nature climate change

Perspective

https://doi.org/10.1038/s41558-024-02016-z

Demand-side strategies key for mitigating material impacts of energy transitions

Received: 8 August 2023

Accepted: 23 April 2024

Published online: 4 June 2024

Check for updates

Felix Creutzig [1,2], Sofia G. Simoes [3], Sina Leipold [4], Peter Berrill [1,2], Isabel Azevedo[5], Oreane Edelenbosch [6], Tomer Fishman [7], Helmut Haberl [8], Edgar Hertwich [9], Volker Krey [9,10], Ana Teresa Lima [11], Tamar Makov [12], Alessio Mastrucci [10], Nikola Milojevic-Dupont [1,2], Florian Nachtigall [1,2], Stefan Pauliuk [13], Mafalda Silva [5], Elena Verdolini [14,15], Detlef van Vuuren [6], Felix Wagner [1,2], Dominik Wiedenhofer [8] & Charlie Wilson[10,16]

As fossil fuels are phased out in favour of renewable energy, electric cars and other low-carbon technologies, the future clean energy system is likely to require less overall mining than the current fossil-fuelled system. However, material extraction and waste flows, new infrastructure development, land-use change, and the provision of new types of goods and services associated with decarbonization will produce social and environmental pressures at localized to regional scales. Demand-side solutions can achieve the important outcome of reducing both the scale of the climate challenge and material resource requirements. Interdisciplinary systems modelling and analysis are needed to identify opportunities and trade-offs for demand-led mitigation strategies that explicitly consider planetary boundaries associated with Earth's material resources.

Continuing fossil fuel development and consideration of currently implemented policies implies that climate targets will be missed by a wide margin[1]. However, many technologies required to effectively address climate change are already available in the market. There are emerging signs that some societies can rally enough political support and practical action to slow climate change. Peak coal may have arrived[2]. Renewable energy technologies are diffusing exponentially as costs decrease[3], are outcompeting fossil fuels and are integrating into increasingly digitalized networks[4]. Energy end-use technologies enabling low-carbon electrification of mobility and heating services—such as batteries for electric vehicles (EVs) and heat pumps for housing—are becoming ever cheaper and expanding rapidly[5]. If these trends continue and are coupled with policies for tackling GHG emissions from land use and agriculture, the goal of limiting global warming to below 2 °C may remain within reach (disinvesting from fossil fuels is, however, the harder part, given the power of fossil fuels in energy markets and the geopolitical implications associated with phase-out[6]). Large-scale deployment of carbon dioxide removal (CDR) technologies—such as direct air carbon capture and storage—may even offer the opportunity to reverse temperature increases further in the future.

[1]Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany. [2]Technical University Berlin, Berlin, Germany. [3]LNEG – National Laboratory for Energy and Geology, Amadora, Portugal. [4]Department of Environmental Politics, Helmholtz Centre for Environmental Research, Leipzig, Germany. [5]INEGI - Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial, Porto, Portugal. [6]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands. [7]Institute of Environmental Sciences (CML), Leiden University, Leiden, The Netherlands. [8]Institute of Social Ecology, BOKU University, Vienna, Austria. [9]Department of Energy and Process Engineering, Industrial Ecology Programme, Norwegian University of Science and Technology, Trondheim, Norway. [10]International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. [11]DTU Sustain, Department of Environmental and Resource Engineering, Technical University of Denmark, Kgs Lyngby, Denmark. [12]Guilford Glazer Faculty of Business and Management, Ben Gurion University, Be'er Sheva, Israel. [13]Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany. [14]University of Brescia, Brescia, Italy. [15]RFF-CMCC European Institute on Economics and the Environment, Euro-Mediterranean Center on Climate Change, Milan, Italy. [16]Environmental Change Institute, University of Oxford, Oxford, UK. e-mail: creutzig@mcc-berlin.net

https://doi.org/10.1038/s41558-024-02016-z

This optimistic scenario comes with intensifying and compounding trade-offs. Low-carbon technologies such as wind turbines, solar panels or batteries—and the infrastructures they require—are material-intensive[7], and specifically more mineral-intensive than their fossil fuel counterparts[8]. Their sourcing from the Earth and sinking via mining and post-consumer waste will drive environmental burdens to new levels globally, including increased water pollution, ecosystem destruction from mining operations[9] and supply-chain-related GHG emissions[10]. Main drivers include deployment of large-scale renewable power plants, mining for resources, such as lithium and cobalt required for novel digital and low-carbon technologies[11], and other land footprints[12]. This expected surge in impacts counteracts biodiversity protection and other healthy ecosystem targets and is likely to meet increased conflicts with supply chain legislation and environmental protection in mining countries, as well as resistance among non-governmental organizations and the general public. Socially, the current energy transition path risks creating new social burdens, including disproportionate siting of extractive projects in low-income or Indigenous communities[13], and investment uncertainties that may exacerbate issues of energy poverty and inequality (within and between countries)[14,15].

Environmental and social impacts and geopolitical relations, not resource scarcity, constitute the main risks in metals and minerals supply[16–20]. Biodiversity and deforestation impacts of mining are well documented both for metals[9] and for bulk materials such as sand[21]. Large-scale extraction of energy resources and metals and construction of transport infrastructures can have negative socio-environmental impacts disproportionately affecting ecosystem-based livelihoods (for example, fishermen, pastoralists)[22], marginalized communities, and lower income neighbourhoods in both the Global North and Global South. High-resolution mapping reveals that mining is a major force in compromising biodiversity-rich areas by direct and indirect impacts, for example, via widespread logging[23,24]. While phasing out fossil fuels will reduce the overall impact of material extraction, a large literature shows that supply-side solutions to support the energy transition will enlarge and intensify social and ecological injustices[13,25]. Mining, fossil fuels, dams and energy infrastructure cause more than 60% of all documented environmental conflicts[26]. In this respect we argue that demand-side strategies can subtantially mitigate the risks associated with supply-side solutions.

Digital technologies, platforms and applications support a rapid clean energy transition, helping to improve the resource efficiency of service provisioning systems. However, relative efficiency gains can be undermined by the resources required to build and operate digital infrastructure, as well as rebound effects that grow absolute levels of consumption and associated material demand[27]. Digitalization also creates new types of environmental footprint related to material use including copper ore, lithium, rare earth minerals and many other materials.

Here we explain, illustrate and discuss a main emerging problem with the transition towards climate neutrality: large-scale transitions to a renewable energy supply, afforestation and potentially new CDR technologies such as direct air carbon capture and storage can have substantial trade-offs for material use, land use, the biosphere and local social systems, requiring mitigation of their impact

In this Perspective, we first establish the critical environmental and social burdens introduced by decarbonization strategies, such as increased mineral extraction with substantial ecological and societal impacts. This foundation is essential for understanding the subsequent part, which advocates for demand-side solutions as a necessary countermeasure to these burdens.

Environmental and social burden of decarbonization strategies

Decarbonization influences material footprints differently across provisioning and service sectors, including energy, mobility, shelter, nutrition, general purpose technologies such as digitalization and mitigation-specific technologies such as CDR for atmospheric carbon management. We illustrate these impacts with five salient examples.

First, high levels of electricity consumption in ambitious solar photovoltaic (PV) and wind power scenarios will require additional bulk materials (for example, steel, cement, aluminium) and land[7,28,29]. While the overall material footprint of low-carbon electricity goes down by 85% compared with fossil alternatives, higher metal ore extraction partly compensates for avoided fossil mass flow[30]. CO_2 emissions associated with construction also increase[7] (see also Table 1). Expansion of renewable energy and electrification of other sectors will rapidly increase the demand for most materials[31]. While the overall impact is uncertain, global demand for steel and aluminium in the electricity sector is estimated to grow by a factor of 2 in a baseline scenario or by a factor of 2.6 in a 2 °C climate policy scenario[32]. Annual demand for neodymium in the 2 °C scenario could more than quadruple[32]. Scenarios achieving a 1.5 °C target have even larger material requirements. Material stocks in 2050 could increase by up to 30% for copper, 100% for concrete, 150% for iron/steel and 260% for aluminium[33]. Most of these materials have moderate or high recycling rates and once stocks are built up, they can be used as a source of secondary materials. However, primary material production will still need to increase to develop new infrastructure[34,35].

Second, electrification is an essential strategy to decarbonize mobility[36]. However, detailed life-cycle analyses show that EVs have higher impacts than conventional fossil-fuelled vehicles in terms of metal and mineral consumption and human toxicity potential, even as they reduce GHG emissions over the full life cycle[34]. In the EV industry, substantial supply risks originate in rapidly rising demand for battery-grade natural graphite, lithium and cobalt for batteries, and the rare earth elements (REEs) dysprosium, terbium, praseodymium and neodymium[37]. Also, in this case, most of these materials have moderate or high recycling rates and once stocks are built up they can be used as a source of secondary materials.

Third, the requirements for lower carbon footprints in construction materials for buildings are driving a shift from mineral-based materials to bio-based materials[38]. From a life-cycle perspective, bio-based materials such as wood not only emit less CO_2 during the manufacturing phase than cement and steel, but also store CO_2[39,40]. However, large-scale use of bio-based materials in construction raises important trade-offs with other ecosystem services; it would also imply the expansion of forestry to nearly 150 Mha by 2100[41]. This is equivalent to the current size of the entire global urban land area or one-third of the entire land area of the European Union (EU)[42].

These land-use pressures can be ameliorated by shifting to plant-based diets with much lower agricultural land footprints as well as dramatically lower GHG emissions[43]. Large-scale adoption of meat substitutes, including alternative proteins and cultivated meat, by non-vegetarians can also reduce emissions, but may marginally increase demand for electricity, water treatment facilities and high-grade stainless steel[44]. The carbon reduction potential of these novel foods varies, but generally hinges on the assumption that they will utilize renewable energy (for example, during the production of cultivated cells)[45].

Fourth, the increased use of digital technologies in the provision of goods and services is one of the fastest and most pervasive forces shaping our societies, with disruptive consequences affecting both demand and supply across all sectors[27,46]. Digitalization is also a critical and integral element of the clean energy transition: for balancing intermittent renewable supply in real time with distributed storage and flexible demand in a low-carbon electricity system[47]; for enabling low-carbon urban mobility modes such as car sharing[48]; and for promoting virtualization and servitization to reduce demand for energy-intensive products and activities[49]. However, digital infrastructure and devices have distinctive material footprints and relatively

https://doi.org/10.1038/s41558-024-02016-z

Table 1 | The clean energy transition impacts or is influenced by key materials, services, current extraction rates, demand evolution, environmental, social and geopolitical risks, supply chain concentration, and transition dynamics

Material	Service(s)	Current extraction	Demand evolution	Environmental impacts (water depletion and pollution, waste-related contamination and air pollution)	Social impacts (misuse of government resources, fatalities and injuries, human rights abuse)	Geopolitical risk/critical material	Supply chain concentration (national, global)	Dynamics of the transition
Oil	All	5.3 Gt yr^{-1} in 2019[103]	In 2030: +5% to −20% than in 2022; in 2050: +1% to −75% depending on scenario[104]	Oil spillages lead to water and soil contamination, with impacts in aquatic and terrestrial ecosystems. Crude oil refining releases several toxic substances such as benzene[105]. Oil combustion causes air pollution (particles, smog, acid rains and so on) with highly relevant health impacts. Impacts aggravated when fracking is used[106].	Higher disease prevalence in communities near oil drilling operations[107]. Indigenous communities particularly suffer, for example, in northern Alberta[108]. People displacement, food insecurity, disruption of social and cultural cohesion, among others felt across the world, for example, Uganda.	High (cartelization and war)	The United States, Russia and Saudi Arabia extract 42% of world supply[109]	Not applicable
Natural gas	All	2.8 Gt yr^{-1} in 2019[103]	In 2030: +3% to −31% than in 2022; in 2050: 0% to −78% depending on scenario[104]	Water depletion, toxic wastewater production contaminating underground water/water bodies[105]. Impacts aggravated when fracking is used[106]. Land subsidence has occurred in The Netherlands[110]. Natural gas combustion leads to acidifying emissions, besides GHG emissions.	People displacement and homelessness, disruption of social and cultural cohesion, lack of government, poor health and well-being[111]. Food insecurity has also been reported. Widespread impacts across the world, such as Uganda[112] and Nigeria[113].	High (cartelization and war)	The United States, Russia and Iran extract 47% of world supply[109]	Not applicable
Coal	All	7.8 Gt yr^{-1} in 2019[103]	In 2030: −14% to −44% than in 2022; in 2050: −40% to −91% depending on scenario[104]	Soil, aquifers/surface water contamination, water depletion, land subsidence reported in many countries such as Bangladesh, Brazil, China, India, the United Kingdom, Greece and Colombia, among others[114,115]. 26% of global mining-related biodiversity loss in 2014 due to coal mining[116]. Coal combustion leads to particulate emission, smog, acid rains besides GHG emissions[105].	Health-related issues and impoverished community cohesion[105,117]. Human casualties and injuries in disasters, for example, incident in an open-pit coal mine in northern China in 2023[118].	Lower than oil and gas	China produced 50% of global supply in 2022, followed by India (10%), Australia and Indonesia (10% each), the United States (6%), Russia (5%) and the EU (4%). Rest of the world supplied 11%[119].	Not applicable
Lithium (Li)	Mobility (EV batteries)	1.30 Gt × 10^{-4} ore in 2023[120]	20–30× increase 2018–2100[121]; 18–20× increase 2020–2050 for use in batteries[122]	Groundwater depletion, ecosystem degradation[123,124]	Forced displacement of populations[124]	Considered a critical material in the EU[125], the United States[126] and the IEA[127]	Reserves quite concentrated (>50% of global) in Chile, Argentina and Bolivia[123]	Between 2010 and 2022, Li mining output rose by a factor of five
Cobalt (Co)	Mobility (EV batteries)	1.90 Gt × 10^{-4} ore extracted in 2023[128]	2–4× increase 2020–2050[129]; 17–19× increase 2020–2050 for use in batteries[122]	Similar to Cu (about 60% of world Co is co-mined with Cu)[129]. Soil, aquifers/surface water contamination, air pollution due to dust[130].	The DRC reported severe health impacts, child labour[131], accidents and occupational hazards, loss of community health, as well as violent conflict and deaths[130]	Considered a critical material in the EU[125], the United States[126] and the IEA[127]	Highly concentrated in both mining and refining countries with DRC providing 60–70% of world supply[5]. Strongly related to production of Cu and nickel[129].	Now 7.2 million EVs, which could become 140–245 million in 2030[132]. Between 2010 and 2022, mining output rose by a factor of five[133].

https://doi.org/10.1038/s41558-024-02016-z

Table 1 (continued) | The clean energy transition impacts or is influenced by key materials, services, current extraction rates, demand evolution, environmental, social and geopolitical risks, supply chain concentration, and transition dynamics

Material	Service(s)	Current extraction	Demand evolution	Environmental impacts (water depletion and pollution, waste-related contamination and air pollution)	Social impacts (misuse of government resources, fatalities and injuries, human rights abuse)	Geopolitical risk/critical material	Supply chain concentration (national, global)	Dynamics of the transition
Limestone (for example, cement, glass, others)	Buildings, civil engineering, energy infrastructure (offshore wind, hydropower)	6.7 Gt yr^{-1} in 2019 of limestone[103]	30% increase by 2100[134]. Well below 2 °C warming compatible supply of concrete only compatible with 22–56% (interquartile range) of the expected baseline demand in 2050[135].	Concrete production from limestone and clinker caused 2.7% of global GHG emissions in 2018[136]. 'Resources' and 'climate change' are the two greatest environmental impacts of the limestone rock production[137], followed by changes in land-use pattern, habitat loss, higher noise levels, particulate matter emissions and changes in aquifer regimes[138].	Human casualties and injuries in disasters, for example, limestone mine collapse in India, 2022[139]	Not a critical material	Potential resources of pure carbonate rocks are of the order of several tens of thousands of gigatonnes, which are widespread[140]	Global materials use is projected to more than double from 79 Gt in 2011 to 167 Gt in 2060. Non-metallic minerals, such as sand, gravel and limestone, represent more than half of total materials use[141]. The need for cement-grade limestone will increase 43–72% by 2050[142].
Copper (Cu)	Energy (power grids), mobility (motors, batteries)	2.7 Gt yr^{-1} in 2019 of Cu ore[103]	Future Al and Cu demand for power sector infrastructure could require 18% of current production[8]; 1.5–5× demand growth by 2050[134]	Toxicity from (sulfidic) mining tailings leaching into groundwater and soils. Also, eutrophication from phosphate leaching from tailings[29,143].	Many mine tailing spilling incidents. Chile reports 43 Cu miners died in Chile in 2010 due to accidents in mining operations, and relates higher fatalities with higher commodity prices[144].	Not a critical material, yet strategic material in the EU[125]	Chile supplies 26% global primary production, followed by Peru (11%), DRC (9%), China (9%) and the United States (9%). Smelting/refining well distributed across countries[145].	5 Mt yr^{-1} for power grids in 2020 to 7.5–10 Mt yr^{-1} in 2040[109]. 2–3× annual Cu demand in 2050 over 2021 for energy distribution and transmission grids, as well as power plants and transformers[146]. 2.5× annual Cu demand for EVs in a 1.5 °C scenario[147].
REEs, particularly dysprosium (Dy)	Mobility and magnets	300 kt of total rare earths mined in 2023 in rare earth oxide equivalent[148] 3.1 kt of Dy_2O_3 mined in 2021[145]	2–30× increase expected[149]	Human toxicity[150]. Impacts include localized pollution sources due to acidifying mining wastewater impacting soil and groundwater. Radioactive materials and heavy metal contamination can also occur. Important damage has been reported due to REE-specific extraction and metallurgic processes[151].	Health complications due to exposure to these toxic chemicals. Human rights abuses have been reported throughout mines in these areas as labourers are overworked and underpaid[152].	Considered a critical material in the EU[2], United States[3], IEA[4]	Reserves evenly distributed between China (36%), Brazil (18%), Vietnam (18%), Russia (10%)[153]. However, China responsible for 40% of global Dy production, followed by Myanmar (31%) and Australia (20%)[145].	By 2050, maximum annual demand for energy could represent 309% of current production[154]
REEs, particularly neodymium (Nd)	Energy (permanent magnets of onshore and offshore wind power plants)	300 kt of total REEs mined in 2023 in rare earth oxide equivalent[148] 4.75 kt of Nd_2O_3 mined in 2021[145]	2–30× increase expected[149]; 3–4.4× increase of Nd by 2050 only for electricity infrastructure[32]	Same as for Dy	Health complications due to exposure to these toxic chemicals. Human rights abuses have been reported throughout mines in these areas as labourers are overworked and underpaid[152].	Considered a critical material in the EU[2], the United States[3] and the IEA[4]	See Dy for REE reserves. China responsible for 62% of global Nd production, followed by Myanmar (14%), the United States (11%) and Australia (7%)[145]	By 2050, maximum annual demand for energy could represent 271% of current production[154]
Aluminium (Al)	Transport, buildings, packaging, machinery, electricity distribution	0.4 Gt yr^{-1} in 2019 of bauxite extraction[103]	2–8× increase by 2050[16]; 2–8× increase by 2050[16]; 2–2.3× increase by 2050 only for electricity infrastructure[32]	12% of global mining-related biodiversity loss in 2014 due to bauxite mining[116], well-below 2 °C feasible steel supply will only meet 58–65% (interquartile range) of the expected baseline demand in 2050[135]. Air and water pollution and land degradation reported in Guinea[155].	Corruption and high social inequalities among mining workforce, for example, in Guinea[155]. Human casualties in disasters, for example, explosion of Al alloy plant in Kunshan, China, 2014[156].	Considered a critical material in the EU[2], the United States[3] and the IEA[4]	Australia responsible for 27% of global primary production, followed by Guinea (25%). >50% of smelting occurs in China[145]	30% increase in EU demand for Al by 2040, driven mainly by the growth of EVs, solar PV and electricity grids[157]. Global demand can double from 2017[141].

https://doi.org/10.1038/s41558-024-02016-z

Table 1 (continued) | The clean energy transition impacts or is influenced by key materials, services, current extraction rates, demand evolution, environmental, social and geopolitical risks, supply chain concentration, and transition dynamics

Material	Service(s)	Current extraction	Demand evolution	Environmental impacts (water depletion and pollution, waste-related contamination and air pollution)	Social impacts (misuse of government resources, fatalities and injuries, human rights abuse)	Geopolitical risk/critical material	Supply chain concentration (national, global)	Dynamics of the transition
Iron (for example, steel)	Buildings, infrastructure, machinery, electricity system	3.1 Gt yr^{-1} in 2019 of iron ore extraction[103]	2–2.6× increase by 2050 only for electricity infrastructure[32]	10% of global mining-related biodiversity loss in 2014 due to iron ore mining[116]	Human casualties in disasters, interruption in water supply, and Indigenous people impacted. For example, dam tailing rupture in the Doce River, Brazil, in 2015 and 2018[158].	Not a critical material, no geopolitical risks at this stage	Reserves quite distributed, Australia biggest producer followed by Brazil, China and India[150]	Global demand can double from 2017[141]
Non-metallic construction minerals (sand, gravel, clays, stones, gypsum)	Buildings and infrastructure	42.9 Gt yr^{-1} in 2019[103]	Substantial increase in demand for buildings and infrastructure expansion around the world[159,160]. Aggregates extraction projected to grow from 24 to 55 Gt yr^{-1} in 2011–2060[141].	33% of global mining-related biodiversity loss in 2014 due to minerals[116]. River sand mining can cause riverbed modifications, reduced biodiversity, and reduced water, air and soil quality due to pollution[161,162].	Local livelihoods negatively affected through degradation of local ecosystems, especially in developing countries and coastal/river regions. Potential increase in vector-borne diseases. Reports of organized crime groups in India and Italy, among others, where illegal trade in sand occurs[159].	Not a critical material, no geopolitical risks	Widespread deposits, often illegal extraction[159]	~45% increase in global sand use for buildings from 2020 to 2060 with 300% increase in low-and lower-middle-income regions and a slight decrease in higher-income regions[160]

As social impacts are highly context-dependent and extractive projects have both negative and positive social impacts, the table should be read as an indication of overall trends in social burdens resulting from specific extraction practices in relation to different natural resources. We conceptualize social burdens as perceived difficulties or disadvantages that extractive projects impose on communities or societies. Burdens can include the need for resettlement, increased cost of living, forced acquisitions or conflicts over land use and property rights. Social burdens are typically unevenly distributed, with marginalized and vulnerable populations bearing a disproportionate share of the burden.

low levels of material recovery from waste streams. They also depend on critical mineral extraction and often result in rapid turnover of short-lived consumer goods[50]. Electronic waste, estimated at 54 Mt in 2019, is the fastest growing waste stream in the world, doubling every 16 years[50], yet is worth over US\$60 billion annually[51]. Impacts of digitalization are also unequally distributed: benefits accrue more in the service-intensive economies of the Global North, while negative economic and social impacts associated with both resource sourcing and waste sinking are higher in the Global South[52]. Improving recycling of electronic waste is a pressing concern and a high priority for future research[53].

Fifth, direct air capture has been proposed as a scalable but cost- and energy-intensive option to absorb CO_2 from the atmosphere. However, per unit of CO_2 emission reduced/sequestered, direct air capture (using temperature swing adsorption) is estimated to have similar renewable energy requirements and land footprints as a switch from gasoline to EVs, but with approximately five times higher material consumption[54]. In some specific cases, existing mining operations can be better managed to improve carbon sequestration through enhanced weathering[55], with a technical potential of up to 400 $MtCO_2\ yr^{-1}$, according to one study[56]. More broadly, both the logistics (piping) and the geological storage capacity requirements for large-scale application of carbon capture and storage infrastructure also carry large land-use footprints.

In the clean energy transition, these different forces driving new material extraction are set against reduced mining of fossil fuels. The current scale of fossil fuel extraction from coal, gas and oil surpasses those of all other materials together (excluding construction aggregates and limestone; Fig. 1 and Table 1). Focusing just on the energy transition, total extraction will be halved from now until 2040 or shortly thereafter under the International Energy Agency's (IEA) net zero emission pathway[57]. This dynamic is grounded in a sharp decline in the currently dominant fossil fuels, only partially compensated by rising demand for materials required for wind, solar, EVs, batteries and hydrogen. There is sufficient physical supply and economic potential for most of these material resources[17]. Nonetheless, the material-specific mining increment is substantial. Depending on scenario assumptions, the total material requirement flows associated with mineral production increase by around 200–900% in the electricity sector and by 350–700% in the transport sector respectively from 2015 to 2050[8]. Aggregates and clay-based materials are extracted at higher rates than fossil fuels, but their impacts are comparatively lower.

Most of the 'new' required minerals, metals and other materials have environmental and social consequences, as well as geopolitical risks of supply (Fig. 1). Sometimes, resources, impacts and the capacity to refine and process them are highly localized[58]. The Democratic Republic of the Congo (DRC), for example, has half the world's supply of cobalt, and China produces 90% of the semiconductor wafers used to make solar cells[58]. However, a large literature shows that the need for minerals and metals necessary to develop low-carbon infrastructure will augment the stress placed on people and the environment in extractive locations. The orebodies of energy transition metals, for instance, are geographically concentrated in already marginalized communities characterized by a co-occurrence of environmental, social and governance risks[13,25,59]. Existing decarbonization scenarios do not account for the fact that local operational impacts associated with new and existing extraction projects are fundamentally incompatible with global sustainability objectives and will exacerbate existing inequalities and marginalization (for example, of Indigenous people and peasants), undermine local governance, and also pose wider socio-political risks negatively impacting economic growth and human development[60–62]. Importantly, conflicts associated with environmental and social risk translate into business costs, undermining the transition to a low-carbon future[62].

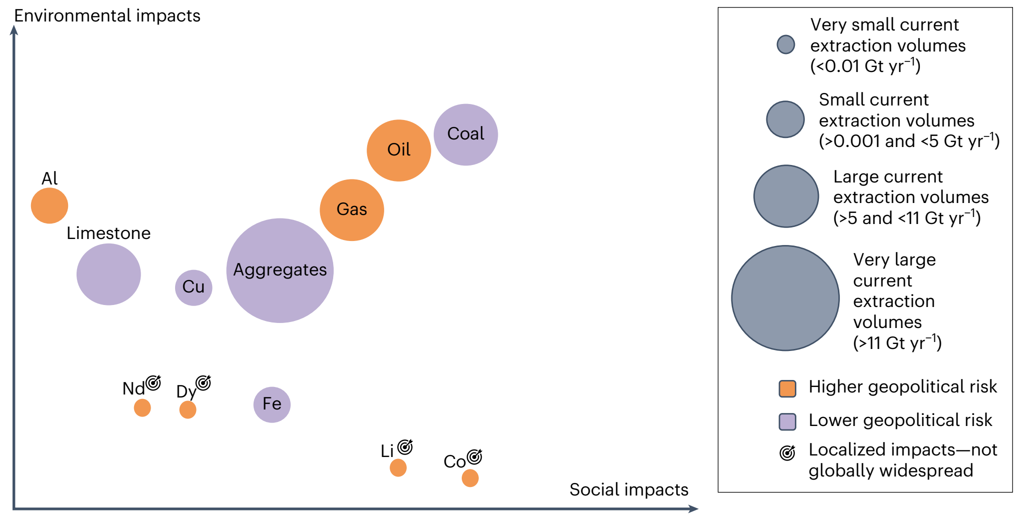

Fig. 1 | Comparative overview of impacts of extracting and supplying emerging materials and fossil fuels. The relative location of materials and fuels is by expert judgement underpinned by the insights from Table 1. Only the extraction and processing stages are included, not fossil fuel combustion.

Of particular concern is the fast-tracking of mining operations for critical energy transition minerals, such as lithium. Such practices threaten the rights of local and often Indigenous communities[59] (for example, in Latin America and Canada) by circumventing their prior informed consent and participation in decision-making processes. In the EU, current regulatory initiatives also push for accelerated application processes for new mines and processing plants for critical minerals[63]. This not only undermines local governance but also poses wider socio-political risks. A 'social licence to operate' is important for companies to manage local as well as national risks, as illustrated for copper[61,64]. Without the socio-political legitimacy conferred by local communities and stakeholders, corporate operations risk triggering local conflicts, which can have the capacity to generate substantial financial costs, influence national electoral outcomes and shape public policy on a wider scale[62,65]. Big projects such as large-scale solar parks in India or northern Africa can similarly amplify environmental and social risks[66,67].

There is an extensive body of literature that demonstrates how impacts can be substantially mitigated by adopting responsible and advanced mining, refining and processing approaches. Nonetheless, adverse social and environmental impacts cannot be wholly eliminated. At the same time, the transition also has great potential to ameliorate the social burdens of the fossil energy system, such as mitigating climate change, reducing air pollution from fossil fuels and increasing energy security through decentralized production. Community-owned renewable energy projects, as already in place[68], could further empower local communities and reduce the social burdens and inequalities of centrally owned resources.

The shift from fossil fuels to material extraction also has different impacts on planetary boundaries: lower pressure on the climate change and ocean acidification boundaries, but increased tensions for biosphere integrity, land-system change and freshwater change. Shifting impacts on planetary boundaries for biogeochemical flows remain unclear.

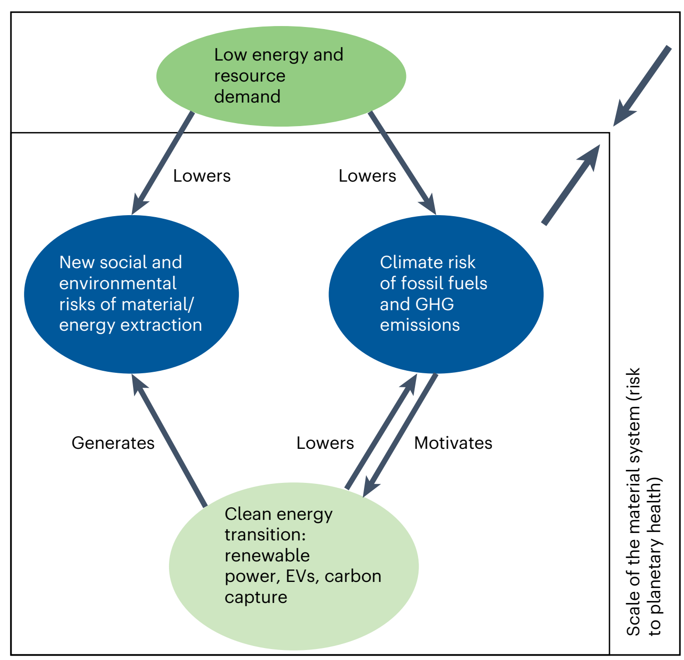

Fig. 2 | Shifting risks and response strategies from the clean energy transition. Partially motivated by ref. 163.

Demand-side strategies reduce burdens

Demand-side strategies focus on how services can be provided to achieve higher well-being at lower levels of energy and material use. This is achieved through social and behavioural change, low-carbon infrastructures, resource-efficient design of material stocks, and circularity strategies aimed at recycling materials and reducing overall material demand. Demand-side strategies are concerned with both final consumption and the service-provisioning systems enabling that consumption[69]. Consequently, they make best use of demand–supply interdependencies instead of maintaining traditional sectoral distinctions between end use (for example, buildings, transport), intermediate production (for example, manufacturing) and upstream supply (for example, energy, materials).

Demand-side strategies achieve the important outcome of reducing both the scale of the climate challenge and material resource requirements (Fig. 2). First, demand-side approaches avoid energy use and associated GHG emissions, directly lowering climate-related risks while also reducing the required scale of the energy transition. Second, demand-side approaches directly reduce adverse material impacts by dematerializing goods and services provision ('narrow' strategies for circularity). Third, demand-side strategies can further

Table 2 | Summary of demand-side strategies that contribute both to climate change mitigation and material resource challenges

Service	Demand-side strategies to mitigate adverse material impacts
Energy	Limit energy and material demand including through more efficient design of plants to reduce material footprints, integrated solar PVs in building designs to reduce material demand of support structures, optimized location of new installations to reduce the need for network expansion and limits on sprawling settlements
Mobility	Use vehicles as shared devices to downsize the size of the vehicle fleet; rapidly expand public transport systems
Buildings	Increase lifetime of existing buildings and infrastructure by following circular economy and sufficiency principles, such as repairing buildings, sharing spaces, intensifying use of existing buildings, material efficiency and natural building materials, and limiting sprawling settlements
Nutrition	Curb meat consumption and shift to unprocessed plant protein, sufficiency in line with dietary recommendations
Communication and information processing	Increase material efficiency in the design and manufacturing of ICTs, value capture from material recovery and recirculation
CDR	Rapidly reduce GHG emissions to avoid the need for large-scale carbon cature and storage infrastructure

enable circular material flows by extending product lifetimes and recovering and reusing materials ('slow' and 'close' strategies). However, with few exceptions[70], demand-side strategies have not yet been systematically explored at the nexus of climate change mitigation and the material dimensions to the clean energy transition.

Demand-side solutions hold high potential for the previously discussed examples of energy, mobility, buildings, food, digitalization and CDR (Table 2). Strategies in the energy sector include material-efficient technologies, low-carbon industrial processes and increased material recycling[33]. A shift from underutilized private cars (<1.2 passengers on average and in use <1 hour per day) to shared pooled mobility achieves similar or better mobility services at reduced material intensity[71].

In the building sector, sufficiency (reduced floorspace per capita) and higher material efficiency (increased yields, light design, material substitution, fewer domestic appliances, extended service life and increased service efficiency, reuse and recycling) reduce material burdens and associated GHG emissions[72]. More intense building use alone has as much potential as all other measures combined[72]. In the food sector, transitioning away from meat (whether to processed or unprocessed plant protein) is most effective[43,73]. The material impact of CDR technologies can be best avoided by minimizing their use, emphasizing overall demand-side strategies and advancing renewable energy technologies[5].

In the case of digitalization and information and communication technologies (ICTs), demand-side solutions can narrow material cycles through resource-efficient design and dematerialization (for example, functional convergence with more services delivered through fewer devices[74,75]). Material cycles can also be slowed by redesigning ICT business models and consumption practices, enabling repair, longevity, lifetime extension, resale, remanufacturing, component reuse and modularity. Upscaling end-of-life recovery and recycling capacities including through improved provenance and sorting systems can close material cycles, enabled by simplifying material design choices[76].

Despite these substantial potentials, demand-side strategies are not without trade-offs. Resource-efficient design of material stocks, and circularity strategies aimed at recycling materials and reducing overall material demand, also have social and environmental costs.

Recycling raises environmental and justice questions. Resource-rich countries can face substantial challenges in securing investments for novel technologies such as battery recycling and repurposing. These investments play a pivotal role in driving economic development and job creation and ensuring equitable access to clean energy[77]. Furthermore, tightening environmental standards in some countries can lead to relocation of recycling operations, resulting in negative health outcomes for communities in other (often low-income) countries[78]. Another issue is the export of waste from high-income countries. Transporting large quantities of waste has a high environmental impact, and the health and safety conditions under which informal workers and communities collect and sort waste is a major concern in many low-income countries[79,80].

Both examples emphasize that the clean energy transition will require not only technical and economic changes but also a strategic approach to political issues of justice and equity in a world with substantial global inequalities and (historical) injustices.

New challenges require interdisciplinary approaches

The interdependencies between energy and materials, demand and supply, supply chains and service-provisioning systems, as well as diverse societal debates and policy paths across sectors and geographies raise complex new research challenges. Navigating this landscape requires systems analysis and integration between technical and social scientific expertise.

Global integrated assessment models (IAMs) are currently widely used to inform long-term climate mitigation strategies but cannot address these intricacies. They need upgrades enabling them to effectively analyse the material dimensions of low-carbon futures, particularly in terms of sectoral interdependencies. IAMs are widely used for providing a systems perspective on decarbonization pathways and the design of global and national GHG reduction strategies for the energy and land-use sectors[81,82]. However, IAMs do not consider the interplay between materials and energy or the emerging challenges of a clean energy transition (Fig. 1)[81]. For example, material demand in IAMs is often either absent or represented in monetary rather than physical units, or modelled as a simple function of economic development. Demand is also segmented by sector—industry, transport and buildings. This overlooks important interactions between sectors, such as how infrastructure and technologies used by the transport and buildings sectors directly influence industrial demand through material consumption[83,84]. Climate mitigation strategies like EV deployment or building insulation can reduce energy consumption but raise material demand[85]. Conversely, recycling or reusing materials can decrease material demand but push up energy consumption.

As discussed earlier, the currently dominant supply-side strategies for decarbonization imply large and worrying footprints for material extraction at a planetary scale. This reinforces the need for new analytical tools capable of representing the systemic interplay between energy and material dimensions. Progress is being made with focused empirical questions such as: what are the specific material needs of decarbonization strategies? How are material footprints developing over time? How are material sources and sinks spatially distributed, and with what environmental consequences? Ongoing research in these areas needs rebalancing to better represent the Global South, and to address key questions around the material equivalent of climate justice.

Another set of fundamental questions relates to the compatibility of current net-zero strategies with planetary boundaries[86]. What strategies can mitigate both GHG emissions and material use in industrialized countries? How can emerging economies attain welfare and material comfort with lower material requirements? What is the scope for repurposing or reusing materials from stranded fossil-based assets, and what are the implications for GHG emissions?

Answering these questions requires gathering and scaling up technology- and material-specific knowledge to explicitly represent and simulate the material dimension in scenarios of climate change mitigation and global environmental change[72]. Here, IAMs can build on the research methods and data collection efforts in the industrial ecology (IE) field[81]. Material flow models provide a quantitative understanding of the material cycle stages from extraction, production and use, up to disposal or other end-of-life options. This allows for the identification of materials inefficiencies and losses, as well as circularity potentials and opportunities for improvement.

Connecting IE tools (materials) with IAMs (energy, land) represents the frontier for advancing systems analysis of the trade-offs involved in the clean energy transition. Accounting for material demand in IAMs requires the following: (1) an enhanced quantitative representation of specific sectors in physical terms, including products and service levels (for example, building types and floorspace levels for residential and commercial sectors with associated material requirements[87,88]); (2) reconfiguring models to depict industry as an intermediate sector and not as end-use sector, whose output is consistent with demand from households, the public sector and investments; and (3) detailed coupling between IAM and IE models[89] to link material cycles, including mining, manufacturing and end-of-life treatment to the services and products. This linkage would allow the generation of material demand futures coupled to projected energy transitions, and vice versa, the estimation of energy requirements for producing required materials. Economic aspects of material cycles are also important but typically not covered by IE methods, whereas they are at the core of decision-making in IAMs. Related data are hard to find and typically proprietary, which amplifies the challenge of integrated modelling in this domain.

In addition to IE–IAM model coupling, a complementary approach to projecting global energy and material systems draws on artificial intelligence (AI) and empirical big data techniques. These methods are increasingly linked to climate change mitigation and adaptation[90]. In particular, studies with explicit spatial resolution have delivered promising results in predicting building attributes, and material and energy demand with high generalization capacity[91,92]. Using satellite imagery and volunteered geographic information from OpenStreetMap, studies have created high-resolution maps of material stocks in buildings and infrastructures[93], and identified rooftop areas for solar PVs that avoid land-use conflicts[94]. The flexibility of these approaches allows analyses to be extended to areas with sparse official data where conventional material flow models cannot be applied[95], particularly in the Global South. Incorporating temporal dynamics can further reveal long-term trends, such as urban expansion[96], and help project future material demand of settlements. If data of appropriate spatial resolution are unavailable, AI techniques can facilitate the downscaling and upscaling of data via clustering and disaggregation methods[97,98]. While these use cases show some promise, the application of AI to material and energy analyses of urban areas is a recent development: its full potential has yet to been fully explored.

These methodological advances for understanding the feedbacks between energy, land and material systems are required not just to design robust mitigation scenarios but also to evaluate demand-led strategies such as material efficiency and sharing economies that reduce both energy and material demand. The importance of demand-side measures, and the policies for incentivizing their adoption, have so far not been well captured in either global or regional pathway analyses (for a recent notable exception see the analysis of China's bulk material loops[70]).

Material and energy demand interact with human behaviour and cultural context[99]. Resource efficiency savings, including those advanced by the circular economy, are often compromised by rebound effects[100]. Leverage points for reducing material-intensive supply and demand include changing norms, the provision of low-carbon services and infrastructures, combined with the update of new services and technical solutions[99]. Policy instruments, such as carbon pricing, and equivalent pricing of harmful material extraction, are central for keeping overall demand in check[101].

There is also an urgent need for ex ante assessments of justice and equity implications of policy paths, together with their socio-political feasibility. This underlines the importance of an approach that integrates social science insights with advanced modelling techniques to analyse the complex relationship between social impacts, material flow dynamics and policy development. A holistic, interdisciplinary perspective is essential to ensure that the material and societal burdens of the energy transition are mitigated. Correspondingly, the complex, multi-level dynamics of these socio-political risks require a nuanced and integrated approach to resource governance and corporate responsibility.

Demand-side strategies emerge as holistic solutions

The clean energy transition to address climate change may be just in time to keep global warming within limits consistent with human survival. Yet, many communities encounter new essential challenges to their livelihoods, as the mineral demand underpinning the energy transition creates new environmental and social risks. To date, analytical and policy focus has rightly been on the energy and land-use dimensions to the climate challenge. While the new stressors are not at the scale of fossil fuel extraction and current agricultural practices[102], they will nonetheless compromise sustainability in new locations at large scales. This implies that demand-side strategies, as detailed in the recent IPCC report[43], matter not only for climate change mitigation but simultaneously serve to limit material-related environmental and social burdens. For example, urban planning and transport system strategies such as compact cities, transit-oriented development, the 15-minute city and novel systems of shared pooled mobility can improve accessibility while decreasing the demand for cars, and thus materials needed for electric motors and batteries. Future research should aim to develop a comprehensive understanding of demand-side measures, including experience of their implementation and mapping of available data on their effectiveness. Given the extensive and interdisciplinary nature of this literature, which sometimes presents ambivalent results, such a review could be a crucial aid to policy and practice. Most importantly, this review should also seek to establish links with studies on the specific environmental and social impacts of extractive projects, in order to focus efforts on the most pressing problem areas. The tools and thinking underpinning global climate mitigation need to be updated, linked and extended to provide robust policy advice on the supply and demand-side strategies that jointly address the energy and material dimensions of future sustainable development pathways.

References

1. Rogelj, J. et al. Credibility gap in net-zero climate targets leaves world at high risk. *Science* **380**, 1014–1016 (2023).
2. Bertram, C. et al. COVID-19-induced low power demand and market forces starkly reduce CO_2 emissions. *Nat. Clim. Change* **11**, 193–196 (2021).
3. Creutzig, F., Hilaire, J., Nemet, G., Müller-Hansen, F. & Minx, J. C. Technological innovation enables low cost climate change mitigation. *Energy Res. Soc. Sci.* **105**, 103276 (2023).
4. Bogdanov, D. et al. Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy* **227**, 120467 (2021).
5. IPCC: Summary for Policymakers. In *Climate Change 2022: Mitigation of Climate Change* (eds Shukla, P. R. et al.) (Cambridge Univ. Press, 2022).
6. Thompson, H. *Disorder: Hard Times in the 21st Century* (Oxford Univ. Press, 2022).

7. Simoes, S. G. & Lima, A. T. M. Materials, resources, and CO_2 impacts of building new renewable power plants to reach EU's goals of carbon neutrality. *J. Clean. Prod.* **418**, 138138 (2023).
8. Watari, T. et al. Total material requirement for the global energy transition to 2050: a focus on transport and electricity. *Resour. Conserv. Recycl.* **148**, 91–103 (2019).
9. Giljum, S. et al. A pantropical assessment of deforestation caused by industrial mining. *Proc. Natl Acad. Sci. USA* **119**, e2118273119 (2022).
A seminal study revealing the location of industrial mining activities and their environmental impacts in pantropical areas.
10. Hertwich, E. G. Increased carbon footprint of materials production driven by rise in investments. *Nat. Geosci.* **14**, 151–155 (2021).
11. Turley, B. et al. Emergent landscapes of renewable energy storage: considering just transitions in the western United States. *Energy Res. Soc. Sci.* **90**, 102583 (2022).
12. Pimentel Da Silva, G. D. & Branco, D. A. C. Is floating photovoltaic better than conventional photovoltaic? Assessing environmental impacts. *Impact Assess. Proj. Appraisal* **36**, 390–400 (2018).
13. Owen, J. R. et al. Energy transition minerals and their intersection with land-connected peoples. *Nat. Sustain.* **6**, 203–211 (2023).
14. Jones, A. W. Perceived barriers and policy solutions in clean energy infrastructure investment. *J. Clean. Prod.* **104**, 297–304 (2015).
15. Pueyo, A. What constrains renewable energy investment in sub-Saharan Africa? A comparison of Kenya and Ghana. *World Dev.* **109**, 85–100 (2018).
16. Jowitt, S. M., Mudd, G. M. & Thompson, J. F. H. Future availability of non-renewable metal resources and the influence of environmental, social, and governance conflicts on metal production. *Commun. Earth Environ.* **1**, 13 (2020).
17. West, J. Decreasing metal ore grades. *J. Ind. Ecol.* **7**, 88 (2011).
18. Graedel, T. E., Harper, E. M., Nassar, N. T., Nuss, P. & Reck, B. K. Criticality of metals and metalloids. *Proc. Natl Acad. Sci. USA* **112**, 4257–4262 (2015).
19. Bordoff, J. & O'Sullivan, M. L. The age of energy insecurity. *Foreign Aff.* **102**, 104 (2023).
20. Vakulchuk, R., Overland, I. & Scholten, D. Renewable energy and geopolitics: a review. *Renew. Sustain. Energy Rev.* **122**, 109547 (2020).
21. Torres, A., Brandt, J., Lear, K. & Liu, J. A looming tragedy of the sand commons. *Science* **357**, 970–971 (2017).
22. Hanaček, K., Kröger, M., Scheidel, A., Rojas, F. & Martinez-Alier, J. On thin ice—the Arctic commodity extraction frontier and environmental conflicts. *Ecol. Econ.* **191**, 107247 (2022).
23. Maus, V. et al. An update on global mining land use. *Sci. Data* **9**, 433 (2022).
24. Tang, L. & Werner, T. T. Global mining footprint mapped from high-resolution satellite imagery. *Commun. Earth Environ.* **4**, 134 (2023).
25. Bainton, N., Kemp, D., Lèbre, E., Owen, J. R. & Marston, G. The energy–extractives nexus and the just transition. *Sustain. Dev.* **29**, 624–634 (2021).
26. Scheidel, A. et al. Global impacts of extractive and industrial development projects on Indigenous peoples' lifeways, lands, and rights. *Sci. Adv.* **9**, eade9557 (2023).
27. Creutzig, F. et al. Digitalization and the Anthropocene. *Annu. Rev. Environ. Resour.* **47**, 479–509 (2022).
Arguably the first paper that presents illustrative scenarios of how digitalization can support the energy transition, illustrating trade-offs between planetary stability, democracy, and political agency and equity.
28. Manjong, N. B., Usai, L., Burheim, O. S. & Strømman, A. H. Life cycle modelling of extraction and processing of battery minerals—a parametric approach. *Batteries* **7**, 57 (2021).
29. Berrill, P., Arvesen, A., Scholz, Y., Gils, H. C. & Hertwich, E. G. Environmental impacts of high penetration renewable energy scenarios for Europe. *Environ. Res. Lett.* **11**, 014012 (2016).
30. Pauliuk, S. Material footprint implications of low-carbon technologies. *Industrial Ecology Freiburg Blog* https://www.blog.industrialecology.uni-freiburg.de/index.php/2022/10/30/material-footprint-implications-of-low-carbon-technologies/ (2022).
31. Luderer, G. et al. Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nat. Commun.* **10**, 5229 (2019).
32. Deetman, S., de Boer, H. S., Van Engelenburg, M., van der Voet, E. & van Vuuren, D. P. Projected material requirements for the global electricity infrastructure—generation, transmission and storage. *Resour. Conserv. Recycl.* **164**, 105200 (2021).
33. Kalt, G., Thunshirn, P., Krausmann, F. & Haberl, H. Material requirements of global electricity sector pathways to 2050 and associated greenhouse gas emissions. *J. Clean. Prod.* **358**, 132014 (2022).
34. Xia, X. & Li, P. A review of the life cycle assessment of electric vehicles: considering the influence of batteries. *Sci. Total Environ.* **814**, 152870 (2022).
35. Jaramillo, P. et al. in *Climate Change 2022: Mitigation of Climate Change* (eds Shukla, P. R. et al.) Ch. 10 (Cambridge Univ. Press, 2022).
36. Creutzig, F. et al. Transport: a roadblock to climate change mitigation? *Science* **350**, 911–912 (2015).
37. Ballinger, B. et al. The vulnerability of electric vehicle deployment to critical mineral supply. *Appl. Energy* **255**, 113844 (2019).
38. Churkina, G. et al. Buildings as a global carbon sink. *Nat. Sustain.* **3**, 269–276 (2020).
39. Hurmekoski, E., Smyth, C. E., Stern, T., Verkerk, P. J. & Asada, R. Substitution impacts of wood use at the market level: a systematic review. *Environ. Res. Lett.* **16**, 123004 (2021).
40. Werner, F., Taverna, R., Hofer, P., Thürig, E. & Kaufmann, E. National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. *Environ. Sci. Policy* **13**, 72–85 (2010).
41. Mishra, A. et al. Land use change and carbon emissions of a transformation to timber cities. *Nat. Commun.* **13**, 4889 (2022).
42. Pomponi, F., Hart, J., Arehart, J. H. & D'Amico, B. Buildings as a global carbon sink? A reality check on feasibility limits. *One Earth* **3**, 157–161 (2020).
43. Creutzig, F. et al. in *Climate Change 2022: Mitigation of Climate Change Change* (eds Shukla, P. R. et al.) Ch. 5 (IPCC, Cambridge Univ. Press, 2022).
44. Tuomisto, H. L. Challenges of assessing the environmental sustainability of cellular agriculture. *Nat. Food* **3**, 801–803 (2022).
45. Sinke, P., Swartz, E., Sanctorum, H., van der Giesen, C. & Odegard, I. Ex-ante life cycle assessment of commercial-scale cultivated meat production in 2030. *Int. J. Life Cycle Assess.* **28**, 234–254 (2023).
46. *Towards Our Common Digital Future* (WBGU, 2019); https://www.wbgu.de/fileadmin/user_upload/wbgu/publikationen/hauptgutachten/hg2019/pdf/WBGU_HGD2019_S.pdf
47. *Digitalization & Energy* (IEA, 2017); https://doi.org/10.1787/9789264286276-en
48. *Transition to Shared Mobility: How Large Cities Can Deliver Inclusive Transport Services* (ITF, 2017).
49. *Digital Technology and the Planet: Harnessing Computing to Achieve Net Zero* (Royal Society, 2020).
50. Forti, V., Balde, C. P., Kuehr, R. & Bel, G. *The Global E-waste Monitor 2020: Quantities, Flows and the Circular Economy Potential* (United Nations Univ., 2020).

51. *A New Circular Vision for Electronics: Time for a Global Reboot* (World Economic Forum, 2019).
52. Luckeneder, S., Giljum, S., Schaffartzik, A., Maus, V. & Tost, M. Surge in global metal mining threatens vulnerable ecosystems. *Glob. Environ. Change* **69**, 102303 (2021).
This paper assessed 3,000 mine sites and found that 79% of global metal ore extraction in 2019 originated from 5 of the 6 most species-rich biomes, with mining volumes doubling since 2000 in tropical moist forest ecosystems.
53. Jowitt, S. M., Werner, T. T., Weng, Z. & Mudd, G. M. Recycling of the rare earth elements. *Curr. Opin. Green. Sustain. Chem.* **13**, 1–7 (2018).
54. Madhu, K., Pauliuk, S., Dhathri, S. & Creutzig, F. Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment. *Nat. Energy* **6**, 1035–1044 (2021).
55. Wilson, S. et al. Offsetting of CO_2 emissions by air capture in mine tailings at the Mount Keith nickel mine, Western Australia: rates, controls and prospects for carbon neutral mining. *Int. J. Greenh. Gas. Control* **25**, 121–140 (2014).
56. Power, I. M. et al. Strategizing carbon-neutral mines: a case for pilot projects. *Minerals* **4**, 399–436 (2014).
57. Nijnens, J., Behrens, P., Kraan, O., Sprecher, B. & Kleijn, R. Energy transition will require substantially less mining than the current fossil system. *Joule* **7**, 2408–2413 (2023).
58. Bordoff, J. & O'Sullivan Meghan, L. Green upheaval: the new geopolitics of energy. *Foreign Aff.* **101**, 68 (2022).
59. Owen, J. R., Kemp, D., Harris, J., Lechner, A. M. & Lèbre, É. Fast track to failure? Energy transition minerals and the future of consultation and consent. *Energy Res. Soc. Sci.* **89**, 102665 (2022).
60. Lèbre, É. et al. The social and environmental complexities of extracting energy transition metals. *Nat. Commun.* **11**, 4823 (2020).
61. Valenta, R. K., Kemp, D., Owen, J. R., Corder, G. D. & Lèbre, É. Re-thinking complex orebodies: consequences for the future world supply of copper. *J. Clean. Prod.* **220**, 816–826 (2019).
62. Franks, D. M. et al. Conflict translates environmental and social risk into business costs. *Proc. Natl Acad. Sci. USA* **111**, 7576–7581 (2014).
63. Some EU states baulking at streamlined mine permitting, says commissioner. *MINING.COM* https://www.mining.com/web/some-eu-states-baulking-at-streamlined-mine-permitting-says-commissioner/ (2023).
64. Prno, J. & Slocombe, D. S. Exploring the origins of 'social license to operate' in the mining sector: Perspectives from governance and sustainability theories. *Resour. Policy* **37**, 346–357 (2012).
65. Moffat, K., Lacey, J., Zhang, A. & Leipold, S. The social licence to operate: a critical review. *Forestry* **89**, 477–488 (2016).
66. Stock, R. Illuminant intersections: injustice and inequality through electricity and water infrastructures at the Gujarat solar park in India. *Energy Res. Soc. Sci.* **82**, 102309 (2021).
67. Yenneti, K. & Day, R. Distributional justice in solar energy implementation in India: the case of Charanka solar park. *J. Rural Stud.* **46**, 35–46 (2016).
68. Kung, A., Holcombe, S., Hamago, J. & Kemp, D. Indigenous co-ownership of mining projects: a preliminary framework for the critical examination of equity participation. *J. Energy Nat. Resour. Law* **40**, 413–435 (2022).
69. Rao, N. D. & Wilson, C. Advancing energy and well-being research. *Nat. Sustain.* **5**, 98–103 (2022).
70. Song, L. et al. China's bulk material loops can be closed but deep decarbonization requires demand reduction. *Nat. Clim. Change* **13**, 1136–1143 (2023).
71. Creutzig, F. et al. Leveraging digitalization for sustainability in urban transport. *Glob. Sustain.* **2**, e14 (2019).
72. Pauliuk, S. et al. Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. *Nat. Commun.* **12**, 5097 (2021).
73. Springmann, M. et al. Mitigation potential and global health impacts from emissions pricing of food commodities. *Nat. Clim. Change* **7**, 69–74 (2017).
74. Hertwich, E. G. et al. Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. *Environ. Res. Lett.* **14**, 043004 (2019).
75. Ryen, E. G., Babbitt, C. W. & Williams, E. Consumption-weighted life cycle assessment of a consumer electronic product community. *Environ. Sci. Technol.* **49**, 2549–2559 (2015).
76. Graedel, T. E. & Miatto, A. Alloy profusion, spice metals, and resource loss by design. *Sustainability* **14**, 7535 (2022).
77. Franco, A., Shaker, M., Kalubi, D. & Hostettler, S. A review of sustainable energy access and technologies for healthcare facilities in the Global South. *Sustain. Energy Technol. Assess.* **22**, 92–105 (2017).
78. Tanaka, S., Teshima, K. & Verhoogen, E. North–south displacement effects of environmental regulation: the case of battery recycling. *Am. Econ. Rev. Insights* **4**, 271–288 (2022).
79. Ádám, B. et al. From inequitable to sustainable e-waste processing for reduction of impact on human health and the environment. *Environ. Res.* **194**, 110728 (2021).
80. Gutberlet, J., Carenzo, S., Kain, J.-H. & Mantovani Martiniano de Azevedo, A. Waste picker organizations and their contribution to the circular economy: two case studies from a Global South perspective. *Resources* **6**, 52 (2017).
81. Pauliuk, S., Arvesen, A., Stadler, K. & Hertwich, E. G. Industrial ecology in integrated assessment models. *Nat. Clim. Change* **7**, 13–20 (2017).
82. Lima, A. T. et al. Climate mitigation models need to become circular – let's start with the construction sector. *Resour. Conserv. Recycl.* **190**, 106808 (2023).
83. Hertwich, E. G. & Wood, R. The growing importance of scope 3 greenhouse gas emissions from industry. *Environ. Res. Lett.* **13**, 104013 (2018).
84. Zhong, X. et al. Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060. *Nat. Commun.* **12**, 6126 (2021).
85. Sen, B., Onat, N. C., Kucukvar, M. & Tatari, O. Material footprint of electric vehicles: a multiregional life cycle assessment. *J. Clean. Prod.* **209**, 1033–1043 (2019).
86. Rockström, J. et al. A safe operating space for humanity. *Nature* **461**, 472–475 (2009).
87. Mastrucci, A., van Ruijven, B., Byers, E., Poblete-Cazenave, M. & Pachauri, S. Global scenarios of residential heating and cooling energy demand and CO_2 emissions. *Climatic Change* **168**, 14 (2021).
88. Edelenbosch, O., Rovelli, D., Levesque, A., Marangoni, G. & Tavoni, M. Long term, cross-country effects of buildings insulation policies. *Technol. Forecast. Soc. Change* **170**, 120887 (2021).
89. Pehl, M. et al. Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nat. Energy* **2**, 939–945 (2017).
90. Rolnick, D. et al. Tackling climate change with machine learning. *ACM Comput. Surv.* **55**, 42 (2022).
91. Silva, M. C., Horta, I. M., Leal, V. & Oliveira, V. A spatially-explicit methodological framework based on neural networks to assess the effect of urban form on energy demand. *Appl. Energy* **202**, 386–398 (2017).
92. Milojevic-Dupont, N. et al. Learning from urban form to predict building heights. *PLoS ONE* **15**, e0242010 (2020).
93. Haberl, H. et al. High-resolution maps of material stocks in buildings and infrastructures in Austria and Germany. *Environ. Sci. Technol.* **55**, 3368–3379 (2021).

94. Joshi, S. et al. High resolution global spatiotemporal assessment of rooftop solar photovoltaics potential for renewable electricity generation. *Nat. Commun.* **12**, 5738 (2021).
95. Kerner, H. et al. Rapid response crop maps in data sparse regions. Preprint at https://arxiv.org/abs/2006.16866 (2020).
96. He, T. et al. Global 30 meters spatiotemporal 3D urban expansion dataset from 1990 to 2010. *Sci. Data* **10**, 321 (2023).
97. Dietrich, J. P., Popp, A. & Lotze-Campen, H. Reducing the loss of information and gaining accuracy with clustering methods in a global land-use model. *Ecol. Model.* **263**, 233–243 (2013).
98. Folberth, C. et al. Spatio-temporal downscaling of gridded crop model yield estimates based on machine learning. *Agric. For. Meteorol.* **264**, 1–15 (2019).
99. Creutzig, F. et al. Demand-side solutions to climate change mitigation consistent with high levels of well-being. *Nat. Clim. Change* **12**, 36–46 (2022).
This paper evidences the multiple benefits of demand-side strategies for managing resource consumption and resulting greenhouse emissions.
100. Castro, C. G., Trevisan, A. H., Pigosso, D. C. A. & Mascarenhas, J. The rebound effect of circular economy: definitions, mechanisms and a research agenda. *J. Clean. Prod.* **345**, 131136 (2022).
A much-needed conceptualization of the rebound effect in circular economy and associated systematic literature review.
101. Haites, E. et al. Contribution of carbon pricing to meeting a mid-century net zero target. *Clim. Policy* **24**, 1–12 (2023).
102. Creutzig, F. et al. Assessing human and environmental pressures of global land-use change 2000–2010. *Glob. Sustain.* **2**, e1 (2019).
103. *UNEP IRP Global Material Flows Database* (UNEP, accessed January 2024); https://unep-irp.fineprint.global/
104. *World Energy Outlook 2023* (IEA, 2023).
105. Shamoon, A. et al. Environmental impact of energy production and extraction of materials—a review. *Mater. Today Proc.* **57**, 936–941 (2022).
106. Thomas, M., Partridge, T., Harthorn, B. H. & Pidgeon, N. Deliberating the perceived risks, benefits, and societal implications of shale gas and oil extraction by hydraulic fracturing in the US and UK. *Nat. Energy* **2**, 17054 (2017).
107. Johnston, J. E., Lim, E. & Roh, H. Impact of upstream oil extraction and environmental public health: a review of the evidence. *Sci. Total Environ.* **657**, 187–199 (2019).
108. Baker, J. M. & Westman, C. N. Extracting knowledge: social science, environmental impact assessment, and Indigenous consultation in the oil sands of Alberta, Canada. *Extr. Ind. Soc.* **5**, 144–153 (2018).
109. *The Role of Critical Minerals in Clean Energy Transitions* (IEA, 2021).
110. van der Voort, N. & Vanclay, F. Social impacts of earthquakes caused by gas extraction in the province of Groningen, The Netherlands. *Environ. Impact Assess. Rev.* **50**, 1–15 (2015).
111. Nkem, A. C., Topp, S. M., Devine, S., Li, W. W. & Ogaji, D. S. The impact of oil industry-related social exclusion on community wellbeing and health in African countries. *Public Health* **10**, 858512 (2022).
112. Ogwang, T. & Vanclay, F. Social impacts of land acquisition for oil and gas development in Uganda. *Land* **8**, 109 (2019).
113. Bello, T. & Nwaeke, T. Impacts of oil exploration (oil and gas conflicts: Niger Delta as a case study). Preprint at *SSRN* https://ssrn.com/abstract=4137463 (2022).
114. Masood, N., Hudson-Edwards, K. & Farooqi, A. True cost of coal: coal mining industry and its associated environmental impacts on water resource development. *J. Sustain. Min.* **19**, 1 (2020).
115. Feng, Y., Wang, J., Bai, Z. & Reading, L. Effects of surface coal mining and land reclamation on soil properties: a review. *Earth Sci. Rev.* **191**, 12–25 (2019).
116. Cabernard, L. & Pfister, S. Hotspots of mining-related biodiversity loss in global supply chains and the potential for reduction through renewable electricity. *Environ. Sci. Technol.* **56**, 16357–16368 (2022).
117. De Valck, J., Williams, G. & Kuik, S. Does coal mining benefit local communities in the long run? A sustainability perspective on regional queensland. *Aust. Resour. Policy* **71**, 102009 (2021).
118. Associated Press Massive mine collapse in China leaves at least 5 dead and 48 missing. *NBC News* https://www.nbcnews.com/news/world/massive-mine-collapse-china-missing-rcna71920 (2023).
119. *Coal Information: Overview: Production* (IEA, 2023); https://www.iea.org/reports/coal-information-overview/production
120. *Mineral Commodities Summary—Lithium* (USGS, 2023); https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-lithium.pdf
121. Ambrose, H. & Kendall, A. Understanding the future of lithium: part 1, resource model. *J. Ind. Ecol.* **24**, 80–89 (2020).
122. Xu, C. et al. Future material demand for automotive lithium-based batteries. *Commun. Mater.* **1**, 99 (2020).
123. Kaunda, R. B. Potential environmental impacts of lithium mining. *J. Energy Nat. Resour. Law* **38**, 237–244 (2020).
124. Agusdinata, D. B., Liu, W., Eakin, H. & Romero, H. Socio-environmental impacts of lithium mineral extraction: towards a research agenda. *Environ. Res. Lett.* **13**, 123001 (2018).
125. *Critical Raw Materials* (European Comission, 2023).
126. *U.S. Geological Surveys Releases 2022 List of Critical Minerals* (USGS, 2022).
127. *Final List of Critical Minerals 2022* (IEA, 2023).
128. *Mineral Commodities Summary—Cobalt* (USGS, 2023); https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-cobalt.pdf
129. van der Meide, M., Harpprecht, C., Northey, S., Yang, Y. & Steubing, B. Effects of the energy transition on environmental impacts of cobalt supply: a prospective life cycle assessment study on future supply of cobalt. *J. Ind. Ecol.* **26**, 1631–1645 (2022).
130. Sovacool, B. K. The precarious political economy of cobalt: balancing prosperity, poverty, and brutality in artisanal and industrial mining in the Democratic Republic of the Congo. *Extr. Ind. Soc.* **6**, 915–939 (2019).
131. Brusselen et al. Metal mining and birth defects: a case-control study in Lubumbashi, Democratic Republic of the Congo. *Lancet Planet. Health* **4**, 158–167 (2020).
132. van den Brink, S., Kleijn, R., Sprecher, B. & Tukker, A. Identifying supply risks by mapping the cobalt supply chain. *Resour. Conserv. Recycl.* **156**, 104743 (2020).
133. *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach* (IEA, 2023).
134. Kermeli, K. et al. The scope for better industry representation in long-term energy models: modeling the cement industry. *Appl. Energy* **240**, 964–985 (2019).
A good illustration of the importance of capturing cross-sectoral relationships between industries in IAMs.
135. Watari, T., Cabrera Serrenho, A., Gast, L., Cullen, J. & Allwood, J. Feasible supply of steel and cement within a carbon budget is likely to fall short of expected global demand. *Nat. Commun.* **14**, 7895 (2023).
136. Lamb, W. F. et al. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environ. Res. Lett.* **16**, 73005 (2021).
Comprehensive analysis and synthesis of knowledge on sectoral GHG emission trends worldwide.
137. Kittipongvises, S. Assessment of environmental impacts of limestone quarrying operations in Thailand. *Environ. Clim. Technol.* **20**, 67–83 (2017).
138. Ganapathi, H. & Phukan, M. in *Environmental Processes and Management: Tools and Practices* (eds Singh, R. M. et al.) 121–134 (Springer, 2020).

139. PTI Seven killed as part of limestone mine collapses in Chhattisgarh village. *The Indian Express* https://indianexpress.com/article/india/seven-killed-limestone-mine-collapses-chhattisgarh-village-bastar-8302732/ (2022).
140. Caserini, S., Storni, N. & Grosso, M. The availability of limestone and other raw materials for ocean alkalinity enhancement. *Glob. Biogeochem. Cycles* **36**, e2021GB007246 (2022).
141. *Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences* (OECD, 2019); https://doi.org/10.1787/9789264307452-en
142. Fry, M. Cement, carbon dioxide, and the 'necessity' narrative: a case study of Mexico. *Geoforum* **49**, 127–138 (2013).
143. Cacciuttolo, C. & Cano, D. Environmental impact assessment of mine tailings spill considering metallurgical processes of gold and copper mining: case studies in the Andean countries of Chile and Peru. *Water* **14**, 3057 (2022).
144. Arratia-Solar, A. & Paredes, D. Commodity price and fatalities in mining—evidence from copper regions in Chile. *Resour. Policy* **82**, 103489 (2023).
145. *Raw Materials Profiles: Dysprosium* (Raw Materials Information System, European Commission Joint Research Centre, 2023); https://rmis.jrc.ec.europa.eu/rmp/Dysprosium
146. Kalt, G. et al. Material stocks in global electricity infrastructures—an empirical analysis of the power sector's stock-flow-service nexus. *Resour. Conserv. Recycl.* **173**, 105723 (2021).
147. Watari, T. et al. Global copper cycles and greenhouse gas emissions in a 1.5 °C world. *Resour. Conserv. Recycl.* **179**, 106118 (2022).
148. *Mineral Commodities Summary—Rare Earths* (USGS, 2023); https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-rare-earths.pdf
149. Watari, T., Nansai, K. & Nakajima, K. Review of critical metal dynamics to 2050 for 48 elements. *Resour. Conserv. Recycl.* **155**, 104669 (2020).
    This paper compiles several hundred estimates for future global demand of 48 potentially critical metals and stresses the need to include component reuse and remanufacturing as well as the linkage between host and by-product metals in future scenario assessments.
150. Langkau, S. & Erdmann, M. Environmental impacts of the future supply of rare earths for magnet applications. *J. Ind. Ecol.* **25**, 1034–1050 (2021).
151. Bai, J. et al. Evaluation of resource and environmental carrying capacity in rare earth mining areas in China. *Sci. Rep.* **12**, 6105 (2022).
152. Bradsher, K. In China, illegal rare earth mines face crackdown. *The New York Times* (29 December 2010); https://www.nytimes.com/2010/12/30/business/global/30smuggle.html
153. Lima, A. T. & Ottosen, L. Recovering rare earth elements from contaminated soils: critical overview of current remediation technologies. *Chemosphere* **265**, 129163 (2021).
154. Wang, S. et al. Future demand for electricity generation materials under different climate mitigation scenarios. *Joule* **7**, 309–332 (2023).
155. Dibattista, I., Camara, A. R., Molderez, I., Benassai, E. M. & Palozza, F. Socio-environmental impact of mining activities in Guinea: the case of bauxite extraction in the region of Boké. *J. Clean. Prod.* **387**, 135720 (2023).
156. Li, G., Yang, H.-X., Yuan, C.-M. & Eckhoff, R. K. A catastrophic aluminium-alloy dust explosion in China. *J. Loss Prev. Process Ind.* **39**, 121–130 (2016).
157. Bobba, S., Carrara, S., Huisman, J., Mathieux, F. & Pavel, C. *Critical Raw Materials for Strategic Technologies and Sectors in the EU: A Foresight Study* (Publications Office of the European Union, 2020); https://doi.org/10.2873/865242
158. Lima, A. T. et al. Strengths and weaknesses of a hybrid post-disaster management approach: the Doce River (Brazil) mine-tailing dam burst. *Environ. Manag.* **65**, 711–724 (2020).
159. Toirres, A., Brandt, J., Lear, K. & Lin, J. A looming tragedy of the sand commons: increasing sand extraction, trade, and consumption pose global sustainability challenges. *Science* **357**, 970–971 (2017).
160. Zhong, X., Deetman, S., Tukker, A. & Behrens, P. Increasing material efficiencies of buildings to address the global sand crisis. *Nat. Sustain.* **5**, 389–392 (2022).
161. Rentier, E. S. & Cammeraat, L. H. The environmental impacts of river sand mining. *Sci. Total Environ.* **838**, 155877 (2022).
162. Torres, A. et al. Sustainability of the global sand system in the Anthropocene. *One Earth* **4**, 639–650 (2021).
163. Sieferle, R. & Müller-Herold, U. P. Überfluß und Überleben-Risiko, Ruin und Luxus in primitiven Gesellschaften. *GAIA Ecol. Perspect. Sci. Soc.* **5**, 135–143 (1996).

Acknowledgements

The authors disclose support for the research of this work from Horizon Europe research and innovation programme under grant agreement numbers 101056810 (F.C., P.B., I.A., H.H., V.K., A.M., N.M.-D., F.N., M.S., F.W. and D.W.), 101056868 (O.E., T.F., E.H., S.P. and D.v.V.), 101056862 (S.G.S. and A.T.L.), 101003083 (C.W.) and 853487 (E.V.). This work was also supported by the Energy Demand Changes Induced by Technological and Social Innovations (EDITS) network, an initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and the International Institute for Applied Systems Analysis (IIASA) and funded by the Ministry of Economy, Trade and Industry (METI), Japan.

Author contributions

F.C. conceptualized the paper. S.G.S. designed Fig. 1 and Table 1 with input from P.B., H.H., S.L., A.T.L., F.N., S.P. and D.W. F.C., S.G.S., S.L., P.B., I.A., O.E., T.F., H.H., E.H., V.K., A.T.L., T.M., A.M., N.M.-D., F.N., S.P., M.S., E.V., D.v.V., F.W., D.W. and C.W. wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence should be addressed to Felix Creutzig.

Peer review information *Nature Climate Change* thanks the anonymous reviewers for their contribution to the peer review of this work.