Demand-side Strategies Key for Mitigating Material Impacts of Energy Transitions

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Abstract. As fossil fuels are phased out in favor 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 fueled 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 modeling and analysis is needed to the opportunities and tradeoffs for demand-led mitigation strategies that explicitly consider planetary boundaries associated with the 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 (DACCS) – may even offer the opportunity to reverse temperature increases further in the future.

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 NGOs 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, metals, and construction of transport infrastructures can have negative socio-environmental impacts disproportionately affecting ecosystem-based livelihoods (e.g., fishermen, pastoralists)[22], marginalized communities, and lower income neighborhoods in both global North and South. High-resolution mapping reveals that mining is a major force in compromising biodiversity-rich areas by direct and indirect impacts, e.g., via wide-spread 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 significantly 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]. ~~Pervasive d~~Digitalization also creates new types of environmental footprint related to material use including copper ore, lithium, rare earth minerals, and many other materials.

In this perspective 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 DACCS can have substantial trade-offs for material use, land use, the biosphere and local social systems, requiring mitigation of their impact

In the following, we first establish the critical environmental and social burdens introduced by decarbonization strategies, such as increased mineral extraction with significant 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. Texposition on the impacts of decarbonization solutions underlines the importance of incorporating demand-side measures to mitigate these effects, thus supporting a holistic approach to achieving sustainable energy transitions.

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 (e.g., steel, cement, aluminum) and land [7,28,29]. While the overall material footprint of low-carbon electricity goes down by 85% compared to 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 aluminum 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 aluminum[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 lifecycle analyses (LCA) show that electric vehicles (EVs) have higher impacts than conventional fossil-fueled vehicles in terms of metal and mineral consumption and human toxicity potential, even as they reduce GHG emissions over the full lifecycle[34]. In the EV industry, significant supply risks originate in rapidly rising demand for battery grade natural graphite, lithium and cobalt for batteries, and the rare earth elements 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 lifecycle 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, there are important trade-offs with other ecosystem services and carbon sinks provided by forests and would 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 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 (e.g., 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]. Digitalisation 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 virtualisation and servitization to reduce demand for energy-intensive products and activities[49]. However, digital infrastructure and devices have distinctive material footprints and relatively 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]. E-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 $60bn annually[51]. Impacts of digitalisation 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 e-waste is a pressing concern and a high priority for future research[53].

Fifth, DAC 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, DAC (using temperature swing adsorption) is estimated to have similar renewable energy requirements and land footprints as a switch from gasoline to electric vehicles, 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 Mt CO_2/yr, according to one study[56]. More broadly, both the logistics (piping) and the geological storage capacity requirements for large-scale application of CCS infrastructure also carries 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) (Figure 1, Table 1). Focusing just on the energy transition, total extraction will be halved from now until 2040 or shortly thereafter under the IEA's 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 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 ~~impacts~~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 Congo, for example, has half the world's supply of cobalt, and China produces 90 per cent 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, e.g. of indigenous people and peasants, undermine local governance but also pose wider socio-political risks negatively impacting economic growth, 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].

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] (e.g., in Latin America and Canada) by circumventing their prior informed consent and participation in decision-making processes. In the European Union, 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 license 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 significant 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.

Demand-side strategies reduce burdens

Demand-side strategies focus on how services can be provided to achieve higher wellbeing at lower levels of energy and material use. This is achieved through social and behavioral 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 (e.g., buildings, transport), intermediate production (e.g., manufacturing) and upstream supply (e.g., energy, materials).

Demand-side strategies achieve the important outcome of reducing both the scale of the climate challenge and material resource requirements (Figure 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 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 ICTs, demand-side solutions can narrow material cycles through resource-efficient design and dematerialisation (e.g. functional convergence with more services delivered through fewer devices[74,75]). Material cycles can also be slowed by re-designing 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 significant 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 significant 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 significant 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.

The 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 analyze 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 (Figure 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 industrial ecology (IE) tools (materials) with integrated assessment modelling (IAM) (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: first, an enhanced quantitative representation of specific sectors in physical terms, including products and service levels (e.g. building types and floorspace levels for residential and commercial sectors with associated material requirements[87,88]); second, re-configuring 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 third, 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 industrial ecology methods, whereas they are at the core of decision making in IAMs. Related data is hard to find and typically proprietary which amplifies the challenge of integrated modeling 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 PV 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 behavior 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 analyze 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.

*Table 1. **The clean energy transition impacts or is influenced by** ~~**Overview of**~~ **key materials, services, current extraction rates, demand evolution, environmental, social and geopolitical risks, supply chain concentration and** ~~**relevant**~~ **transition dynamics** ~~of the clean energy transition~~. 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. Find a complete list of references cited in the table in the Supplementary Material.*

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/y 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 as benzene [105]. Oil combustion causes air pollution (particles, smog, acid rains, etc.) 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, e.g. in Northern Alberta [108]. People displacement, food insecurity, disruption of social and cultural cohesion, among other felt across the world, e.g. Uganda	High (cartelization and war)	USA, Russia, Saudi Arabia extract 42% world supply [109]	Not applicable
Natural gas	All	2.8 Gt/year 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 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 wellbeing [111]. Food insecurity has also been reported. Widespread impacts across the world, as Uganda [112], Nigeria [113].	High (cartelization and war)	USA, Russia, Iran extracts 47% world supply [109]	Not applicable
Coal	all	7.8 Gt/year 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 as Bangladesh, Brazil, China, India, UK, Greece, Colombia, among other [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 [117] [105]. Human casualties and injuries in disasters, e.g. incident in an open-pit coal mine in northern China in 2023 [118]	Lower than oil and gas. xx	China produced 50% of global supply in 2022, followed by India (10%), Australia and Indonesia (10% each), USA (6%), Russia (5%), EU (4%). Rest of the world supplied 11% [119]	Not applicable
Lithium (Li)	Mobility (EV batteries)	1.30 Gt E-04 ore in 2023 [120]	20-30x increase from 2018-2100 [121]; 18-20x increase 2020-2050 for use in batteries [122]	Groundwater depletion, ecosystem degradation [123] [124]	Forced displacement of populations [124]	Considered a critical material in EU [125], USA [126], IEA [127]	Reserves quite concentrated (>50% of global) in Chile, Argentina, Bolivia [123]	Between 2010 and 2022, lithium mining output rose by a factor of five xx ref

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
Cobalt (Co)	Mobility (EV batteries)	1.90 Gt E-04 ore extracted in 2023 [128]	2x-4x increase from 2020-2050 [129]; 17-19x increase 2020-2050 for use in batteries [122]	Similar to copper (circa 60% of world cobalt is co-mined with copper) [129]. Soil, aquifers/surface water contamination, air pollution due to dust [130].	In Democratic Republic of Congo (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 EU [125], USA [126], IEA [127]	Highly concentrated in both mining and refining countries with DRC providing 60-70% world supply [5]. Strongly related to production of copper and nickel [129]	Now 7.2 million EV that could become 140 -245 million in 2030 [132]. Between 2010 and 2022 mining output rose by a factor of five [133]
Limestone (for e.g. cement, glass, others)	Buildings, Civil Engineering, Energy Infrastructure (offshore wind, hydropower)	6.7 Gt/year in 2019 of limestone [103]	Constant-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. e.g. limestone mine collapse in India, 2022 [139]	Not a critical material	Potential resources of pure carbonate rocks are in the order of several tens of thousands of Gt, that 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/year in 2019 of copper ore [103]	Future Al and Cu demand for power sector infrastructure could require 18% of current production [8]; 1.5x-5x demand growth by 2050 [134]	Toxicity from (sulfidic) mining tailings leaching into groundwater and soils. also, eutrophication from phosphate leaching from tailings [143] [144]	Many mine tailing spilling incidents. Chile reports 43 copper miners died in Chile in 2010 due to accidents in mining operations, and relates higher fatalities with higher commodity prices [145]	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 USA (9%). Smelting/refining well distributed across countries [146].	5 Mt/yr for power grids in 2020 to 7.5-10 Mt/yr in 2040 [109] 2-3x annual copper demand in 2050 over 2021 for energy distribution and transmission grids, as well as power plants and transformers [147] 2.5x annual copper demand for electric vehicles in a 1.5°C scenario [148]
Rare earth elements, particularly Dysprosium (Dy)	Mobility & magnets	300 kt of total rare earths mined in 2023 in rare-earth-oxide (REO) equivalent [149] 3.1 kt of Dy_2O_3 mined in 2021 [146]	2x-30 x increase expected [150]	Human toxicity [151]. 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 [152]	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 [153]	Considered a critical material in EU [2], USA [3], IEA [4]	Reserves evenly distributed between China (36%), Brazil (18%), Vietnam (18%), Russia (10%) [154]. However, China responsible for 40% of global Dy production, followed by Myanmar (31%) and Australia (20%) [146]	By 2050 maximum annual demand for energy could represent 309% of current production [155]

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
Rare earth elements, particularly Neodymium (Nd)	Energy (permanent magnets of onshore and offshore wind power plants)	300 kt of total rare earths mined in 2023 in rare-earth-oxide (REO) equivalent [149] 4.75 kt of Nd_2O_3 mined in 2021 [146]	2x-30x increase expected [150]; ; 3x-4.4x increase of Nd by 2050 only for electricity infrastructure [156]	Same as for Dysprosium	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 [153]	Considered a critical material in EU [2], USA [3], IEA [4]	See Dy for REE reserves. China responsible for 62% of global Nd production, followed by Myanmar (14%), USA (11%) and Australia (7%) [146]	By 2050 maximum annual demand for energy could represent 271% of current production [155]
Aluminium	Transport, buildings, packaging, machinery, electricity distribution	0.4 Gt/year in 2019 of bauxite extraction [103]	2x-8x increase by 2050 [16]; 2x-8x increase by 2050 [16]; 2x-2.3x increase by 2050 only for electricity infrastructure [156]	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 [157]	Corruption and high social inequalities among mining workforce, e.g. in Guinea [157]. Human casualties in disasters. E.g. explosion aluminium-alloy plant in Kunshan, China, 2014 [158]	Considered a critical material in EU [2], USA [3], IEA [4]	Guinea responsible for 36% of global primary production, followed by Australia (25%), and Russia (17%). >50% of smelting occurs in China [146]	30% increase in EU demand for aluminium by 2040, driven mainly by the growth of electric vehicles, solar PV and electricity grids [159]. Global demand can double from 2017 [141]
Iron (for e.g. steel)	Buildings, infrastructure, machinery, electricity system	3.1 Gt/year in 2019 of iron ore extraction [103]	2x-2.6x increase by 2050 only for electricity infrastructure [156]	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. E.g. Dam tailing rupture in the Doce River, Brazil in 2015 and 2018 [160]	Not a critical material, no geopolitical risks at this stage	Reserves quite distributed, Australia biggest producer followed by Brazil, China, India [151]	Global demand can double from 2017 [141]
Non-metallic construction minerals (sand, gravel, clays, stones, gypsum)	Buildings and infrastructure	42.9 Gt/year in 2019 [103]	Substantial increase in demand for buildings and infrastructure expansion around the world [161] [162]. Aggregates extraction projected to grow from 24 to 55 Gt per year 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 [163] [164]	Local livelihoods negatively affected through degradation of local ecosystems, esp. in developing countries and coastal/river regions. Potential increase in vector borne diseases. Reports of organized crime groups in India, Italy among other where illegal trade in sand occurs [161]	Not a critical material, no geopolitical risks	Widespread deposits, often illegal extraction [161]	~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 [162]

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 PV in building designs to reduce material demand of support structures, optimize location of new installations to reduce the need for network expansion, 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, limit sprawling settlements
Nutrition	Curb meat consumption and shift to unprocessed plant protein, sufficiency in line with dietary recommendations
Communication and information processing	Material efficiency in design and manufacturing of ICTs, value capture from material recovery and recirculation
Carbon dioxide removal	Rapid GHG emission reductions avoid the need for large-scale CCS infrastructure

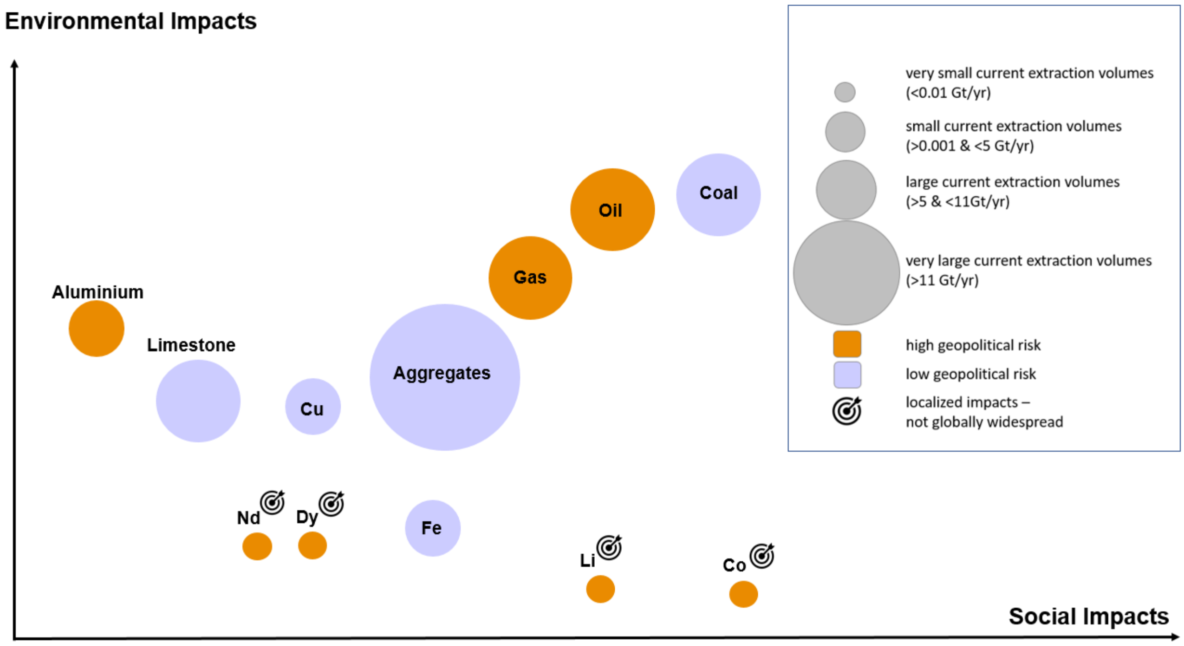

Figure 1. Comparative overview of impacts of extracting and supplying emerging materials and fossil fuels. The relative location of materials and fuels is by expert judgement underpinned by the insights from Table 1. Only the extraction and processing stages are included, not fossil fuel combustion.

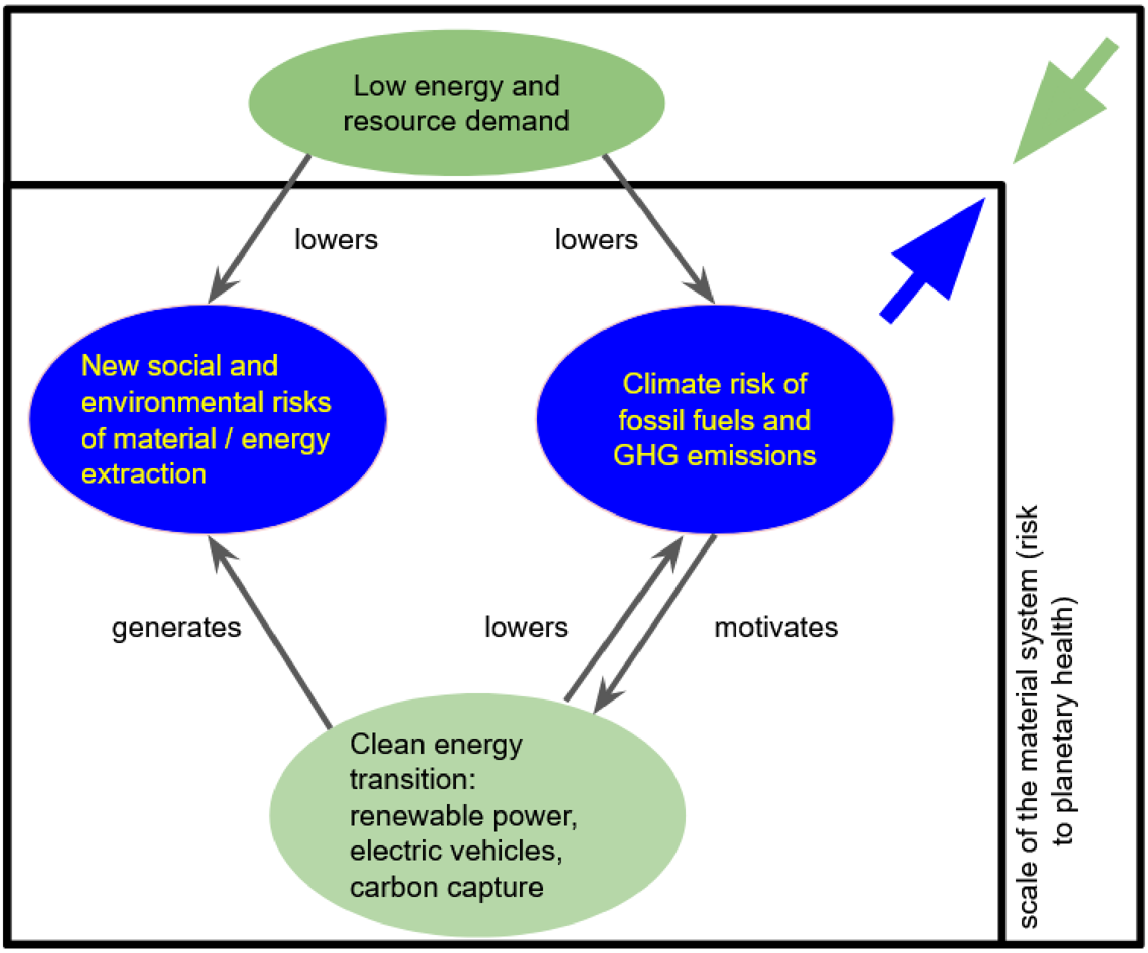

Figure 2. Shifting risks and response strategies from the clean energy transition. Partially motivated by[165].

Conflict of interests

We declare no conflict of interests.

Author contributions

Felix Creutzig conceptualized the paper. Sofia Simoes designed Figure 1 and Table 1 with input by Peter Berrill, Helmut Haberl, Sina Leipold Ana Teresa Macas Lima, Florian Nachtigall, Stefan Pauliuk, and Dominik Wiedenhofer. All authors wrote the paper.

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 CO2 emissions. *Nature Climate 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 Research & Social Science* **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. Skea, J., Shukla, P., Reisinger, A., Slade, R. & Pathak, M. *Climate Change 2022. Mitigation of Climate Change. Summary for Policymaker.* (IPCC, 2022).
6. Thompson, H. *Disorder: Hard Times in the 21st Century*. (Oxford University Press, 2022).
7. Simoes, S. G. & Lima, A. T. M. Materials, resources, and CO2 impacts of building new renewable power plants to reach EU's goals of carbon neutrality. *Journal of Cleaner Production* **418**, 138138 (2023).
8. Watari, T. *et al.* Total material requirement for the global energy transition to 2050: A focus on transport and electricity. *Resources, Conservation and Recycling* **148**, 91–103 (2019).
9. Giljum, S. *et al.* A pantropical assessment of deforestation caused by industrial mining. *Proceedings of the National Academy of Sciences* **119**, e2118273119 (2022).
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 Research & Social Science* **90**, 102583 (2022).
12. Pimentel Da Silva, G. D. & Branco, D. A. C. Is floating photovoltaic better than conventional photovoltaic? Assessing environmental impacts. *Impact Assessment and Project 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. *Journal of Cleaner Production* **104**, 297–304 (2015).

15. Pueyo, A. What constrains renewable energy investment in Sub-Saharan Africa? A comparison of Kenya and Ghana. *World Development* **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**, 1–8 (2020).

17. West, J. Decreasing Metal Ore Grades. *Journal of Industrial Ecology* (2011).

18. Graedel, T. E., Harper, E. M., Nassar, N. T., Nuss, P. & Reck, B. K. Criticality of metals and metalloids. *Proceedings of the National Academy of Sciences* **112**, 4257–4262 (2015).

19. Bordoff, J. & O'Sullivan, M. L. The Age of Energy Insecurity. *Foreign Affairs* (2023).

20. Vakulchuk, R., Overland, I. & Scholten, D. Renewable energy and geopolitics: A review. *Renewable and Sustainable Energy Reviews* **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. *Ecological Economics* **191**, 107247 (2022).

23. Maus, V. *et al.* An update on global mining land use. *Scientific data* **9**, 1–11 (2022).

24. Tang, L. & Werner, T. T. Global mining footprint mapped from high-resolution satellite imagery. *Commun Earth Environ* **4**, 1–12 (2023).

25. Bainton, N., Kemp, D., Lèbre, E., Owen, J. R. & Marston, G. The energy-extractives nexus and the just transition. *Sustainable Development* **29**, 624–634 (2021).

26. Scheidel, A. *et al.* Global impacts of extractive and industrial development projects on Indigenous Peoples' lifeways, lands, and rights. *Science Advances* **9**, eade9557 (2023).

27. Creutzig, F. *et al.* Digitalization and the Anthropocene. *Annual Review of Environment and Resources* **47**, (2022).

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 – STATE OF AFFAIRS. 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. *Resources, Conservation and Recycling* **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. *Journal of Cleaner Production* **358**, 132014 (2022).

34. Xia, X. & Li, P. A review of the life cycle assessment of electric vehicles: Considering the influence of batteries. *Science of The Total Environment* **814**, 152870 (2022).

35. Jaramillo, P. *et al.* Transport (Chapter 10). (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. *Applied 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. *Environmental Science & 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.* Chapter 5: Demand, services and social aspects of mitigation. in *Climate Change 2022: Mitigation of Climate Change* (IPCC, 2022).

44. Tuomisto, H. L. Challenges of assessing the environmental sustainability of cellular agriculture. *Nature 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. WBGU. *Towards Our Common Digital Future*. https://www.wbgu.de/fileadmin/user_upload/wbgu/publikationen/hauptgutachten/hg2019/pdf/WBGU_HGD2019_S.pdf (2019).

47. IEA. *Digitalization & Energy*. (OECD, 2017). doi:10.1787/9789264286276-en.

48. ITF. *Transition to Shared Mobility: How Large Cities Can Deliver Inclusive Transport Services*. (2017).

49. Royal Society. *Digital Technology and the Planet: Harnessing Computing to Achieve Net Zero*. (London, UK, 2020).

50. Forti, V., Balde, C. P., Kuehr, R. & Bel, G. The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential. (2020).

51. World Economic Forum. *A New Circular Vision for Electronics: Time for a Global Reboot.* (2019).

52. Luckeneder, S., Giljum, S., Schaffartzik, A., Maus, V. & Tost, M. Surge in global metal mining threatens vulnerable ecosystems. *Global Environmental Change* **69**, 102303 (2021).

53. Jowitt, S. M., Werner, T. T., Weng, Z. & Mudd, G. M. Recycling of the rare earth elements. *Current Opinion in Green and Sustainable Chemistry* **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. *Nature Energy* **6**, 1035–1044 (2021).

55. Wilson, S. *et al.* Offsetting of CO2 emissions by air capture in mine tailings at the Mount Keith Nickel Mine, Western Australia: Rates, controls and prospects for carbon neutral mining. *International Journal of Greenhouse 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 Research & Social Science* **89**, 102665 (2022).

60. Lèbre, É. *et al.* The social and environmental complexities of extracting energy transition metals. *Nature communications* **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. *Journal of Cleaner Production* **220**, 816–826 (2019).

62. Franks, D. M. *et al.* Conflict translates environmental and social risk into business costs. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 7576–7581 (2014).

63. Reuters. 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. *Resources policy* **37**, 346–357 (2012).

65. Moffat, K., Lacey, J., Zhang, A. & Leipold, S. The social licence to operate: a critical review. *Forestry: An International Journal of Forest Research* **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 Research & Social Science* **82**, 102309 (2021).

67. Yenneti, K. & Day, R. Distributional justice in solar energy implementation in India: the case of Charanka solar park. *Journal of rural studies* **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. *Journal of Energy & Natural Resources Law* **40**, 413–435 (2022).

69. Rao, N. D. & Wilson, C. Advancing energy and well-being research. *Nature Sustainability* **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. Chang.* **13**, 1136–1143 (2023).

71. Creutzig, F. *et al.* Leveraging Digitalization for Sustainability in Urban Transport. *Global Sustainability* **2**, 1–6 (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. *Nature Climate 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. *Environmental Research Letters* **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. *Sustainable Energy Technologies and Assessments* **22**, 92–105 (2017).

78. Tanaka, S., Teshima, K. & Verhoogen, E. North-South Displacement Effects of Environmental Regulation: The Case of Battery Recycling. *American Economic Review: 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. *Environmental Research* **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. *Nature 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. *Resources, Conservation and Recycling* **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. *Journal of Cleaner Production* **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 CO2 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. *Technological Forecasting and Social 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**, 42:1-42:96 (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. *Applied 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. *Environmental science & technology* **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. *arXiv preprint arXiv:2006.16866* (2020).

96. He, T. *et al.* Global 30 meters spatiotemporal 3D urban expansion dataset from 1990 to 2010. *Scientific 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. *Ecological modelling* **263**, 233–243 (2013).
98. Folberth, C. *et al.* Spatio-temporal downscaling of gridded crop model yield estimates based on machine learning. *Agricultural and forest meteorology* **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. Chang.* 1–11 (2021) doi:10.1038/s41558-021-01219-y.
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. *Journal of Cleaner Production* **345**, 131136 (2022).
101. Haites, E. *et al.* Contribution of carbon pricing to meeting a mid-century net zero target. *Climate Policy* 1–12 (2023).
102. Creutzig, F. *et al.* Assessing human and environmental pressures of global land-use change 2000–2010. *Global Sustainability* **2**, (2019).
103. UNEP. United Nations Environment Programme, International Resource Panel, Global Material Flows Database. *UNEP IRP Global Material Flows Database* https://unep-irp.fineprint.global/.
104. IEA. *World Energy Outlook 2023*. (2023).
105. Shamoon, A. *et al.* Environmental impact of energy production and extraction of materials - a review. *Materials Today: Proceedings* **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. *Nature 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. *Science of The Total Environment* **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. *The Extractive Industries and Society* **5**, 144–153 (2018).

109. IEA. *The Role of Critical Minerals in Clean Energy Transitions*. (2021).

110. van der Voort, N. & Vanclay, F. Social impacts of earthquakes caused by gas extraction in the Province of Groningen, The Netherlands. *Environmental Impact Assessment Review* **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**, (2022).

112. Ogwang, T. & Vanclay, F. Social Impacts of Land Acquisition for Oil and Gas Development in Uganda. *Land* **8**, (2019).

113. Bello, T. & Nwaeke, T. Impacts of Oil Exploration (Oil and Gas Conflicts: Niger Delta as a Case Study). *SSRN* (2022) doi:10.2139/ssrn.4137463.

114. Masood, N., Hudson-Edwards, K. & Farooqi, A. True cost of coal: coal mining industry and its associated environmental impacts on water resource development. *Journal of Sustainable Mining* **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-Science Reviews* **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. *Environmental Science & Technology* **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, Australia. *Resources Policy* **71**, 102009 (2021).

118. Associated Press. Massive mine collapse in China leaves at least 5 dead and 48 missing. *NBC News* (2023).

119. IEA. Coal Information Overvivew. https://www.iea.org/reports/coal-information-overview/production (2023).

120. USGS United States Geological Surveys. Mineral Commodities Summary - Lithium. *Mineral Commodities Summary* 4 https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-lithium.pdf (2023).

121. Ambrose, H. & Kendall, A. Understanding the future of lithium: Part 1, resource model. *Journal of Industrial Ecology* **24**, 80–89 (2020).

122. Xu, C. *et al.* Future material demand for automotive lithium-based batteries. *Communications Materials* **1**, 99 (2020).

123. Kaunda, R. B. Potential environmental impacts of lithium mining. *Journal of Energy & Natural Resources 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. *Environmental Research Letters* **13**, 123001 (2018).

125. European Comission. *Critical Raw Materials*. (2023).

126. USGS. *U.S. Geological Surveys Releases 2022 List of Critical Minerals*. (2022).

127. International Energy Agency. *Final List of Critical Minerals 2022*. (2023).

128. USGS United States Geological Surveys. Mineral Commodities Summary - Cobalt. *Mineral Commodities Summary* 5 https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-cobalt.pdf (2023).

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. *Journal of Industrial Ecology* **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. *The Extractive Industries and Society* **6**, 915–939 (2019).
131. Brusselen, D. Van *et al.* Metal mining and birth defects: a case-control study in Lubumbashi, Democratic Republic of the Congo. *The Lancet Planetary Health* **4**, E158–E167 (2020).
132. van den Brink, S., Kleijn, R., Sprecher, B. & Tukker, A. Identifying supply risks by mapping the cobalt supply chain. *Resources, Conservation and Recycling* **156**, 104743 (2020).
133. IEA. *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach*. (2023).
134. Kermeli, K. *et al.* The scope for better industry representation in long-term energy models: Modeling the cement industry. *Applied Energy* **240**, 964–985 (2019).
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. *Nature Communications* **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. *Environmental Research Letters* **16**, 73005 (2021).
137. Kittipongvises, S. Assessment of Environmental Impacts of Limestone Quarrying Operations in Thailand. *Environmental and Climate Technologies* **20**, 67–83 (2017).
138. Ganapathi, H. & Phukan, M. Environmental Hazards of Limestone Mining and Adaptive Practices for Environment Management Plan BT - Environmental Processes and Management: Tools and Practices. in (eds. Singh, R. M., Shukla, P. & Singh, P.) 121–134 (Springer International Publishing, Cham, 2020). doi:10.1007/978-3-030-38152-3_8.
139. PTI. Seven killed as part of limestone mine collapses in Chhattisgarh village. *The Indian Express* (2022).

140. Caserini, S., Storni, N. & Grosso, M. The Availability of Limestone and Other Raw Materials for Ocean Alkalinity Enhancement. *Global Biogeochemical Cycles* **36**, e2021GB007246 (2022).

141. OECD. *Global Material Resources Outlook to 2060 - Economic Drivers and Environmental Consequences*. (2019) doi: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. Berrill, P., Arvesen, A., Scholz, Y., Gils, H. C. & Hertwich, E. G. Environmental impacts of high penetration renewable energy scenarios for Europe. *Environmental Research Letters* **11**, 14012 (2016).

144. 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**, (2022).

145. Arratia-Solar, A. & Paredes, D. Commodity price and fatalities in mining – Evidence from copper regions in Chile. *Resources Policy* **82**, 103489 (2023).

146. JRC Joint Research Centre. RMIS - Raw Material Information System of the European Commission. *RMIS Raw Materials Information System* https://rmis.jrc.ec.europa.eu/rmp/Dysprosium (2023).

147. Kalt, G. *et al.* Material stocks in global electricity infrastructures – An empirical analysis of the power sector's stock-flow-service nexus. *Resources, Conservation and Recycling* **173**, 105723 (2021).

148. Watari, T. *et al.* Global copper cycles and greenhouse gas emissions in a 1.5 °C world. *Resources, Conservation and Recycling* **179**, 106118 (2022).

149. USGS United States Geological Surveys. Mineral Commodities Summary - Rare Earths. *Mineral Commodities Summary* 2 https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-rare-earths.pdf (2023).

150. Watari, T., Nansai, K. & Nakajima, K. Review of critical metal dynamics to 2050 for 48 elements. *Resources, Conservation and Recycling* **155**, 104669 (2020).

151. Langkau, S. & Erdmann, M. Environmental impacts of the future supply of rare earths for magnet applications. *Journal of Industrial Ecology* **25**, 1034–1050 (2021).

152. Bai, J. *et al.* Evaluation of resource and environmental carrying capacity in rare earth mining areas in China. *Scientific Reports* **12**, 6105 (2022).

153. In China, Illegal Rare Earth Mines Face Crackdown. *The New York Times* (2010).

154. Lima, A. T. & Ottosen, L. Recovering rare earth elements from contaminated soils: Critical overview of current remediation technologies. *Chemosphere* **265**, 129163 (2021).

155. Wang, S. *et al.* Future demand for electricity generation materials under different climate mitigation scenarios. *Joule* **7**, P309-332 (2023).

156. 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. *Resources, Conservation and Recycling* **164**, 105200 (2021).

157. 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. *Journal of Cleaner Production* **387**, 135720 (2023).

158. Li, G., Yang, H.-X., Yuan, C.-M. & Eckhoff, R. K. A catastrophic aluminium-alloy dust explosion in China. *Journal of Loss Prevention in the Process Industries* **39**, 121–130 (2016).

159. Bobba, S., Carrara, S., Huisman, J., Mathieux, F. & Pavel, C. *Critical Raw Materials for Strategic Technologies and Sectors in the EU - A Foresight Study*. (2020) doi:10.2873/865242.

160. Lima, A. T. *et al.* Strengths and Weaknesses of a Hybrid Post-disaster Management Approach: the Doce River (Brazil) Mine-Tailing Dam Burst. *Environmental Management* **65**, 711–724 (2020).

161. 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).

162. Zhong, X., Deetman, S., Tukker, A. & Behrens, P. Increasing material efficiencies of buildings to address the global sand crisis. *Nature Sustainability 2022* 1–4 (2022) doi:10.1038/s41893-022-00857-0.

163. Rentier, E. S. & Cammeraat, L. H. The environmental impacts of river sand mining. *Science of The Total Environment* **838**, 155877 (2022).

164. Torres, A. *et al.* Sustainability of the global sand system in the Anthropocene. *One Earth* **4**, P639-650 (2021).

165. Sieferle, R. & Müller-Herold, U. P. Überfluß und Überleben-Risiko, Ruin und Luxus in primitiven Gesellschaften. *GAIA-Ecological Perspectives for Science and Society* **5**, 135–143 (1996).