least mature of the modelled technologies. Solid-state and vanadium-flow batteries are outside our scope owing to their limited commercial deployment.

EV motors are mainly permanent magnet or induction motors. Permanent magnet motors hold about 90% of the market owing to their higher efficiency and power density, whereas induction motors avoid magnet rare earths[3]. Wind turbines differ mainly in generator type: direct-drive permanent magnet synchronous generators (PMSGs) have the highest magnet rare earth demand, followed by gearbox PMSGs[2]. In the Wind magnet pull scenario, we use gearbox doubly fed induction generator (DFIG) turbines onshore, as they have the lowest rare earth demand, and gearbox PMSGs for most offshore turbines (Table 1).

Crystalline silicon cells dominate the solar market; thin-film technologies, which have varying material footprints, hold about 5%.

We derive grid material demand from the line and cable lengths built in the energy system model for its three grid technologies: high-voltage alternating current (HVAC), high-voltage direct current (HVDC), and distribution (Sector-coupled energy system modelling). Each technology comprises sub-technologies with life cycle inventory data (Material intensities). HVAC has a single sub-technology, HVDC comprises subsea and land cables, and the distribution grid is split by voltage level. For the Grid aluminium push scenario, we keep the sub-technology mix fixed but replace each sub-technology's copper conductor with aluminium of equal conductance, as recommended in the literature[2,4,10]. Because aluminium already dominates overhead lines, where weight matters more than cross-section, the substitution has the least effect on HVAC lines, which are mostly overhead (Supplementary Fig. 24).

Sector-coupled energy system modelling

To model the energy system material demand, we require the built capacities of energy system infrastructure. We model the European sector-coupled energy system by augmenting the open-source energy system model, PyPSA-Eur[24], with an EV stock turnover and grid expansion model. PyPSA-Eur models technologies and demands across generation, heating, transport, industry, and other sectors. In generation, we enable wind, solar, grid batteries, hydroelectricity (dammed, pumped, and run-of-river), nuclear, and open- and combined-cycle gas plants. The sector-coupling technologies we enable are EVs, heat pumps, hydrogen electrolysis, and synthetic fuel production, with vehicle-to-grid technology and hydrogen fuel cells depending on

the scenario. We also enable direct air capture and storage to provide expensive offsets for the gas plants, aviation, and other sectors. We run PyPSA-Eur as an overnight optimisation of 2050 with a net-zero CO_2 constraint to represent the final state of the transition. We keep hydroelectricity at its existing capacity and calculate material demand from the expanded capacities only. We optimise over 12 months of weather data (2013), and we set the temporal resolution to 2 hours, finer than the 3-hour maximum needed for the optimisation to produce a realistic amount of battery storage[43]. The costs for each technology are the defaults from PyPSA-Eur[24], and we do not adjust these for different sub-technology market shares.

Modelling to generate alternatives (MGA) is a way to explore other feasible but not cost-optimal energy systems[21,22]. We use MGA to explore energy systems that rely less on wind or solar, and therefore less on their critical materials, or more on nuclear. We use 15% slack, which is within the 9–23% deviation of real-world energy systems found by Trutnevyte[44]. We choose a higher slack than the values of 10% or less common in the literature, which have been criticised as too low[45] and because we want the MGA scenarios to match the extremity of the market share scenarios. More important than its absolute value is that the slack is constant across MGA scenarios, so that they can be compared. The results of different PyPSA-Eur optimisations are shown in Supplementary Figs. 15–17.

Formally, we first solve for the cost-optimal system, where x is the vector of all capacity and dispatch variables, c is the vector of their annualised costs, and $Ax \leq b$ represents the full set of PyPSA-Eur constraints (including energy balances, capacity limits, and the net-zero emissions constraint). This yields the optimal total system cost, C^*, in Equation 1.

$$C^* = \min_x c^\top x \quad \text{s.t. } Ax \leq b \tag{1}$$

For each MGA scenario, we then minimise (wind pull and solar pull) or maximise (nuclear push) the total installed capacity of the focus technology, k, subject to the same constraints and to total system cost rising by at most the slack, ε, above C^*, as shown in Equation 2.

$$\min/\max_x \sum_{n \in N} \sum_{s \in S_k} G_{n,s} \quad \text{s.t. } Ax \leq b, \qquad c^\top x \leq (1+\varepsilon) C^* \tag{2}$$

where $G_{n,s}$ is the installed capacity of generator type s at node n, N is the set of all nodes, and S_k is the set of generator types belonging to the focus technology (e.g., onshore and offshore wind for wind pull). We set $\varepsilon = 0.15$ in all MGA scenarios.

To estimate the material demand from EV batteries and motors, we calculate EV sales from 2025 to 2050 with a stock turnover model with a fixed lifetime, driven by PyPSA-Eur's projected EV share of the car fleet (Equations 3 and 4). t is a year between the model start year, when no EVs yet exist, t_0 (2020), and 2050, t_e. t_s (2025) is the first year for which we count EV sales; 2020–2024 are spin-up years. $s(t)$ is the EV share of the car fleet, taken from PyPSA-Eur at 5-year intervals and linearly interpolated in between. S is the stock, X is the number of sales, and R is the number of retirements, which equals the sales one lifetime earlier (the second term of Equation 3, where the indicator function $\mathbb{1}$ equals 1 if $t - L \geq t_0$ and 0 otherwise, so retirements

are zero before 2035); F is the total car fleet across the modelled region (306 M in 2023, from PyPSA-Eur, held constant), and L is the EV lifetime (15 years). Sales in each year are the growth in the EV stock plus the replacement of EVs retiring that year (Equation 3).

$$S(t) = Fs(t), \quad X(t) = S(t) - S(t-1) + \mathbb{1}_{t-L \geq t_0} X(t-L) \qquad [3]$$

Starting from $S(t_0 - 1) = 0$, the total number of EVs sold from 2025 to 2050 is given by Equation 4.

$$N = \sum_{t=t_s}^{t_e} X(t) \qquad [4]$$

Supplementary Fig. 8 visualises the resulting EV sales and retirements. Over 2025–2050, this gives 431 M EVs (1.41 times the fleet). We convert these sales into battery capacity assuming 50 kWh per EV (21.6 TWh in total) and one motor per EV.

To combine the grid expansion with the circuit-length-specific material inventories (Material intensities), we augment PyPSA-Eur to model the circuit-length added until 2050 for each of the HVAC, HVDC, and distribution grids from the optimised PyPSA-Eur network. Circuit-length is the total length of all circuits, counting parallel circuits separately, so it can be multiplied directly by the per-kilometre material inventories.

We estimate the added HVAC grid circuit-length, L_{HVAC}, using Equation 5. The final real-world circuit-length of the PyPSA network is not available, since PyPSA-Eur clusters the network before optimisation. Therefore, we calculate the network expansion ratio, r_{HVAC}, and multiply it by the initial brownfield unclustered circuit-length, L_b. l_b and l_f are the brownfield and final capacity-lengths, respectively, of the clustered PyPSA network.

$$L_{\mathrm{HVAC}} = r_{HVAC} L_b = \frac{l_f - l_b}{l_b} L_b \ [\mathrm{circuit-km}] \qquad [5]$$

We estimate the added HVDC circuit-length, L_{HVDC}, differently, because HVDC is modelled as a PyPSA component that reports capacity-length rather than circuit-length. Equation 6 shows this calculation, where G_b and g_b (GW-km) are the capacity-lengths of the brownfield unclustered and clustered network, respectively, giving the clustering correction, c_{HVDC}. G_e (GW-km) is the expanded capacity-length created by the optimisation, and $P_{ref} = 0.7$ GW is the reference capacity of a NorNed-class 450 kV bipole described by the ecoinvent HVDC inventories[46].

$$L_{\mathrm{HVDC}} = c_{HVDC} \frac{G_e}{P_{ref}} = \frac{G_b}{g_b} \frac{G_e}{P_{ref}} \ [\mathrm{circuit-km}] \qquad [6]$$

We estimate the added distribution circuit-length, L_{dist}, differently again, since PyPSA-Eur models this as a single node without a circuit-length or a capacity-length. However, the distribution links have a present-day counterpart, the peak exogenous low-voltage load they already serve, which we use to estimate the distribution network capacity growth, r_d. P_f is the model's optimised distribution-link rating, summed over nodes; P_0 is the present-day low-

voltage load peak, calculated as the sum of each node's peak exogenous load; and $L_0 = 10^7$ circuit-km is the existing European distribution grid stock[47].

$$L_{dist} = r_d L_0 = \frac{P_f - P_0}{P_0} L_0 \text{ [circuit} - \text{km]} \quad [7]$$

Material intensities

To find the energy system material demand, we multiply the built capacity from the energy system model by the material intensities of each sub-technology, weighted by their market shares. To find the material intensities, we build a database with foreground and background inventories, run a life cycle inventory (LCI) to find the raw mineral flows for each sub-technology, and finally clean the output and derive the induction motor intensities.

We build the inventory database from multiple sources using the Python package, Brightway[48]. Using premise 2.3.0[25], we project the ecoinvent 3.10 (cut-off) database[49,50] to 2030 under the TIAM-UCL SSP2-RCP1.9 pathway. Most sub-technologies are existing activities in this database. For wind turbines, PV modules, and electrolysers, we use bills of materials from the literature and build each sub-technology as a new activity that purchases every listed material from the database. For the aluminium-conductor grid, we copy the five ecoinvent grid datasets and replace their conductor copper with the mass of aluminium of equal resistance (0.477 kg per kg of copper[51,52]), leaving every other input unchanged; a comparison of each grid sub-technology with its aluminium counterpart is in Supplementary Fig. 24. Supplementary Tables 6 and 7 show the source of each sub-technology's material database and the years of the foreground and background inventories, respectively.

We run the LCI for each activity and extract the biosphere flows for each material. The exception is graphite, which we read from the technosphere supply of battery-grade synthetic graphite. We clean the raw LCI output by keeping only embodied materials (those that end up in the product) and excluding other materials extracted alongside them in the same ore, which are used elsewhere. Finally, since a bill of materials for an induction motor was not available in the literature, we derive its intensities directly from ecoinvent's permanent magnet motor and multiply the copper and rare earth proportions by a factor derived from the literature[53]. The resulting material intensities are visualised in Supplementary Figs. 18–23 .

For battery anodes, ecoinvent uses "synthetic graphite, battery grade". We assume this accounts for both natural and synthetic pathways to provide battery-grade graphite, so this demand is comparable with the IEA's "graphite (battery-grade)" supply projections (Material supply and allocation).

Material supply and allocation

To estimate the future global supply of the critical materials in this study, we use multiple sources and methods to address inconsistent coverage across materials. Where available, we use the IEA's critical minerals data[3], which provides projections for four metals (cobalt, copper, lithium, nickel) and battery-grade graphite. Next, we use Our World in Data (OWID)[54], who

compile and process historical mining and final supply data from the US Geological Survey[55], Kelly et al.[56], and the British Geological Survey[57]; linearly extrapolating this historical data provides estimates for most of our materials. Finally, Lundaev et al.[58] provide further historical time series (notably for the individual magnet REEs), which we also linearly extrapolate, as well as their own projection (termed "source projection"), which the authors intended as a theoretical output rather than a realistic projection.

Different sources report different materials at different processing stages (e.g., mine or refined production) (Supplementary Table 8). Where possible, we directly use time series for the final stage of production, after which a material enters the market (usually the "refinery" stage), which we refer to as "direct". For materials without such direct data, we use mining data multiplied by a recovery ratio (accounting for material lost between mining and the final stage) from Nassar et al.[59]. For by-products, we multiply the projection of the host metal's mining output by a yearly extrapolated by-product ratio, i.e., the amount of refined by-product that enters the market for each unit of host metal mined. This means the projection of by-product supply is derived mechanistically from the trajectory of its host metal and by the development of additional recovery capacities to follow market demand, as it is in the real world. We note the similarities in this method to the approach in the literature[4]. Supplementary Section 2.6 describes this process in detail.

To allocate global demand to a European level, we use a framework developed by Malmaeus et al.[16], who investigate different allocations of the global metal demand to Europe's energy transition using different justice principles. They derive a *GDP-share* based on a grandfathering principle, a *per-capita share* based on an equality principle, and a *per-capita share adjusted for energy use* (which we term *per-capita-reduced*) based on an equality principle that also considers the greater needs of other world regions to develop energy infrastructure. We rederive these shares for our study's 34 countries.

Non-energy-based demand

Non-energy demand accounts for material demand from parts of the European economy we do not model. We consider consumption-based demand, which accounts for the material embedded in imported finished products, since most goods used in Europe are not made in Europe; this is consistent with how we estimate the embedded material demand of the energy system. For most materials, we calculate this quantity in a base year using a series of material system analysis (MSA) reports produced by the European Commission[27–30] and assign these estimates high confidence. These MSA reports aggregate magnet rare earths into one reported figure, so we assume a per-element composition for each application and assign a medium confidence. The remaining seven materials are not reported in the MSA reports, so we estimate the base year demand by scaling global figures from the literature[4,18] by Europe's share of global GDP; we do not use these studies' extrapolations of non-energy demand, since these apply global, not European, GDP growth until 2050.

Equation 8 shows our calculation, based on the MSA reports, of the non-energy consumption, $C^{non-energy}$, for a material, m, and base year of that material's report, $t_0(m)$,

$$C_{m,t_0}^{non-energy} = C_{m,t_0}^{total} \times f_{m,t_0}^{charged} \times f_{m,t_0}^{region}, t_0 = t_0(m) \quad [8]$$

where $t_0(m)$ is the base year of the report in which the material appears, C^{total} is the total EU economy consumption, $f^{charged}$ is the fraction of the total economy's demand charged to non-energy demand, and f^{region} scales the EU-27 or EU-28 region to our study's country set. The assumptions made for $f^{charged}$ are shown in Supplementary Fig. 29 and Supplementary Table 9.

We extrapolate the base-year consumption using first the study region's historical GDP[60] and second a European Commission long-term projection[61]. The full methodology and equations are in Supplementary Section 2.7.

Code availability

The full and reproducible workflow is available at github.com/jonathan-peel/material-balance.

AI statement

We used Claude Opus 4.8 for model development, exploration of data, and writing feedback.

We used Grammarly to correct writing errors.

CRediT author statements

Jonathan N Peel: conceptualisation, methodology, software, validation, data curation, writing – original draft, visualisation, supervision, project administration

Aysha Cotterill: methodology, software, data curation, writing – review and editing

Cyril Chelle-Michou: conceptualisation, methodology, validation, writing - review & editing, supervision

Anthony Patt: writing – review and editing, supervision

Tim Tröndle: conceptualisation, writing – review and editing, visualisation, supervision, project administration

References

1. Carrara, S., Alves Dias, P., Plazzotta, B. & Pavel, C. *Raw Materials Demand for Wind and Solar PV Technologies in the Transition towards a Decarbonised Energy System*. https://publications.jrc.ec.europa.eu/repository/handle/JRC119941 (2020) doi:10.2760/160859.
2. International Energy Agency. *The Role of Critical Minerals in Clean Energy Transitions*. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions (2022).
3. International Energy Agency. *Global Critical Minerals Outlook 2026*. https://www.iea.org/reports/global-critical-minerals-outlook-2026 (2026).
4. Bieuville, P., Majeau-Bettez, G. & de Bortoli, A. Technology flexibility and sobriety to address shortage of energy-transition metals. *Nat. Sustain.* **9**, 419–430 (2026).
5. European Parliament and Council of the European Union. *Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials and Amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020*. *OJ L, 2024/1252* (2024).
6. Herdlitschka, T., Luo, A. & Leipold, S. Supply-security narratives have dominated EU raw materials policy, while demand reduction has been sidelined. *Commun. Earth Environ.* **7**, 435 (2026).
7. Wang, S. *et al.* Future demand for electricity generation materials under different climate mitigation scenarios. *Joule* **7**, 309–332 (2023).
8. Wei, Y.-M. *et al.* Navigating energy transition solutions for climate targets with minerals constraint. *Nat. Clim. Change* **15**, 833–841 (2025).

9. Watari, T., Nansai, K. & Nakajima, K. Review of critical metal dynamics to 2050 for 48 elements. *Resour. Conserv. Recycl.* **155**, 104669 (2020).
10. Ushie, O. J. *et al.* Resilient strategies to mitigate the volatility of copper and aluminium critical mineral demand for net-zero electricity network production. *Sustain. Energy Res.* **12**, 56 (2025).
11. Dong, H. *et al.* Sub-technology market share strongly affects critical material constraints in power system transitions. *Nat. Commun.* **16**, 1285 (2025).
12. García-Gusano, D. *et al.* The future need for critical raw materials associated with long-term energy and climate strategies: The illustrative case study of power generation in Spain. *Energy* **314**, 134266 (2025).
13. Morfeldt, J., Johansson, D. J. A. & Davidsson Kurland, S. A combination of measures limits demand for critical materials in Sweden's electric car transition. *Commun. Earth Environ.* **6**, 163 (2025).
14. Kammen, D. M., Baranowski, M., Jabkowski, P. & Dutta, S. From gigawatts to critical mineral demands for EU solar and wind. *Nat. Energy* 1–10 (2026) doi:10.1038/s41560-026-02147-x.
15. Teixeira, B., Brito, M. C. & Mateus, A. Critical metal supply risks for EU electric vehicle batteries: supply-demand misalignments under production and recycling scenarios. *Miner. Econ.* https://doi.org/10.1007/s13563-026-00700-4 (2026) doi:10.1007/s13563-026-00700-4.
16. Malmaeus, J. M., Alfredsson, E. C. & Lindblom, E. On the allocation of critical metals between nations for a green and just transition. *Environ. Dev.* **54**, 101157 (2025).
17. Mutke, J., Finke, J., Esser, K. & Heinrichs, H. Materealistic? How European energy system models exceed raw material reserves. Preprint at https://doi.org/10.48550/arXiv.2606.12201 (2026).

18. Schlichenmaier, S. & Naegler, T. May material bottlenecks hamper the global energy transition towards the 1.5 °C target? *Energy Rep.* **8**, 14875–14887 (2022).
19. Shi, H. *et al.* Critical mineral constraints pressure energy transition and trade toward the Paris Agreement climate goals. *Nat. Commun.* **16**, 4496 (2025).
20. Eikeng, E., Makhsoos, A. & Pollet, B. G. Critical and strategic raw materials for electrolysers, fuel cells, metal hydrides and hydrogen separation technologies. *Int. J. Hydrog. Energy* **71**, 433–464 (2024).
21. DeCarolis, J. F., Babaee, S., Li, B. & Kanungo, S. Modelling to generate alternatives with an energy system optimization model. *Environ. Model. Softw.* **79**, 300–310 (2016).
22. Pickering, B., Lombardi, F. & Pfenninger, S. Diversity of options to eliminate fossil fuels and reach carbon neutrality across the entire European energy system. *Joule* **6**, 1253–1276 (2022).
23. van Greevenbroek, K., Grochowicz, A., Zeyringer, M. & Benth, F. E. Trading off regional and overall energy system design flexibility in the net-zero transition. *Nat. Sustain.* **8**, 629–641 (2025).
24. Neumann, F., Zeyen, E., Victoria, M. & Brown, T. The potential role of a hydrogen network in Europe. *Joule* **7**, 1793–1817 (2023).
25. Sacchi, R. *et al.* PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renew. Sustain. Energy Rev.* **160**, 112311 (2022).
26. Nassar, N. T., Graedel, T. E. & Harper, E. M. By-product metals are technologically essential but have problematic supply. *Sci. Adv.* **1**, e1400180 (2015).
27. Passarini, F., Ciacci, L., Nuss, P. & Manfredi, S. *Material Flow Analysis of Aluminium, Copper, and Iron in the EU-28*. (2018) doi:10.2760/1079.

28. Matos, C. T. *et al. Material System Analysis of Five Battery-Related Raw Materials: Cobalt, Lithium, Manganese, Natural Graphite, Nickel*. (2020) doi:10.2760/519827.
29. Matos, C. T. *et al. Material System Analysis of Nine Raw Materials: Barytes, Bismuth, Hafnium, Helium, Natural Rubber, Phosphorus, Scandium, Tantalum and Vanadium*. (2021) doi:10.2760/677981.
30. European Commission. *Update of the 2015 Material System Analyses*. (2024) doi:10.2873/440874.
31. Lombardo, T., Paoli, L., Fernandez Pales, A. & Gül, T. Sodium-ion battery momentum grows, but challenges remain. *IEA* https://www.iea.org/commentaries/sodium-ion-battery-momentum-grows-but-challenges-remain (2026).
32. Observatorio Tecnológico del Hidrógeno. *Renewable Hydrogen Production via Electrolysis: State-of-the-Art and Future Prospects*. https://www.enagas.es/content/dam/enagas/en/files/transicion-energetica/red-hidrogeno/observatorio-tecnologico-hidrogeno/oth-report-electrolysis-dic2025-eng.pdf (2025).
33. Gerloff, N. Comparative Life-Cycle-Assessment analysis of three major water electrolysis technologies while applying various energy scenarios for a greener hydrogen production. *J. Energy Storage* **43**, 102759 (2021).
34. European Patent Office & International Renewable Energy Agency. *Offshore Wind Energy: Patent Insight Report*. https://www.irena.org/Publications/2023/Nov/IRENA-EPO-Offshore-Wind-Energy-Patent-Insight-Report (2023).
35. Duke, C., Davies, B., Abdul-Manan, A. F. N. & McKechnie, J. Addressing the material gap in GW-scale Proton Exchange Membrane (PEM) electrolyser deployment is key to meeting the global green hydrogen ambition. *Resour. Conserv. Recycl.* **226**, 108687 (2026).

36. European Commission. *Nuclear Illustrative Programme Presented under Article 40 of the Euratom Treaty for the Opinion of the European Economic and Social Committee*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52025DC0315 (2025).
37. Department for Energy Security and Net Zero. *Civil Nuclear: Roadmap to 2050*. https://www.gov.uk/government/publications/civil-nuclear-roadmap-to-2050/civil-nuclear-roadmap-to-2050-accessible-webpage (2024).
38. Clarke, L. *et al*. Energy Systems. in *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Shukla, P. R. et al.) 613–746 (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022). doi:10.1017/9781009157926.008.
39. Junne, T., Wulff, N., Breyer, C. & Naegler, T. Critical materials in global low-carbon energy scenarios: The case for neodymium, dysprosium, lithium, and cobalt. *Energy* **211**, 118532 (2020).
40. Bigerna, S. & Campbell, G. The impact of by-product production on the availability of critical metals for the transition to renewable energy. *Energy Policy* **198**, 114515 (2025).
41. Holley, E. A. *et al*. By-product recovery from US metal mines could reduce import reliance for critical minerals. *Science* **389**, 1325–1331 (2025).
42. Mudd, G. M., Weng, Z., Jowitt, S. M., Turnbull, I. D. & Graedel, T. E. Quantifying the recoverable resources of by-product metals: The case of cobalt. *Ore Geol. Rev.* **55**, 87–98 (2013).
43. Gøtske, E. K., Andresen, G. B., Neumann, F. & Victoria, M. Designing a sector-coupled European energy system robust to 60 years of historical weather data. *Nat. Commun.* **15**, 10680 (2024).
44. Trutnevyte, E. Does cost optimization approximate the real-world energy transition? *Energy* **106**, 182–193 (2016).

45. Fossas-Tenas, A., Wen, X. & Trutnevyte, E. Empirical evidence for slack in Modeling to Generate Alternatives. *Energy* **360**, 141552 (2026).
46. Jorge, R. S., Hawkins, T. R. & Hertwich, E. G. Life cycle assessment of electricity transmission and distribution—part 1: power lines and cables. *Int. J. Life Cycle Assess.* **17**, 9–15 (2012).
47. Eurelectric. *Distribution Grids in Europe: Facts and Figures 2020*. https://www.eurelectric.org/publications/distribution-grids-in-europe-facts-and-figures-2020/ (2020).
48. Mutel, C. Brightway: An open source framework for Life Cycle Assessment. *J. Open Source Softw.* **2**, 236 (2017).
49. Wernet, G. *et al*. The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* **21**, 1218–1230 (2016).
50. ecoinvent Association. ecoinvent database v3.10, cut-off system model. *ecoinvent Association* https://ecoinvent.org/database/ (2023).
51. *CRC Handbook of Chemistry and Physics*. (CRC Press / Taylor & Francis, Boca Raton, FL, 2016).
52. Nohl, L. *et al*. *Material Requirements for Electricity Grids*. https://publications.jrc.ec.europa.eu/repository/handle/JRC143190 (2025).
53. Månberger, A. & Stenqvist, B. Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development. *Energy Policy* **119**, 226–241 (2018).
54. Our World in Data. Minerals. *Our World in Data* https://catalog.ourworldindata.org/grapher/minerals/2025-12-15/minerals/minerals.parquet (2025).

55. U.S. Geological Survey, National Minerals Information Center. U.S. Geological Survey Mineral Commodity Summaries 2025 Data Release (ver. 2.0, April 2025). U.S. Geological Survey https://doi.org/10.5066/P13XCP3R (2025).
56. Kelly, T. D. & Matos, G. R. *Historical Statistics for Mineral and Material Commodities in the United States (2016 Version)*. (2014) doi:10.3133/ds140.
57. British Geological Survey. World Mineral Statistics, 1970 onwards. *British Geological Survey* https://www.bgs.ac.uk/mineralsuk/statistics/world-mineral-statistics/ (2024).
58. Lundaev, V., Solomon, A. A., Le, T., Lohrmann, A. & Breyer, C. Review of critical materials for the energy transition, an analysis of global resources and production databases and the state of material circularity. *Miner. Eng.* **203**, 108282 (2023).
59. Nassar, N. T., Lederer, G. W., Brainard, J. L., Padilla, A. J. & Lessard, J. D. Rock-to-Metal Ratio: A Foundational Metric for Understanding Mine Wastes. *Environ. Sci. Technol.* **56**, 6710–6721 (2022).
60. Eurostat, OECD, IMF and World Bank. Gross domestic product (GDP) – World Bank – In constant international-$. *Our World in Data* https://ourworldindata.org/grapher/gdp-worldbank.csv?csvType=full&useColumnShortNames=true (2026).
61. European Commission, Directorate-General for Economic and Financial Affairs & Economic Policy Committee. *The 2024 Ageing Report: Economic and Budgetary Projections for the EU Member States (2022–2070)*. https://economy-finance.ec.europa.eu/ecfin-publications_en (2024) doi:10.2765/022983.

Supplementary Files

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

- Supplementaryinformation.pdf