Planetary impact shifts from fossil fuels to material extraction

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Abstract. As societies abandon fossil fuels in favor of renewable energy, electric cars and other low-carbon technologies, environmental pressures shift from atmospheric carbon loading to adverse impacts of material extraction and waste flows, new infrastructure development, land use change, and the provision of new types of goods and services. We call for interdisciplinary modeling to investigate this major change in environmental and social burdens and identify systemic demand-led mitigation strategies that explicitly consider planetary boundaries associated with the earth's material resources.

Many of the technologies required to effectively address climate change exist on the market. There are emerging signs that societies can rally enough political support and practical action to slow climate change. Peak coal may have arrived[1]. Low-cost renewable energy technologies are diffusing exponentially, integrating into increasingly digitalized networks.[2]

Energy end-use technologies enabling low-carbon electrification of mobility and heating services – such as batteries for electric vehicles and heat pumps for housing – are are becoming ever cheaper and expanding rapidly r[3]. If these trends continue alongside policies for tackling GHG emissions from land use and agriculture, the goal of limiting global warming to below 2°C may remain within reach. 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 novel trade-offs. Mitigation technologies such as wind turbines, solar panels or batteries – and the infrastructures they require – are material-intensive[4]. Their sourcing from the earth and their sinking as waste will impose new burdens on the planet, including water pollution, mining operations[5], large-scale renewable power plant deployment and other land footprints[6], and supply chain-related emissions[7]. Environmental and social impacts, not resource scarcity, constitute the main risk in metals and minerals supply[8–12]. Biodiversity and deforestation impacts of mining are well documented both for metals[5] and for bulk materials such as sand[13]. Large-scale extraction of energy resources, metals, and construction of transport infrastructures can bring negative socio-environmental impacts that disproportionately affect resource-based livelihoods (e.g., fishermen, pastoralists)[14], marginalized communities, and lower income neighborhoods in both global North and South. More than three quarters of environmental conflicts harming indigenous communities are caused by mining, fossil fuels, dams, energy infrastructure, and industrial-scale agriculture, forestry, fisheries, and livestock farming[15].

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[16]. Pervasive digitalisation therefore creates new types of environmental footprint related to energy use and materials including copper ore, gold, rare earth minerals, and many other materials.

We here discuss three main emerging problems with the transition towards climate neutrality. First, large-scale transitions to a renewable energy supply, afforestation, and potentially new CDR technologies such as DACCS have significant trade-offs regarding material use, land use, the biosphere and local social systems. Second, such trade-offs trigger opposition to decarbonization for which policy strategies including compensation for local populations are required. Both these phenomena relate to supply-side dimensions of sustainability challenges.

Third, in response to these challenges, demand-side approaches that jointly reduce final consumption of energy *and* materials through dematerialization and resource efficient provisioning systems are robust and complementary climate mitigation strategies. Demand-side transformations downsize the magnitude of supply-side challenges across multiple resource and impact dimensions.

Decarbonization strategies result in higher environmental burden across sectors

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, in ambitious solar PV and wind power scenarios at high levels of electricity consumption the power sector will require additional bulk materials (e.g., steel, cement, aluminum) and land [4,17,18]. 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[19], and CO_2 emissions associated with construction increase[4]. Expansion of renewables and electrification of other sectors will rapidly increase the demand for most materials in the electricity sector [20]. 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 the 2°C climate policy scenario[21]. Annual demand for neodymium in the 2°C scenario could more than quadruple[21]. 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[22].

Second, electrification is crucial strategy for the decarbonization of mobility[23]. However, detailed LCA-based analyses show that EVs have higher impacts than ICEVs in terms of metal and mineral consumption and human toxicity potential, even as they reduce GHG emissions over the full lifecycle[24].

Third, in buildings the requirements for lower carbon footprints in construction materials are driving a shift from mineral-based materials to bio-based materials[25]. Based on a life-cycle understanding, 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 [26]. [27]. However, this approach entails critical trade-offs with other ecosystem services and carbon sinks provided by forests as it would require the expansion of forestry to nearly 150 Mha by 2100[28] , equivalent to the current size of the entire global urban land area (or one third of the entire land area of the EU [29]. Similarly, a diet shift to conventional plant-based diets would drastically reduce GHG emissions and agricultural land footprints[30]. Large scale adoption of meat substitutes, including alternative proteins and cultivated meat, by non-vegetarians can also reduce emissions, yet it may marginally increase demand for electricity, water treatment facilities, and high grade stainless steel[31]. Critically, the carbon reduction potential of these novel foods varies, but generally hinges on the assumption that they will utilize renewable energy (e.g., for input productions of amino acids etc., and more importantly during the production of cultivated cells)[32].

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[16,33]. 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[34], for enabling low-carbon urban mobility modes such as car sharing[35], for promoting virtualisation and servitization to reduce demand for energy-intensive products and activities[36]. However, digital infrastructure and devices have distinctive material footprints, dependence on critical mineral extraction, issues with rapid turnover of short-lived consumer goods, and relatively low levels of material recovery from waste streams[37]. E-waste is the fastest growing waste stream in the world, doubling every 16 years, and estimated at 54 Mt in 2019[37], but is worth over $60bn annually[38]. Impacts of digitalisation are also unequally distributed with benefits accruing 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[39].

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[40]. 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.

These examples illustrate the decarbonization does not necessarily autonomously align with reduced material demand. Furthermore, although there is sufficient physical supply and economic potential for most resources[9], there are strong constraints relating to the social and environmental impositions of mining and other extraction, including working conditions, local air and water pollution, ecosystem destruction, and environmental injustices.

Demand-side strategies and circular material flows alleviate the material, environmental and societal burden of the energy transition

Demand-side strategies focus on how services can be provided to achieve wellbeing at lower levels of energy and material use. This can come about through socio-behavioral change, low-carbon infrastructures, resource-efficient design of material stocks, and circularity strategies aimed at recycling materials and reducing overall material demand. As they are concerned with both final consumption and the service provisioning systems enabling that consumption[41], demand-side strategies 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).

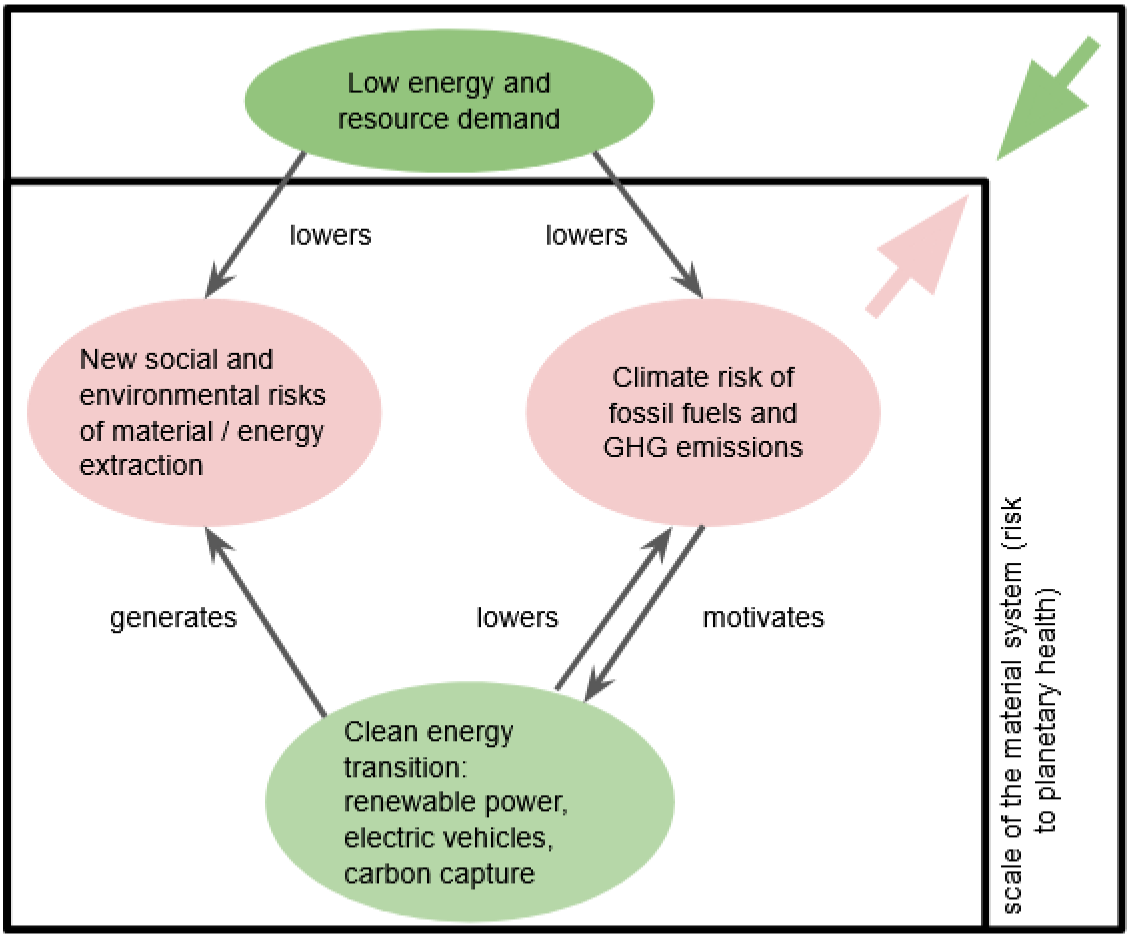

Figure 1. Shifting risks and response strategies from the clean energy transition. Partially motivated by[42].

As illustrated in Figure 1, demand-side strategies achieve the important outcome of reducing both the scale of the climate challenge and material resource requirements. First, demand-side approaches avoid energy use and associated GHG emissions, directly reducing climate-related risks while also reducing the required scale of the energy transition. Second, demand-side approaches directly reduce adverse material impacts because they contribute to the dematerialization of goods and services provision (‘narrow’). Third, demand-side strategies can further enable circular material flows by extended product lifetimes and recovering and reusing materials (‘slow’ and ‘close’).

We illustrate the relevance of demand-side solutions in the previously discussed cases of energy, mobility, buildings and food, digitalisation, and CDR (Table 1). Key demand-side strategies in the energy sector include material-efficient technologies, low-carbon industrial processes, and increased material recycling.[22] In the mobility sector, 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[43]. In the buildings 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) have most potential to reduce material burden and associated GHG emissions[44]. In particular more intense building use has as much potential as all other measures combined[44]. In the food sector, a transition away from meat (whether to processed or unprocessed plant protein) is most effective[30,45].

In the case of digitalization and ICTs, narrowing of material cycles can be promoted through resource-efficient design for dematerialisation (e.g. functional convergence with more services delivered through fewer devices [46],[47]). Slowing of material cycles can be achieved through re-designing ICT business models and consumption practices enabling repair, longevity, lifetime extension, resale, remanufacturing, component reuse and modularity. Closing material cycles can be fostered by massively upscaling end-of-life recovery and recycling capacities, as well as provenance and sorting systems, including potentially simplification of material design choices[48].

Lastly, the material impact of CDR technologies can be best avoided by minimizing its need due to stringent climate change mitigation policies, emphasizing overall demand-side strategies and advancing renewable energy technologies[3].

Table 1. Material implications of service-based climate mitigation options and demand-side responses.

Service	**Material dimension**	**Problematic material implications**	**Demand-side strategies to mitigate adverse material impacts**
Energy	Steel-reinforced concrete for hydropower and wind power plants, aluminium, steel, spice metals, etc. Copper for wind	More materials required. (a) bulk materials, producing these results in additional GHG emissions (b) scarce / geopolitically problematic materials, e.g. rare earths	Limit energy demand through demand-side strategies, more efficient design of plants to reduce material footprint, integrate PV in building designs to reduce material demand of support structures, optimize location of new installations to reduce the need for network expansion
Mobility	Batteries, electric motors, AI for autonomous vehicles, materials for infrastructure	More material, 4-6 times more copper per BEV than per ICEV, lithium extraction	Utilize vehicles as shared devices, thus downsizing the overall vehicle fleet
Buildings	Insulation materials, Shift from gas boilers to heat pumps, Shift from mineral-based to bio-based materials wood instead of cements	Shift from mining to land-use (crops and forest harvest)	Increase lifetime of existing buildings and infrastructure by following the principles of Circular Economy and sufficiency, such as repairing buildings, sharing spaces, better use of existing buildings; material efficiency and natural building materials
Nutrition	Plant-based protein & artificial meat	Marginally more energy required	Shift to unprocessed plant protein, sufficiency
Communication and information processing	Critical minerals for information processing technologies	More materials from supply chains with geopolitical risks, resource scarcities, and environmental burdens	Demand reduction, material efficiency in design and manufacturing, value capture from material recovery and recirculation
Carbon dioxide removal	DAC technologies and CCS transport and storage infrastructure	More chemicals required	Rapid GHG emission reductions to avoid the need for large-scale CCS and CDR

New challenges require interdisciplinary modelling approaches

These challenges related to new material demands and response strategies imply complex interdependencies between energy and materials, demand and supply, supply chains and service provisioning systems across sectors and geographies. Navigating these interdependencies requires systems analysis and the improvement of workhorse tools.

In particular, global IAMs need an urgent upgrade in their capabilities for analyzing material dimensions of low-carbon futures, particularly in their modeling of sectoral interdependencies. IAMs are widely used for providing a systems perspective on decarbonization pathways for climate stabilization - a key analytical role in the design of global and national GHG reduction strategies in energy and land-use sectors in line with the Paris Agreement[49,50]. However, IAMs do not consider in any detail the interplay between materials and energy in mitigation pathways, and so the emerging challenges of a clean energy transition shown in Figure 1[49]. For example, in IAMs material demand is either absent or represented in monetary rather than physical units or driven as a simple function of economic development. Demand is also segmented by sector – industry, transport, and buildings being the largest. This overlooks crucial interactions between sectors. For instance, the infrastructure and technologies used by the transport and buildings sectors directly influence industrial demand through material consumption[51,52]. Moreover, mitigation strategies like electric vehicles or building insulation can reduce energy consumption but raise material demand[53]. Conversely, recycling or reusing materials can decrease material demand but push up energy consumption.

The large and problematic footprint of material extraction at a planetary scale induced by currently dominant supply-side strategies for decarbonization raises important research questions requiring new analytical tools that represent both 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 so open up questions around the material equivalent of climate justice and, if so, how it can it be addressed.

There are also fundamental questions as to the extent current net-zero strategies are compatible with staying within planetary boundaries. Responses emphasize the need to design supply and demand-side approaches to both energy and material dimensions of climate transitions. What strategies can mitigate both GHG emissions and material use? 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. This involves, on the one hand, connecting industrial ecology (IE) tools (materials) with integrated assessment modelling (IAM) (energy, land), and combining engineering detail with spatially-explicit artificial intelligence modelling.

A full understanding of the feedbacks between energy, land and material systems is required for robust mitigation scenarios and for the evaluation of demand-led strategies such as material efficiency and sharing economies that potentially 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. Here, IAMs can build on the research methods and data collection efforts in the industrial ecology field. 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. Accounting for material demand in IAMs would require: 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[54,55]); 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[56] to link the 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. It is important to include in this context the economic aspects related to material cycles which are typically not covered by industrial ecology methods, while 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.

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[57]. In particular, studies with explicit spatial resolution have delivered promising results in predicting building attributes, and material and energy demand with high generalization capacity[58,59]. Using satellite imagery and volunteered geographic information from OpenStreetMap, studies have created high-resolution maps of material stocks in buildings and infrastructures[60], and identified rooftop areas for solar PV thus avoiding land use conflicts[61]. The flexibility of these approaches allows analyses to be extended to areas with sparse official data where conventional material flow models cannot be applied[62], particularly in the Global South. Incorporating temporal dynamics can further reveal long-term trends, such as urban expansion[63], 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[64,65]. 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.

On the end-use side, human behavior and cultural context interact with material and energy demand[66]. Resource efficiency savings, including those advanced by the circular economy, are often compromised by rebound effects[67]. To address this conundrum, 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[66]. Policy instruments, such as carbon pricing, and equivalent pricing of harmful material extraction, are central to keep overall demand in check[68].

Out of the frying pan, but avoiding the fire

The clean energy transition to address climate change creates new risks of material-related environmental and social burdens at a planetary scale. To datem, analytical and policy emphasis has rightly focused on the energy and land-use dimensions to the climate challenge. As the carbon intensity of energy systems continues to fall, the extraction, use and disposal impacts of material resources are becoming ever more important stressors of planetary boundaries. 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.

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