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Critical materials:

demand-side resource efficiency measures for sustainability and resilience

IChemE

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Minerals & Mining

Contents

1. Executive summary

This report provides an overview of the underutilised policy options for achieving reductions in our demands for critical materials and therefore our dependency on imports of scarce materials. This includes both existing uses of critical materials, and future ones associated with low-carbon technologies.

The UK is economically and physically dependent on many materials that are mined elsewhere, and specific technological components that are not made here. Recent supply chain crises have driven increasing concern about the growing need for 'critical' materials, as the projected demands for these are likely to outstrip available supplies. This poses a risk to the resilience of the UK; if material demand significantly exceeds supply, it would interfere with not only economic prosperity but also the capacity of the UK to achieve the infrastructure transformation required to reach net zero. Expansion of demand for critical materials also comes with environmental and social harm that would work against global goals of mitigating climate change and of a just transition to net zero. These impacts are often not visible to the public or decision-makers.

This report presents a range of proactive policy and engineering innovations that can reduce the UK's dependency on critical materials and therefore its risk exposure. Despite increasing attention on critical materials, these 'demand-side' measures have been underutilised, and discussion has been largely limited to what can be done to ensure the UK has access to supplies ('supply-side' measures). Demand-side measures include:

Infrastructure and technology planning: considering material requirements during the upstream planning of future energy, transport and digital systems.

Design and design skills: design changes that minimise or eliminate the need for critical materials and the requisite design skills and cultures that enable this.

Circular economy: ensuring that where such materials are used, they can be recovered and reused or recycled.

Barriers to achieving these policy outcomes include a lack of suitable policy and regulatory frameworks, unclear responsibilities in government, and a lack of basic data. In addition, the UK has limited manufacturing capabilities or influence over the design of products made for global markets such as automobiles and wind turbines. Addressing this requires new skills and approaches to planning, innovation in engineering and design, and new economic structures that value resource efficiency and the resilience of our vital infrastructures.

1.1 Critical materials and the UK's transition to net zero

Materials are designated as critical when their anticipated uses go beyond the expected available supplies. Often supplies are limited because:

- they are less valuable by-products of other mining activities
- their trade may be particularly subject to geopolitics due to geographical concentration
- they are difficult and environmentally damaging to extract.

Developing new extraction infrastructure is slow and often risks worsening the environmental and social harms associated with their extraction. There is currently very little or no recycling capacity for most critical materials.

The Global Resources Outlook 2024, prepared by the United Nations Environment Programme, identified the still-increasing global resource use as the "main driver" of climate change, biodiversity loss and pollution. The report shows that current policy approaches focus almost exclusively on increasing and securing the supply of these materials, and says there must be a much stronger focus on demand-side measures that reduce consumption while improving the provision of essential human needs.

The need to build large amounts of renewable energy technologies is among the major drivers of the forecast increase in demand, as these technologies currently contain critical materials. These technologies are not the only driver of demand and it is vital that we continue to prioritise decarbonisation at national and global levels. However, there are many choices to be made about *how* to reach net zero and the consideration of materials therein. Currently, we are making decisions about how to transform UK infrastructure without considering the material dependencies and demands being created. Unknowingly locking in high reliance on critical materials risks supply shortages and increases the environmental cost of achieving the crucial goal of net zero.

Decarbonisation is essential, but we must also find ways of accomplishing it that do not trade carbon emissions in the UK for chemical pollution, biodiversity loss, drought, and land-use change elsewhere in the world. These effects reduce our capacity to adapt and accelerate the harms caused by greenhouse gases.

1.2 Infrastructure and technology planning

The policy focus on reducing territorial carbon emissions without considering broader material sustainability may 'lock in' infrastructure pathways that mean the UK will be dealing with these risks for decades to come. Infrastructure planning is the most important tool at the UK's disposal to control the volume of critical materials the UK will demand. Decisions made now are crucial due to the 'infrastructure lock-in' effect which would mean that resilience issues and risk of resource scarcity may persist for decades.

In the **energy system**, areas of concern are chiefly related to:

- larger wind turbines, which rely on neodymium magnets
- solar panels, which can use a variety of critical materials
- batteries for energy storage, which are primarily lithium-based and often include materials such as cobalt, manganese and nickel
- nuclear power, which requires chromium as well as other critical materials
- and hydrogen electrolysers, which can use a variety of rare metals.

While copper is not considered a critical material in the UK, it is in the US, in part due to the huge demand from electricity grid upgrades. It may present similar risks despite being more abundant than materials considered critical within the UK.

In many areas there are alternative technologies or strategies for achieving the same outcome using fewer or no critical materials, or using different ones – albeit these currently tend to come with performance trade-offs. There are also higher-level choices around energy system architecture and the technology mix which impact the energy system's critical material demands, such as the degree of decentralisation, the approach to siting and

> Increasingly valuable and strategically important volumes of critical materials are being built into the infrastructure and technologies around us. Too often this is done without planning for their recovery or due attention to material sustainability

transmission, and most importantly the priority placed on energy demand reduction. Reducing overall energy demand, and especially smoothing out peak demand, reduces infrastructure requirements and therefore the requirements for critical materials. This is a stated policy goal of UK government but requires much more focus and prioritisation to achieve.

In the **transport system**, the primary critical material demands are from batteries for electric vehicles (EVs). Infrastructure planning can ensure that more efficient modes of travel are more widely available, enabling greater use of mass transit, active travel, and smaller batteries enabled by reliable charging infrastructure, as well as schemes for vehicle sharing.

The **digital system**, including both consumer goods and large operations such as data centres, is a particular challenge due to the difficulty in recovering the diverse critical materials, which are spread thinly through digital technology, and the often short lifespans of the components. Data centres require greater planning to align the emergence of this new infrastructure with goals for energy demand reduction, co-location, and also the development and implementation of best practices for resource efficiency, especially regarding reuse and recycling.

1.3 Design and design skills

Increasingly valuable and strategically important volumes of critical materials are being built into the infrastructure and technologies around us. Too often this is done without planning for their recovery or due attention to material sustainability. Critical material resource efficiency is undervalued in design incentives, and even if it is incentivised during the design process, progress is limited by a lack of access to reliable data on the sustainability, ethics, and supply chain risks of different materials.

Innovative design approaches can and should be deployed to:

- reduce critical material demands in the short-term
- ensure cheaper and easier access and recovery of the stocks of material accumulated in technology and infrastructure – creating an easily recoverable source of materials in the long-term.

However, designing products, buildings and infrastructure in more sustainable ways requires a paradigm shift in the way engineers and designers think and work. The core requirements are the incorporation of resource efficiency and global perspectives of sustainability and ethics, as well as designing in a way that enables reuse and recycling.

This section of the report gives an overview of design approaches for critical material resource efficiency, including material substitution, material reduction, extended product life, reuse, material recovery, and remanufacturing. It also considers the role of engineering research into novel materials which can displace critical materials without compromising on performance.

The UK has limited influence over the design of imported goods and components, though much of our import market is influenced by European Union regulations which are increasingly targeting material sustainability. However, the UK has significant influence domestically and globally through the production of standards for technologies and processes, an important lever for embedding new design practices. This includes the option of early sponsoring of standards which are important for emerging technologies with potentially high critical material costs. The UK also has existing ecodesign regulations focused on energy efficiency that could be expanded, alongside improvements to monitoring and enforcement.

Design skills are currently a key barrier but also can be enabler. UK design education and research are globally influential. However, less than half of UK designers feel that they have the skills to meet the demand for environmental design, or that their education prepared them for it.[153] Environmental design skills need to be more widespread across the design and engineering professions.

This report presents case studies on wind turbines and EVs that identify barriers to reuse and recycling originating from design, as well as important opportunities to reduce the critical material requirements of batteries through changing vehicle design and battery chemistry. Sodium-ion batteries can be produced without the use of critical materials and can utilise existing battery manufacture and recycling equipment.

1.4 Circular economy

Most critical materials in the global economy are not recycled at the end of their life, nor expected to be. This linear economy means that there is greater

CASE STUDY | Offshore wind turbines

This case study presents an example of the underutilised potential for circular economy in the UK.

Large offshore wind turbines can contain a significant amount of critical materials, for example one current design for a 6MW turbine uses 5,800kg of neodymium magnets. Neodymium has a high value and the magnets can be reused in applications such as electric vehicle motors. However, decisionmakers lack information on the exact volume of neodymium magnets within UK wind farms and when it will be available.

There is too little capacity for decommissioning wind turbines in terms of ports, equipped yards, and specialist engineers.

Work is ongoing to understand the costs and yields of neodymium recovery, informing what recycling capacities are needed. These have not been designed for end-of-life, presenting engineering challenges to recovering the critical material. However, the UK will have immediate access to a large future supply of neodymium, which there are currently few plans to take advantage of. To maximise the future opportunity from material recovery in the future, the UK needs to ensure new turbines are designed for end-of-life and materials recovery.

CASE STUDY | Electric vehicles

EVs are a particularly significant source of forecast demand for critical materials. Novel analysis for this report finds that the EVs projected to be sold in the UK from 2018–2040 would require 268,000 tonnes of lithium.

This case study quantifies the potential for critical material demand reduction in UK EVs through two design choices:

1. Battery size reduction: A 30% reduction in vehicle battery sizes in the largest EVs sold in the UK by 2040 could save 46,000 tonnes of lithium (which to mine would require excavating 75,000,000 tonnes of earth, enough to fill Wembley Stadium 19 times). Smaller battery size does impact vehicle performance, however, this could be partly offset by lightweighting designs and innovation in battery technology, and enabled through provision of reliable charging infrastructure.

2. Material substitution: Sodium-ion batteries are a prime example of an emerging technology for material substitution. These currently have lower performance compared to lithium-ion, but cutting-edge models completely avoid including critical materials. A shift to prioritising sustainable designs requires support, incentives, and engineering research and development. The UK has an opportunity to build on its strengths in these areas to make a domestic sector for sodium-ion battery production and recycling.

demand for extraction, increasing supply risks and adding to environmental and social harm. A circular economy by contrast uses as few materials as possible and maintains them in the economy at their highest possible value. Stocks of critical materials in existing and future infrastructure and technologies should represent future sources of material to meet future demands. Achieving this requires both changes in design practices to enable life extension and recovery, and the emergence of far more comprehensive and mature recycling sectors for critical materials.

Recycling of critical materials is of vital importance to achieving a plateau in material demand. As they become more common in goods, assets and infrastructures that are coming to the end of their lifespan, there will be increasing opportunity to source critical materials from the infrastructure assets and technologies in which they have been used. It is crucial that these recycling sectors begin to grow now in order to meet future needs.

1.5 Conclusion and recommendations

Strategic policymaking for sustainable materials consumption across infrastructure planning and engineering design has been lacking in the UK for many years. Replacing fossil-fuel-powered infrastructure and technologies is a crucial and deliberate shift requiring sustained pace and scale of deployment normally reserved for acute crises such as the COVID-19 pandemic. It will require a new policy approach to materials in order to assure the decarbonisation process as well as the sustainability of the new infrastructure.

Developing a materials strategy within UK government will be complex and far-reaching, with implications for many policy areas. This report sets out a mixture of recommendations:

Build capacity for UK government, businesses and civil society to better understand material flows in the UK and enable strategic decision-making for resource efficiency

Build governance structures that ensure the UK government has an integrated materials strategy, with critical materials considered as part of the net zero strategy. This should sit across infrastructure planning, design regulation, market regulation, industrial strategy, trade policy, and recycling and waste policy, and align these policy areas towards strategic goals such as reducing dependency on critical materials and reducing embodied carbon. ▸ **Recommendation 1**

Target halving the UK's overall materials footprint to drive knowledge, skills, practices and implementation experience of resource efficiency. ▸ **Recommendation 3**

Establish monitoring and forecasting of supply chains, material flows, material requirements of particular technologies, and forecast material use across different scenarios for net zero infrastructure systems. This should be centralised in a National Materials Data Hub. ▸ **Recommendation 4**

Reduce the scale of infrastructure deployment needs by targeting and achieving whole-system energy demand reduction, in line with the 15% reduction target introduced as part of the net zero strategy. ▸ **Recommendation 12**

Build opportunities for engineering education and training that deliver a transformation of UK engineering skills, emphasising resource efficiency and build a global understanding of sustainability so that UK engineers, designers and others are prepared to build, maintain and recycle future technologies.
▸ **Recommendation 21**

Outline approaches for achieving critical material resource efficiency in design, circularity, and especially planning for future infrastructure systems

Incorporate assessment of critical material demands and resulting risks into energy policy, both in whole-system planning and individual decisionmaking. This should aim to deliver a diverse decarbonised energy system which meets public needs and is also resource efficient and resilient to critical material shortages. ▸ **Recommendations 7 and 10**

Include critical-material demand reduction as a goal of transport planning, in particular aimed at the role of batteries, especially through providing enabling infrastructure for more efficient and sustainable mobility solutions such as mass transit, active travel, and the use of smaller electric vehicles. ▸ **Recommendations 7 and 8**

As digital infrastructure such as data centres are being planned, review policy options and required standards for minimising critical material demands arising from e-waste and energy requirements. ▸ **Recommendation 14**

Expand existing ecodesign regulations, as well as monitoring and enforcement capacity, to include material efficiency; encourage design for durability, upgradeability, and disassembly; codify a right to repair; and expand ecolabelling regulations to reflect this.
▸ **Recommendation 18**

Invest in UK and international capacity for recycling critical material intensive products, in particular wind turbines and batteries, reducing dependence on existing supply chains and providing domestic sources of critical materials.
▸ **Recommendations 22–25**

Give examples of specific policies currently available to government that would improve UK critical-material resilience and global sustainability

Support accelerated development of key alternative technologies for reducing critical material use such as sodium-ion batteries, potentially including targeted research funding, supporting facilities to test manufacturing processes, sponsoring standards production, and building connections to industry to ensure take-up. ▸ **Recommendation 16**

The UK government, using existing expertise on net zero innovation, should identify strategic areas where the production of standards and innovation guardrails would accelerate innovation and adoption of goods, products and infrastructure assets that use less critical materials and sponsor the development of these standards. ▸ **Recommendation 17**

Commit to implementing the ban on single-use vapes in England proposed in January 2024 but not implemented prior to the July 2024 general election. ▸ **Recommendation 15**

Business as usual

END OF LIFE CHOICES

Insufficient investment in disassembly, re-use and recycling plants.

Insufficient engineering skills and capacity to recycle critical materials domestically.

Paying to export or landfill valuable critical-material rich waste.

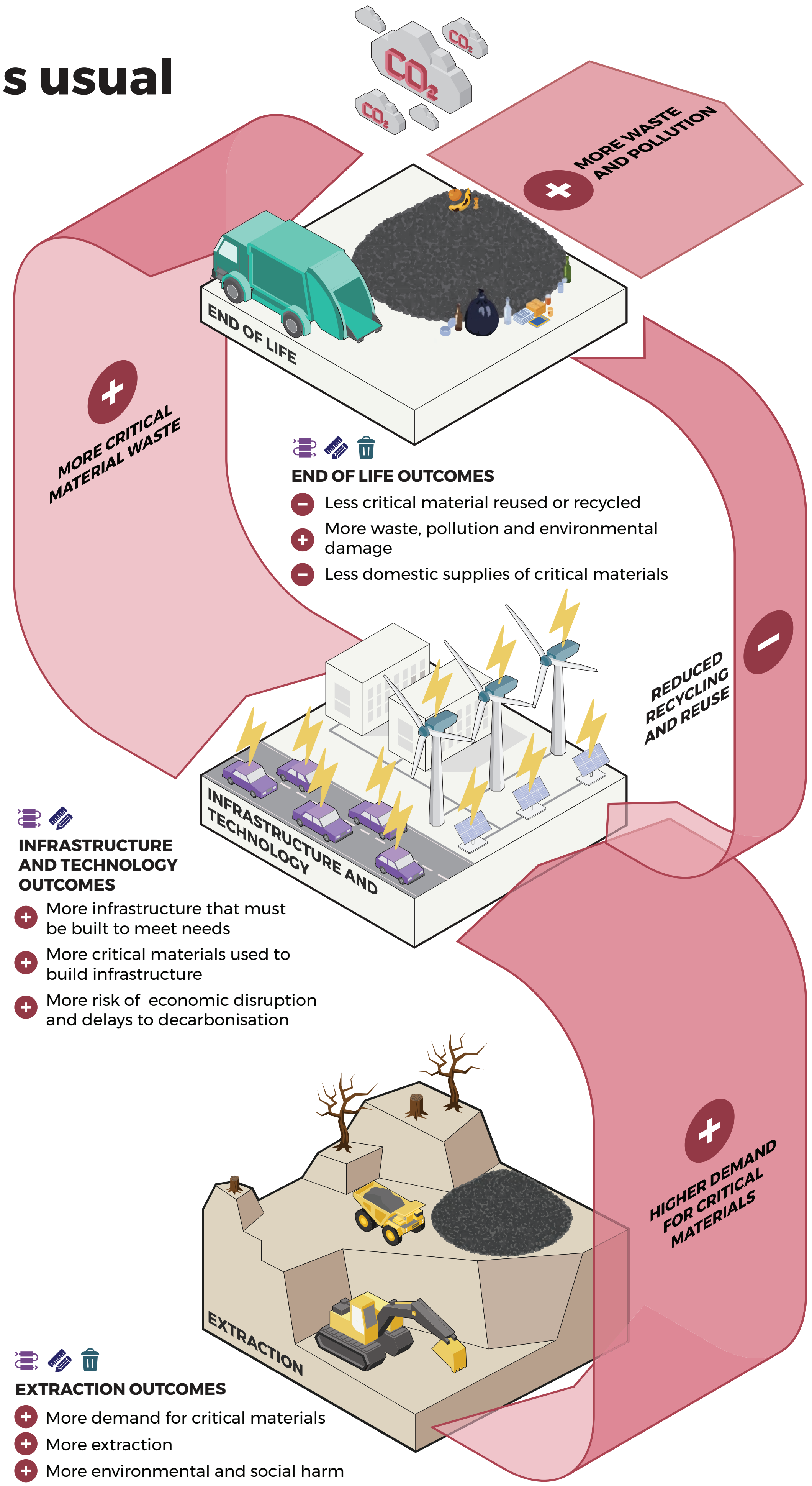
DESIGN AND DESIGN SKILLS CHOICES

Goods and infrastructure are designed only for least cost and highest performance.

INFRASTRUCTURE AND TECHNOLOGY PLANNING CHOICES

System planning doesn't consider reduction of critical material demand.

High critical materials requirements locked in.



END OF LIFE OUTCOMES
- − Less critical material reused or recycled
- + More waste, pollution and environmental damage
- − Less domestic supplies of critical materials

INFRASTRUCTURE AND TECHNOLOGY OUTCOMES
- + More infrastructure that must be built to meet needs
- + More critical materials used to build infrastructure
- + More risk of economic disruption and delays to decarbonisation

EXTRACTION OUTCOMES
- + More demand for critical materials
- + More extraction
- + More environmental and social harm

LEGEND: End of life choices   Design and design skills choices   Infrastructure and technology planning choices

A resource efficient economy

END OF LIFE CHOICES

UK investment and international collaboration delivers a network of recycling infrastructure enabled by circular design.

Engineering skills and capacity match demand required for increased recycling of materials.

Critical material rich waste is reused or recycled.

DESIGN AND DESIGN SKILLS CHOICES

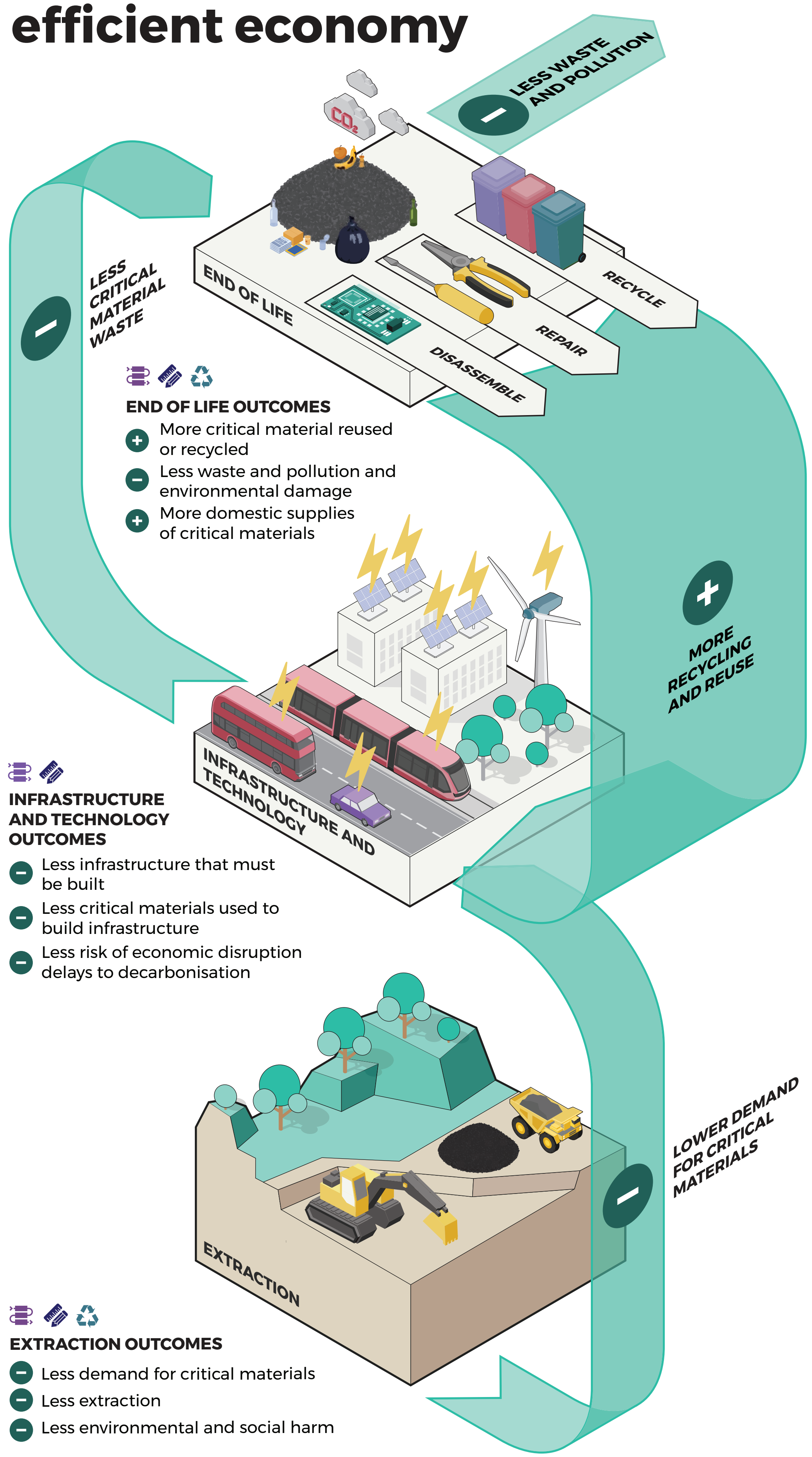
Goods and infrastructure are designed for:
- repairability and longer life
- substitution of critical materials
- resource efficient design
- design for disassembly and re-use or recycling.

INFRASTRUCTURE AND TECHNOLOGY PLANNING CHOICES

Decisions made with materials in mind.

Resource-efficient system design.

Meetings needs in creative ways.



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- − Less risk of economic disruption delays to decarbonisation

EXTRACTION OUTCOMES
- − Less demand for critical materials
- − Less extraction
- − Less environmental and social harm

2. Terminology

2.1 Critical materials

This report will refer throughout to 'critical materials'. Except where otherwise denoted, this refers to the UK list of critical materials set out in the 2022 'Resilience for the Future: The UK's Critical Minerals Strategy'.[1]

While it is still common to refer to such substances as critical raw minerals, this can be misleading since many of the materials that are considered critical by the UK government and other actors are not 'raw', with resource scarcity risks often being related to processed and/or recycled materials such as graphite or silicon compounds, that do not meet common understandings of 'mineral'. Furthermore, most critical materials in the UK are neither extracted in the UK nor imported as raw products, but as whole components or goods. Other reports will also refer to rare earth elements (REEs), a group of elements that are commonly found on lists of critical materials.

2.2 Circular economy

A circular economy is defined, for our purposes, as one in which materials in the economy are maintained at the highest possible value and as few as possible are used to achieve the ends we want.

2.3 Net zero

Net zero refers to a state in which, either globally or for a given territory, emissions of greenhouse gases are equal to or less than the greenhouse gases removed from the atmosphere – either by natural or engineered carbon removal. Functionally, this requires almost complete elimination of greenhouse gas emissions. In the UK, this is a formal legal target, however the way in which this is calculated means that emissions associated with materials and manufacturing may be 'offshored' so they do not appear to be emissions the UK is responsible for, at the cost of carbon emissions elsewhere. Given that the UK is heavily dependent on imported goods and materials, this leaves a significant climate policy gap leading to unsustainable consumption and waste of materials.

3. Introduction

3.1 Understanding critical materials: a systems approach

Critical materials are those that are economically or strategically important but are susceptible to supply chain disruption. These materials have been of increasing concern to governments and policymakers, highlighted by the global supply shortage of semiconductor materials in 2020, as well as by global analyses of future material needs that predict changes to material demands. This section provides an overview of what causes a material to be labelled 'critical', and the factors that determine the likelihood and impact of supply chain crises.

Because material criticality is linked to the risk of supply shortage in a complex global economy, there are a large number of potential sources of disruption, which may be technical, economic, socio-political, environmental, or related to demand. Mapping these factors for any one material is complex, but a 2014 whole-systems analysis funded by the UK government provided a useful overview of how and when the factors are relevant, although data limitations mean not all of these are included in the assessment of criticality used to produce the UK list. Figure 1 presents a simplified chart of a material flow, which highlights the relevant factors that contribute to both the **capacity risk** of a shortage, and also the **capacity readiness** of the supply chain to react to this and match the demand.

$$\text{Criticality} = \frac{\text{Capacity risk}}{\text{Capacity readiness}}$$

When demand increases rapidly and outstrips supply, this increases capacity risk. Demand for imported material is shaped by policy (especially infrastructure choices), technology and design choices and trends among consuming nations, the ability to substitute the materials, and the recyclability and recoverability of the material stocks at their end-of-life within existing products and infrastructure. Many critical materials are originally obtained as **by-products of other mining** operations, so do not have independent supply chains or extraction infrastructure whose production can be increased or decreased in response to demand for the critical material. Capacity risks also arise from concentration of production within one nation or geographical area, as seen during the silicon chip shortage in the early 2020s (see Section 3.2.3) and resulting from the war in Ukraine. For any given importing nation, the capacity risk is impacted by the choices made by both importing and exporting nations globally.

Actors in the supply chain may respond to growth in demand by increasing supply, such as by increasing mining or extraction, or improving the efficiency of material processing. However, this is limited by factors such as the nature of the resources (e.g. diversity and accessibility of source), cost of extraction, political and economic disputes, and the need to avoid social and ecological impacts. The ability to increase the supply in line with demand is measured as capacity readiness.

When there is high capacity risk and low capacity readiness, there is a high chance of a prolonged

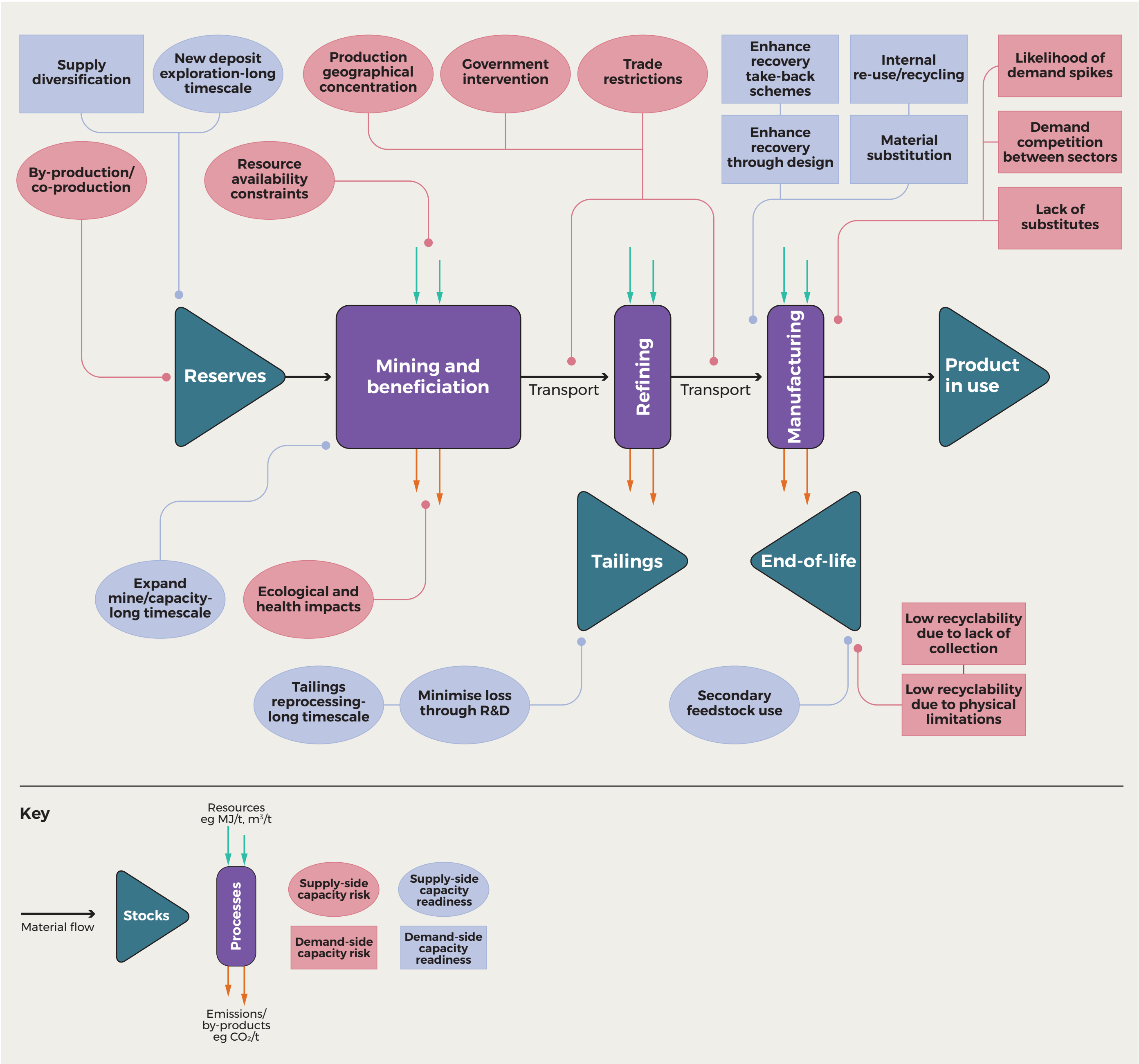


Figure 1 | Model material flow diagram annotated with factors impacting criticality. The supply chain layout shown here provides a way of measuring material flows across the production system and time. This knowledge can be employed as a starting point to track material stocks, quantify capacity risks, and evaluate the readiness of the system. The layout identifies key areas where intervention could lead to increased capacity readiness and faster supply-demand re-balancing within the system. This report focuses on the under-utilised demand-side levers represented here with square boxes. Adapted from Leal-Ayala et al, 2014. HOSANA Whole Systems Analysis: Devising swift responses to critical mineral supply capacity risks and disruptions.

scarcity of the specific resource, which may lead to price increases, national strategic concerns, disruption to manufacturing and value chains, and greater geopolitical tensions. Materials that fit this pattern are called critical materials. It is important to note that the criticality of a material does not include any information on the sustainability of its supply chain in environmental, social or economic terms. However, it is appropriate to assume that extraction of critical materials are generally associated with greater environmental harms than non-critical materials per kg, but are currently extracted in smaller quantities. In Section 3.4 we discuss the environmental harms in more detail.

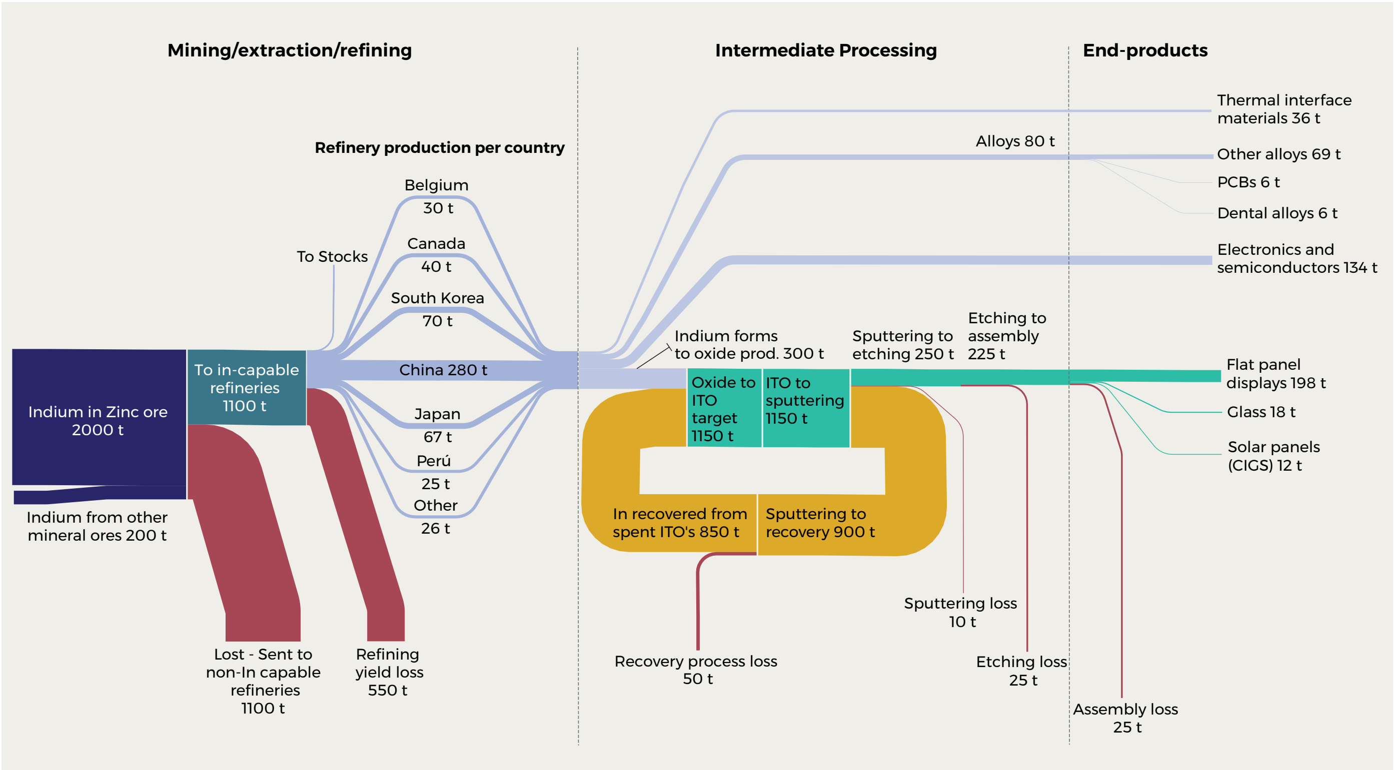


Figure 2 | Global indium mass flow in 2009.
Adapted from Leal-Ayala et al, 2014. HOSANA Whole Systems Analysis: Devising swift responses to critical mineral supply capacity risks and disruptions.

Economics plays a large role in material criticality and also introduces significant uncertainty. Historically, concerns regarding the availability of resources have been a significant driver of technological change and material substitution (see Section 6.2.1), which has impacted the economics of different materials. However, the long lead-times, generally years, for extraction infrastructure mean that supply is slow to respond to increasing demand. Assuring a high pace of decarbonisation, and deployment of infrastructure to displace fossil-fuel-based systems in line with the UK's net zero target, may depend on acting pre-emptively by changing consumption habits.

3.1.1 Case study: indium

Indium provides an illustrative example of some factors discussed above, which are common to critical materials. It is not mined as a primary material, but is mostly extracted from zinc ore processing residues. Like many critical materials this means its production capacity is dependent on the economics of another metal, and it has no dedicated infrastructure. As of 2009, about half of the indium present in extracted ore is wasted through simply failing to collect it during zinc ore processing, and then another half is lost in the indium refining process. This is marked in Figure 1 as the supply-side capacity risk "by-production/co-production". More than half of the total refinement capacity is concentrated in China (see Figure 1, "geographical concentration"), but indium refining facilities are also present in Europe, Canada, South East Asia, South America and elsewhere.

Around half of the indium produced globally is used in the production of metal alloys that are used in electronics and medical technology, among other things. When processed into indium tin oxide (ITO) it is also a component in certain kinds of solar panels.[3] However the largest demand for ITO is to produce screen displays because it conducts electricity, bonds strongly to glass and is transparent.[4] These are therefore the primary supply chains at risk of disruption from indium shortages. Notably, while there is strong recycling of indium within the confines of plants that produce ITO, there is no meaningful recycling of indium from end-products making it an entirely linear economy.

> Overall the available data on the stocks and flows of critical materials in the UK is very limited, making it impossible to identify what specific risks exist or how to target mitigations. As a result, it is difficult to evaluate performance, identify areas for action, build more sustainable and resilient approaches into plans, or set targets for resource efficiency, recycling, and demand management

3.2 Critical materials in the UK

3.2.1 UK policy approach to critical materials

The UK published its first list of critical materials in 2022 as part of the UK Critical Minerals Strategy,[5] and updated this in 2023.[6] These are listed in Table 1 opposite for reference. The methodologies used to derive criticality do not account for potential demand-side approaches such as material substitutability due to lack of reliable indicators.[7]

It is important to note that while this report is focused on critical materials as they are classified by UK government, similar risks – of shortages and of unsustainable extraction – are posed from both rare critical metals used in relatively small quantities, like platinum and tantalum, and materials demanded in great quantity such as copper (considered critical by the US), steel[17] and sand[18], which are not formally listed as critical materials by the UK government.

The 2024 Critical Imports and Supply Chains Strategy builds on the supply-side policy approaches established, and in particular recognised that imported components that are not produced in the UK can produce similar risks as raw materials. Importantly, the strategy states that "Government will expand and entrench our existing work to plan for future shocks; to respond in a rapid and coordinated fashion", including through direct government intervention on a case-by-case basis. The strategy provided a £200m Supply Chain Contingency fund within the Ministry of Defence to "enable supply chain activity that would not be possible under existing finance and commercial process arrangements."

The UK government has also made direct interventions during recent supply shortages such as the 2021 shortage of carbon dioxide (CO_2), which has critical functions in healthcare, water treatment, food processing and nuclear power generation.

However, the management of materials and resource efficiency is currently spread across many departments in government, with no single, overarching strategy or point of ownership. For example, recycling and waste policy, industrial strategy, trade, and national risk assessment are each owned by separate departments. This lack of policy focus has produced a situation in which the in-country 'stocks' of critical materials are not known, there are currently no procedures in place for collecting data in planning processes for infrastructure or large construction projects, and there is no department to report them to.

Overall the available data on the stocks and flows of critical materials in the UK is very limited, making it impossible to identify what specific risks exist or how to target mitigations. As a result, it is difficult to evaluate performance, identify areas for action, build more sustainable and resilient approaches into plans, or set targets for resource efficiency, recycling, and demand management. Collating and publishing this data is a precursor to most of the significant policy actions that could be taken, and could be achieved through techniques such as material passporting, which allows for the tracking of materials from extraction to end-of-life. This would enable more informed decisions regarding sustainability and supply chain resilience to be made both within policy and by engineers, designers and manufacturers.

Recommendation 1 calls for a cross-government materials strategy that would put in place systems to connect these policy areas so that they have the potential to be aligned towards goals such as strategic demand management, crisis response

UK critical materials	Common applications[8,9]
Antimony	Semiconductor devices, such as infrared detectors; lead-acid batteries (lead is alloyed with antimony); flame retardant materials, paint, and glass.
Bismuth	Fire detectors and extinguishers; electric fuses and solders; cosmetics.
Cobalt	EVs and battery storage, superalloys, solid oxide electrolysers, portable electronics.[10]
Gallium	Communication devices; radar systems; semiconductors; thin-film solar cells; sensors; medical imaging devices.
Graphite	EVs and battery storage (used in the anode of lithium-ion batteries); production of solar panels (used in moulds for casting silicon)[11]; pencils.[12]
Indium	Electronic displays; solar panels; semiconductors and microchips; PEM electrolysers.[13]
Lithium	EVs and battery storage; nuclear moderator material; medical implant batteries.
Magnesium	Lightweighting of cars and aeroplanes (magnesium is alloyed with aluminium); flares, fireworks and sparklers; medicines (such as magnesium hydroxide or milk of magnesia).
Niobium	Superconducting magnets; MRI scanners; optical glass; aerospace; oil and gas rigs; wind turbines.[14]
Palladium	Catalytic converters for internal combustion engines (ICEs) cars; ceramic capacitors in electronics such as mobile phones and laptops; catalysts for hydrogen in green hydrogen production.
Platinum	Catalytic converters; hydrogen fuel cells; industrial catalysts; PEM electrolysers; chemotherapy.
Rare earth elements	Permanent magnets (used in wind turbines, EVs); electric motors; nuclear reactor control rods; medical lasers and imaging.
Silicon	Solar cells; semiconductors; nuclear fuel cladding; battery anode doping.
Tantalum	Superalloys for turbine blades; capacitors for electronic circuits; pacemakers.
Tellurium	Solar cells; semiconductors; oil refinement; tints for glass and ceramics; vulcanising rubber.
Tin	Anti-corrosive coating and alloys; glass production; soldering joints of electrical wires.[15]
Tungsten	Strengthening alloys; high-temperature applications (such as arc-welding electrodes); dental drills; metal working; mining; petroleum industry.
Vanadium	Steel alloys (used for armour plate, axles, tools and piston rods); nuclear reactors; pigment in ceramics and glass; catalysts in the production of superconducting magnets.

UK watchlist	Common applications
Iridium	PEM electrolysers[16]; pen tips; compass bearings; spark plugs.
Manganese	Steel alloys (used in railway tracks, rifle barrels and prison bars); drinks cans; fertilisers; ceramics.
Nickel	Superalloys; speciality steels; battery cathodes in EVs; nuclear fuel cladding.
Phosphates	Agricultural fertilisers; detergents; glasses and fine china; steel production.
Ruthenium	Electronic chip resistors; electrical contacts; solar cells; jewellery.

■ **Table 1**

and contingency planning, circular economy, economic development of key sectors that rely on critical materials, and managing available material stocks. Underpinning this, as described in recommendation 3, should be an economy-wide target to halve the UK's material footprint, and consider the potential for targets that more specifically target critical materials or critical-material-intensive sectors and assets.

While this report focuses on critical materials as the most significant sources of risk, and the designation of 'critical' remains useful for identifying materials of greater risk, such a strategy must include all material flows, including bulk materials. Previous work by the Net Zero Infrastructure Industry Coalition identified a similar lack of data, making accurate estimation of the embodied carbon costs of the UK's pipeline of infrastructure extremely difficult.[19] The exact nature of the governance systems required is beyond the scope of this report, but while there are some available levers within individual ministries, many of the policy levers for material sustainability and security described in this report cannot be used without this capability for strategic oversight.

3.2.2 Critical materials and UK resilience

The UK's 2023 Critical Minerals Strategy notes accurately that "modern society is quite literally built on rocks", and that technological change is making the world increasingly reliant on a new set of materials. It notes that the UK has some domestic resources of critical materials, but that the UK would need to work internationally and co-operatively to access these resources.

Of the 18 materials designated critical by the UK government, none are being actively extracted in the UK.[20] Tungsten was being extracted from the combined tin and tungsten Hemerdon mine in Devon between 2015–18. Prior to 2015, it had not been extracted since the Second World War, during which the lack of access to overseas supplies led the UK government to take over the Hemerdon mine for the duration of the conflict, after which extraction was discontinued. A new operation is in the late stages of regulatory approval. There are also three companies exploring lithium extraction in the UK from granite or water, none of which are currently operating at commercial scale.[21]

As a result of our lack of domestic production, the UK is dependent entirely on imports of critical materials – both as materials for manufacturing and within components that are not manufactured domestically. This limits the resilience that can be provided by supply side approaches, with risk factors often being linked to geological constraints, long-term development and operation of extraction infrastructure by private interests, or trade restrictions and other geopolitically driven disruption. Furthermore, as demonstrated by the recent global silicon supply chain crisis, the UK is dependent on components that are manufactured elsewhere, with these manufacturing processes having their own associated risks.

Many nations are in a similar position of having few domestic critical material resources and little strategic manufacturing capacity. This is driving an increased international policy interest in demand-side approaches to both reducing the overall risk exposure through resource efficiency and through encouraging stocks of critical materials to remain within country via economic incentives or export restrictions.

One particular approach to retaining strategic stocks of critical materials is through encouraging domestic reuse and recycling of critical materials. For example, the US Inflation Reduction Act provides investment tax credits of 30% or more for eligible projects that recycle critical materials or renewables technology. However fully domestic supply chains are not practical for a nation of the UK's size, and recycling operations can and should be distributed, with nations identifying their key material requirements and opportunities. For example, as discussed in Section 5.2, the UK is a world leader in offshore wind and yet has invested little to nothing in developing an engineering ecosystem able to disassemble wind turbines and recover the highly valuable materials within them. Restrictions in UK capacity, and competition for much of the existing infrastructure from both the installation of new offshore wind and the decommissioning of oil and gas installations mean that it is likely that UK offshore wind assets will be disassembled and their materials recovered by other nations.

Policy recommendations

Recommendation	Intended outcome	Requirements or enablers
1. Government should have a resource strategy for critical materials. This should be integrated into existing net zero strategy with the aim of managing the necessary trade-offs and reducing unsustainable material consumption, and especially critical materials, in the UK. This should incorporate infrastructure planning, design and market regulation, industrial strategy, trade policy and recycling and waste. **For**: Cabinet Office and all contributing departments including DESNZ, DEFRA, DfT, DBT, CCC. (see relevant recommendations 10, 11, 12, 13)	Ultimately reduced per-capita material consumption, especially of critical materials. Defined policy ownership and responsibility to close the 'gaps' between policies, ensure that tensions between different incentives (e.g. emissions reduction vs domestic manufacture) are resolved. Integration into existing net zero strategy enables risk assessment and mitigation for technology deployment, as well as highlighting potential synergies and opportunities to reduce the scale of the challenge arising from the transition to net zero, through, for example, energy demand reduction as a lever that also reduces material requirements.	A National Materials Data Hub to be in place (*see recommendation* 4). Decision-making framework to manage trade-offs. (E.g. stronger framework requiring use of life cycle analysis in governance system where they are less exploited.) Single point of ownership of this built into policymaking structures, providing the political ability to negotiate across and align departmental incentives and policy drivers. Scrutiny of this strategy should be included within the remit of the Climate Change Committee.
2. Government should explicitly consider critical materials trade-offs and how they will be managed in future net zero strategies **For**: DESNZ, NESO, CCC.	Integration of critical material trade-offs into net zero strategy ensures risk assessment and mitigation is occurring for technology deployment, as well as highlighting potential synergies and opportunities to reduce the scale of the challenge arising from the transition to net zero, through, for example, energy demand reduction as a lever that also reduces material requirements.	A systems approach to evaluation of trade-offs should be taken, to ensure that sector-specific trade-offs do not lead to knock-on effects. Other requirements or enablers are consistent with recommendation 1 (above).
3. Government should implement an economy-wide target to halve the UK's material footprint, based on raw material consumption. Consultation on this should also consider sector- or asset-specific targets on significant points of demand for critical materials, on a case-by-case basis. **For**: DEFRA, ONS.	Drive action to increase resource efficiencies and minimise waste across the all the global supply chains that provide for UK critical material consumption. This provides a broader framework which will incentivise reduction in critical material use. The largest sites of consumption of critical materials in the UK are specifically incentivised to reduce their consumption of, and therefore UK dependency on, the critical materials of greatest concern. This may be a dynamic tool for addressing the most pressing of resource risks.	Use of product material passports to provide more granular consumption data, which could be further supported with an environmental product declaration (which reports objective, comparable and third-party verified data about products and services' environmental performances from a lifecycle perspective) to provide product environmental impact data. There is scope for some such targets to be introduced using the 2021 Environment Act. The scope and implementation of sector- or asset-based targets should be considered

Continued over...

Policy recommendations

Recommendation	Intended outcome	Requirements or enablers
		carefully to avoid unintended consequences, such as shifting consumption from one critical material to another.
4. Government should implement the National Materials Data Hub that has previously been committed to. The hub should capture data on the location, nature and recoverability of material stocks and flows to enable informed policymaking and underpin a materials sustainability strategy.	Enable reliable life-cycle assessment of the environmental impacts of materials and components entering the UK economy. Enable risk assessment of infrastructure and technology plans to account for delivery, economic, and environmental risks associated with critical material demands in infrastructure (*see relevant recommendations 7 and 10*). Enable identification of the largest sources of loss of UK stocks of critical materials and targeted mitigation through tailored resource efficiency, material substitution, and reuse and recycling schemes. Enable contingency planning for the strategic recovery and use of critical materials in the event of a disruptive supply crisis. Enable the accurate assessment of material sustainability of products and built assets to support sustainable design practices and informed consumer choice.	Support existing work on regulatory approaches to the use of life cycle assessments[22], and embedding a strong governance approach that penalises 'gaming' of the system.
5. Government should work internationally to establish monitoring and evaluation for traceability and whole value-chain data collection on the sustainability of materials (including non-greenhouse gas (GHG) impacts such as pollution and social harms), such as through digital passporting, to ensure that reliable data can be used in decision-making. **For**: DBT, FCDO, finance sector, global standards and monitoring bodies. HMT and financial-sector ESG bodies.	Reliable data to use as the basis of responsible, ethical and sustainable policymaking for a whole-system strategy on materials. This will support the UK's National Materials Data Hub by providing the basic knowledge of the provenance of materials entering or being extracted in the UK.	Develop and implement a standard technical system for recording and verifying information and tracing this across material value chains. Shared standards are ideal to maintain trade equity.

3.2.3 Case study: silicon supply chain crisis

In 2020, a combination of rising demand and the immediate and secondary impacts of the COVID-19 pandemic created a global semiconductor shortage. The shortage impacted a huge range of industrial sectors globally, including healthcare, automotives, telecommunications, and agriculture. As well as causing significant disruption to consumers, the chip shortage also "made it more difficult to build devices that look after our health, safety and welfare" and stimulated some manufacturers to adapt by reducing silicon consumption as far as possible through product redesign[23] – as this report discusses further in Section 6.2.2.

Silicon is one of the most abundant elements on earth, being a component in many rock formations and the planet's core. Most of the silicon extracted in the world is in rock and sand, however high purity silicon has been used as an important component in the production of aluminium alloys since the 1940s and requires a source of very high purity silica or quartz (>99.5% SiO_2) with a low fines content, which limits natural sources.[24]

High purity silicon is now an important component in the manufacture of semiconductors, which form the basis of all computer chips on which all electronic devices depend. As a result, this creates a complex cascade of risks associated with a silicon shortage. A recent report from the Parliamentary Office of Science and Technology identified some of these as:

- potential disruptions to critical national infrastructure, for example, power grids, transportation networks and financial systems all rely on semiconductor chips
- national security risks arising from the reliance of many military technologies on semiconductor chips
- delays, shortages and higher prices for consumer technologies.[25]

Previous reports by partners in the National Engineering Policy Centre have highlighted the complex and interdependent risks to infrastructures. The 2016 report Living Without Electricity is a case study of power loss in Lancaster beginning on 5 December 2015 and where power was only permanently restored six days later. The study detailed the knock-on effects of power loss on communications and access to information, finance, fuel pumps and the rail station (and therefore most transport) and even lifts within tall buildings.[26] Similarly, a speculative study in 2011 found a wealth of hidden interdependencies among infrastructure – for example a power station being dependent on transport networks to ensure workers can reach the area, water supplies for cooling, external electricity supplies for starting generators, communications systems to coordinate activity.[27] To this we may add access to replacement materials and components, most of which are not extracted or produced in the UK.

The production of high-grade silicon, and its use in the production of semiconductors, are all highly complex and multistep processes. One report from a semiconductor industry body estimates that inputs into the production of a semiconductor chip cross around 70 international borders.[28]

3.3 Net zero and material criticality in the UK

Decarbonising the UK economy to reach net zero by 2050 requires building and/or replacing a large amount of infrastructure and technology, in particular renewable energy generation, storage and transmission and distribution infrastructure as well as key infrastructure and transport fleets within the transport sector. These technologies and their enabling infrastructure are being deployed at a much larger scale than previously, and the rate of deployment must continue to accelerate at an unprecedented pace to displace high-emission infrastructure and technologies by 2050. However, producing the new infrastructure and technologies required to decarbonise often requires specific materials for which demand has historically been low, but is now set to increase significantly.

Supply crises risk economic disruption and may inhibit the strategic capabilities of the UK, in particular the ability to deploy currently available net zero infrastructure and technologies that rely on critical materials, including the dominant models of offshore wind turbines, solar panels, hydrogen-producing electrolysers, and nuclear reactors.

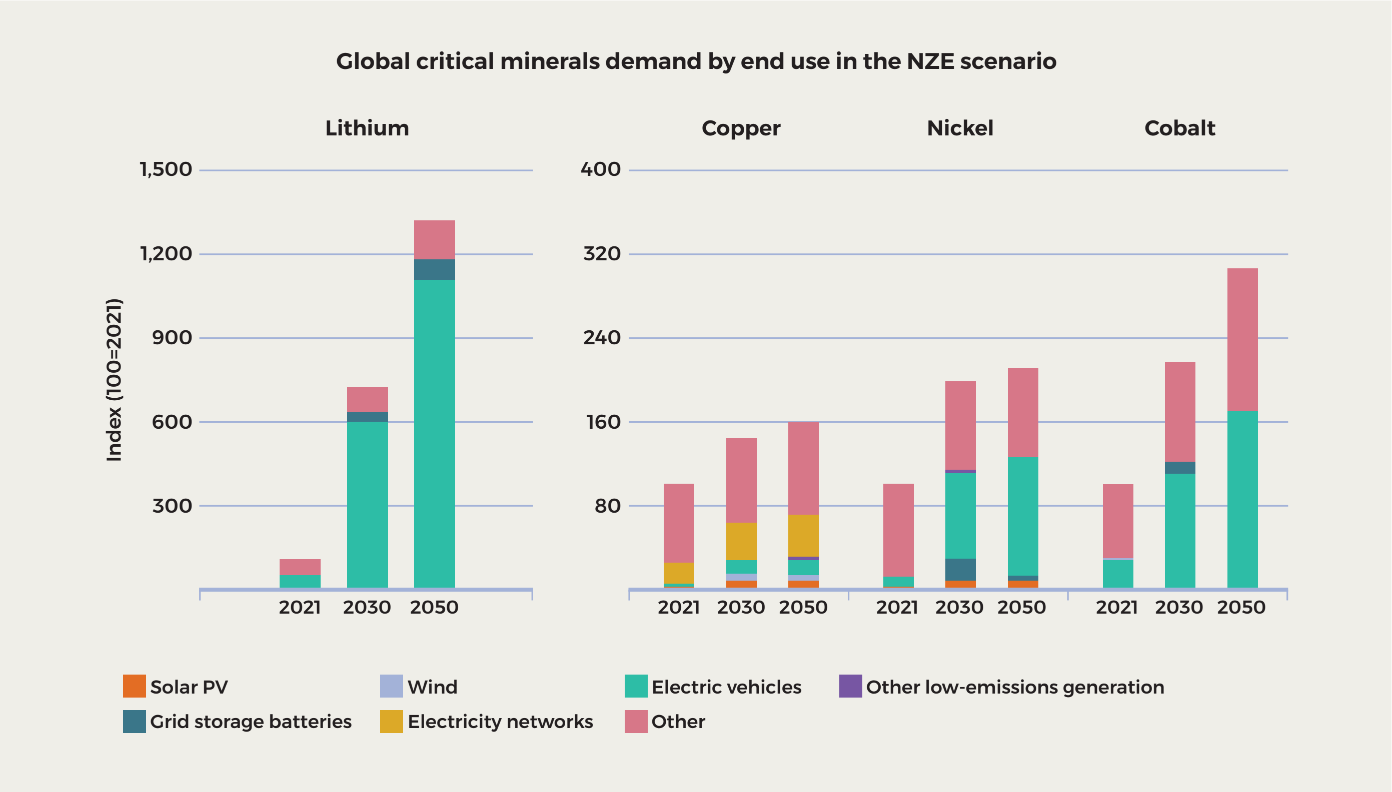


Figure 3 | Projected critical material demand by renewable energy technologies in the International Energy Agency's net zero emissions (NZE) technology scenario. This NZE scenario represents one technological configuration for a decarbonised energy system, which for our purposes may be considered a baseline for improvement in terms of critical material demand reduction. Adapted from: Critical Minerals Market Review 2023. International Energy Agency. Values are given in relative increases in demand for a given material from a 2021 baseline.

It is important to note that the transition to net zero is not the only demand for these materials, and often their other uses constitute the majority of demand. For example, while battery production is now the dominant use of lithium, it is also widely used in the production of and/or contained in pharmaceuticals, ceramics, industrial drying systems and lubricants.[29]

Additionally, while figure 3 above demonstrates some of the ways in which critical materials are used in these technologies, there is often scope for designing out these materials – as we explore more in Section 6.2.1 – although this can entail trade-offs in terms of performance.

3.4 Environmental, economic and social sustainability of critical material extraction

There is significant academic and policy discussion evaluating whether there are sufficient accessible material resources globally to enable this transformation of infrastructure and technologies by 2050 – and if there are not, how to manage this equitably. Regardless of this debate, encouraging or defaulting to maximal extraction of natural resources is an approach that – without transformation of global resource extraction – would lead to irreversible environmental damage and 'lock in' the social and economic impacts and inequalities associated with resource extraction.

It is likely to be technically possible to extract 'sufficient' critical materials to develop currently forecast infrastructure and technology demands based on known reserves,[30] but there are many uncertainties: estimates of longer-term growth, requirements for critical materials in new technology designs, and rates of growth in material recycling.

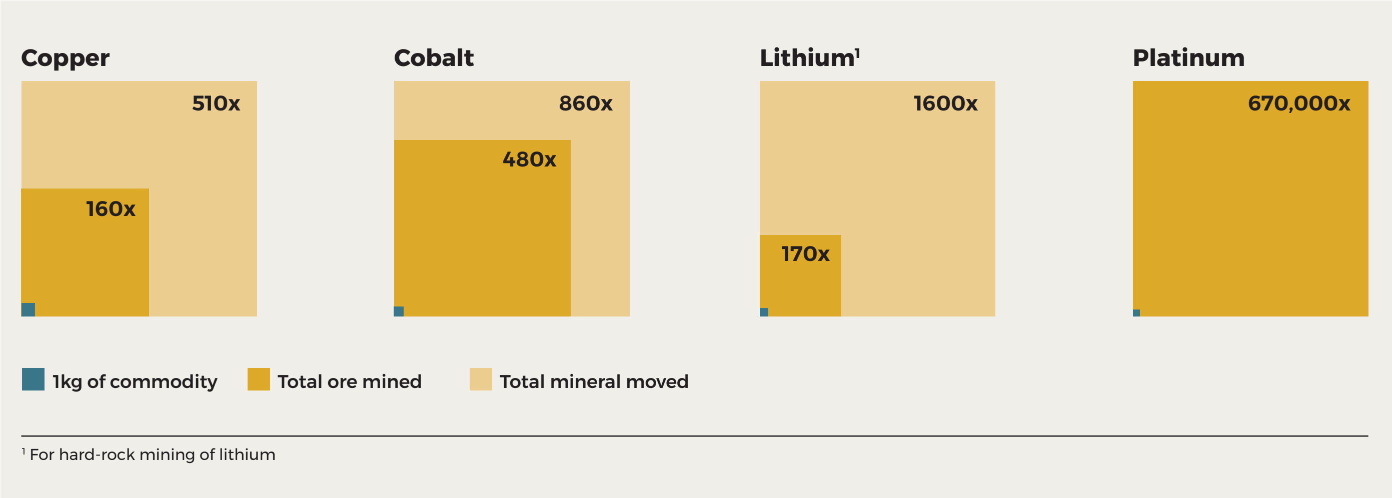


Figure 4 | Visual representation of rock-to-metal ratios of different mined metals, using relative area. For each material, the bottom left box represents 1kg of metal, compared to the ore mined and material (rock) moved. "Ore grades and waste rock production drive differences in environmental impacts from the materials production process." Adapted from Exhibit 4.3 of Material and Resource Requirements for the Energy Transition, 2023. Energy Transitions Commission. The rock-to-metal ratio for lithium represents hard-rock mining for lithium only, and not extraction from brines as is discussed in Section 3.4.1.

This technical discussion is largely divorced from the engineering and ecological realities of extracting that quantity of materials, however. Meeting the demand forecast would require a huge increase in mining operations globally, and diversification of resources extracted. The current practices for extraction of critical materials have significant direct negative social, economic and environmental impacts that – barring transformational changes in mining technology, practices and the associated economic structures – will increase as extraction expands. Sustainability frameworks have been developed for the purposes of mitigating such impacts, however their use and enforcement is limited.[31] Urgent action should be taken to develop and expand responsible mining practices, such as through certification and traceability enforcement, however these are often 'wicked problems' without clear solutions and are dynamically responding to demand.

The risks posed by global forecasted demand for critical materials to sustainability and industrial resilience are unlikely to be mitigated by supply-side approaches alone. Thus, it is imperative for nations such as the UK to reduce demand for these materials, alongside improving the supply-side approach to achieve a resilient and just transition to net zero.

Critical materials tend to be associated with the most harmful mining and extraction operations, due to their geology. Elements such as indium, cobalt, and niobium, and rare earth elements such as neodymium and praseodymium, are not strictly speaking rare. However, they are generally found in very low concentrations, meaning that mines must cover a larger area of land and process much higher volumes of rock in comparison to the extraction of most other metals.

For example, indium is produced primarily as a byproduct of zinc mining and is usually present in the ore at concentrations of 0.007–0.02% (70–200ppm).[32] This means that compared to zinc, the mining of indium requires far more rock excavation, usually through open pit mining, to produce the same quantity of metal. In addition to the increased land-take, the processing of these large rock volumes increases the environmental impacts of production.

Rock-to-metal ratios (RMRs) are used to estimate the amount of rock that must be physically

> Human rights violations and other abuses commonly affect labourers associated with critical material extraction – concerns are particularly acute surrounding ‘artisanal’ cobalt mining in the Congo, in which people, including children, are directly removing toxic ore by hand through unregulated open-pit and tunnel mining in areas with no industrial-scale extraction

processed to obtain the same amount of material. Removing earth and rock is very highly energy, chemical and water intensive and produces large amounts of waste. These operations are currently highly carbon intensive due to the use of fossil fuels to power large plant machinery for digging, crushing, dredging or pumping, although engineering R&D is ongoing to electrify this machinery.

Environmental harms arising from different mining operations can vary but include the loss of land, including any carbon sequestration or other environmental services it may be providing, loss of habitat and biodiversity through direct displacement and chemical pollution, and drought and freshwater pressures which can impact local ecosystems.

In particular, processing ores usually results in mine tailings: concentrated liquid wastes that can include leftover solvent chemicals as well as toxic metals and radionuclides. Tailings and liquid wastes require safe storage and long-term management. Leakage from mine-tailing ponds in the Baotou region in Northern China, the ‘rare-earth capital of the world’, where production for both Chinese and international markets is concentrated, has resulted in groundwater contamination. This has ended the local ecosystem’s ability to support agriculture and cattle-rearing, and necessitated the evacuation and resettlement of whole villages. Such pollution impacts can last for decades or centuries.[33]

Economic unsustainability is common, in terms of both poor economic outlook due to the lower ore grades of many critical materials, but also in terms of economic justice. Resource exporting nations rarely see economic benefit from these industries but instead suffer economic, social and environmental consequences often referred to as the ‘resource curse’. Human rights violations and other abuses commonly affect labourers associated with critical material extraction – concerns are particularly acute surrounding ‘artisanal’ cobalt mining in the Congo, in which people, including children, are directly removing toxic ore by hand through unregulated open-pit and tunnel mining in areas with no industrial-scale extraction.[34] According to Amnesty International, this has led to “the forced eviction of entire communities and grievous human rights abuses including sexual assault, arson and beatings.”[35] Around 70% of the global supply of cobalt is mined in the Congo.[36]

Social harms and violence also tend to arise around large-scale extraction beyond those directly employed in mining. Competition for natural resources is a driver of geopolitical tension and conflict at global and local levels, often involving local and indigenous populations who have no route to prevent developments that threaten their ecosystems and ways of life. This is despite a right to free, prior and informed consent on all matters relating to relocation, culture, legislation, land use, and the environment being enshrined by the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP).[37] There are currently few enforcement mechanisms to ensure that such consultation takes place or to restrict access to financing to projects that comply with these rights. Recently, conflict and violence have occurred due to planned mining projects for critical materials, such as in Argentina[38], Brazil[39], Indonesia[40], Panama[41], Serbia[42], and the United States[43].

Future extraction options for critical materials may include deep seabed mining. This presents significant environmental hazards to currently undisturbed ecosystems. These risks are amplified by a lack of environmental evaluation and reporting frameworks for mining in this environment and a poor understanding of the environments themselves. There are indicators that deep seabed mining may create environmental hazards over long timescales and affect large areas of the ocean floor.[44] Recent evidence also suggests that the metallic nodules themselves, which contain the critical materials in question, play an active role in oxygenating their ecosystems.[45]

Policy recommendation

Recommendation	Intended outcome	Requirements or enablers
6. Maintain the UK’s support for a moratorium on sponsoring or supporting ISA licenses for deep seabed mining exploitation, and support the development of evidence on the impacts of deep seabed mining. In the meantime, the UK should encourage other states to adopt this position and ensure that no ISA mining code that allows for mining ahead of proper environmental evaluation is approved.	Develop the understanding, evidence, and baseline evaluation to enable a clear decision to be made on whether any such activities are acceptable, and determine appropriate regulations, guidelines, standards and enforcement mechanisms.	Prevention of deep seabed mining activity that may inhibit the ability to establish an evidenced baseline understanding of environmental function and health.

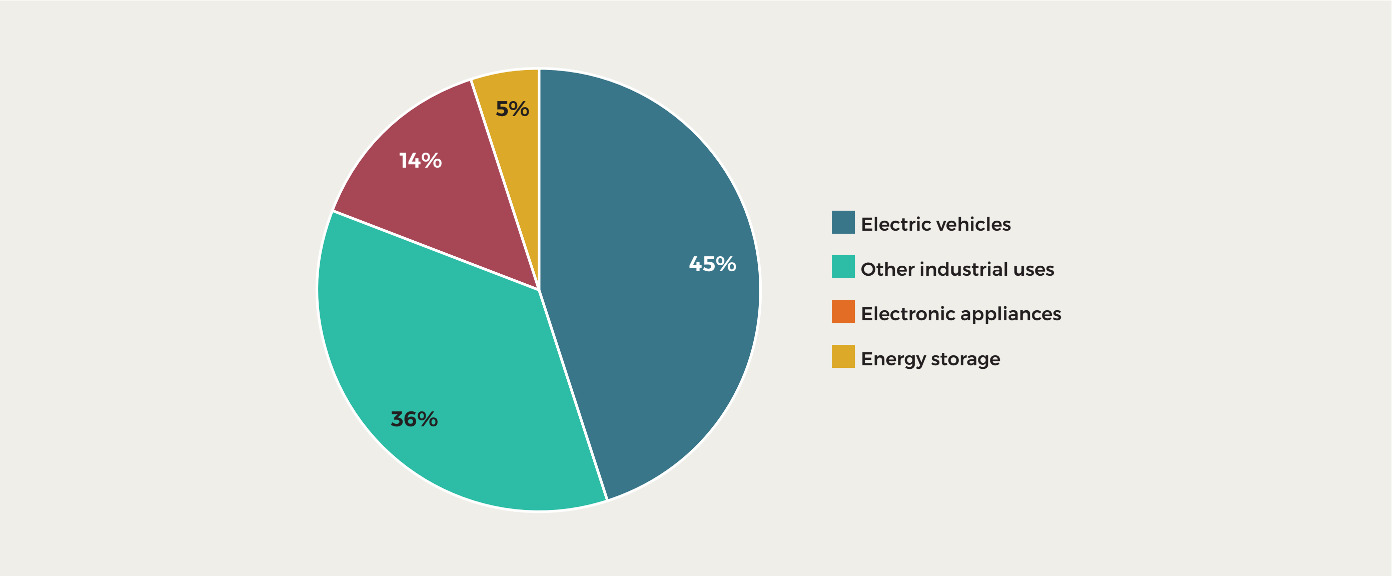
In October 2023, the UK government announced support for a moratorium on granting exploitation licenses for deep seabed mining projects by the International Seabed Authority (ISA).[46] This moratorium is appropriate, and that pause should be used to fully develop a scientific understanding of the ecosystems and potential harms they face, determining environmental baselines and both short- and long-term impacts of various kinds of mining activity. Without a far greater level of confidence in the impact of deep seabed mining on marine environments, which address the primary concerns raised, deep seabed mining should not be relied upon to address risks relating to critical material security.

3.4.1 Lithium extraction from brines in South America

A large proportion of the global lithium market is extracted from an area in the Andes shared by Chile, Argentina and Bolivia known as the ‘lithium triangle’. Copper is also mined in this region. This area is the home of many indigenous communities, as well as being an ecosystem of great importance both to native species, and to migratory birds.[47]

Almost all lithium extracted from the lithium triangle is done through the pumping of brines from the base of salt flats, evaporation of over 90% of the water in large solar ponds (Figure 6) and subsequent chemical extraction of the lithium from the concentrated solution. Depending on the lithium concentration, it requires evaporating between 100–800m^3 (tonnes) of brine to produce 1 tonne of lithium.[48] The drying process takes 10–24 months, meaning that this form of lithium extraction is very slow to increase or decrease production in response to changes in demand, with approximately a four-year lead-time for any increase. The lithium triangle is estimated to contain 50–85% of the world’s brine deposits that are suitable for this form of extraction. Evaporation of the brines also produces many other salts, 90% of which are considered waste.[49]

Additional fresh water is consumed at various stages of this process, including in the preparation of solvents and chemical solutions related to the extraction of lithium carbonates from concentrated brines, for the subsequent washing of the lithium carbonate crystals, and in the generation of steam. While it is sometimes argued that the evaporated brines should not count as water use, these brine aquifers are part of a complex groundwater system. The removal of this brine directly determines the volume of fresh water that consequently flows



■ **Figure 5 | Projected global uses of lithium in 2022**.
Adapted from Poveda Bonilla, Estudio de caso sobre la gobernanza del litio en Chile, 2020. CEPAL.

into the brine aquifer and becomes unsuitable for agriculture or consumption.[50] One operator in the region began a voluntary water monitoring programme only in 2020, which has been criticised for being reliant on self-monitoring and for excluding the brine extraction from its assessment of the water impacts.[51]

Alternative technologies, collectively known as ‘direct lithium extraction’ (DLE), allow for removal of dissolved lithium without evaporation of the water. DLE is also applicable to less concentrated sources of lithium such as geothermal brines and oilfield brines, which are more widespread around the planet. However recent reviews suggest that many DLE technologies, including the one hybrid DLE-evaporation extraction facility in the lithium triangle, consume a larger amount of freshwater per tonne of lithium than current solar evaporation practices.[52] This highlights a crucial engineering challenge, regardless of future increases in lithium demand.

Despite concerns being raised by local communities in the early 2000s, environmental analysis of evaporitic lithium extraction has focused on quantifying energy consumption and carbon emissions, and has overlooked the impacts of water and land use. Available quantitative data remain limited, as are baseline hydrogeological records taken prior to extraction that would enable quantitative evaluation of the hydrogeological impacts. (See recommendation 6, which is concerned with avoiding similar problems arising in the context of deep seabed mining.) However, observation wells in the lithium triangle have shown a “radical reduction in the water table” between 1986 (before extraction began) and 2015. This water loss is pushing the region into ‘desertification’, with land surface temperature increasing annually, all of which has significant consequences for local ecosystems. On one mining property, a third of the otherwise drought-tolerant native carob trees died between 2013 and 2017, while local flamingo populations have decreased by over 10% as a result on their reliance on affected wetlands.[53]

3.4.2 Climate change mitigation and material sustainability

Despite the crucial need to reduce and eliminate net greenhouse gas (GHG) emissions into the atmosphere, GHG emissions continue to increase as a result of policy and technology choices. These choices have led to our present situation of “unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production”[54] around the globe. The early impacts of climate change have worsened in all regions of the world, in particular causing damage to infrastructure, reduced water availability, flooding, displacement of people, detrimental impacts on agriculture, and deaths resulting from heat and wildfires. These climate change impacts disproportionately impact those communities who have historically contributed least to climate change.[55]

■ **Figure 6 | Aerial view of lithium fields in the Atacama desert in Chile, South America**.
Taken from: Shutterstock.com, 2023, Freedom_Wanted. [Accessed 15/08/24].

Reaching a global state of net-negative emissions as soon as possible is essential to avoid more significant and irreversible damage to global systems arising from climate tipping points, and to begin repairing the climate.[56] It is in this context that many new technologies and infrastructures are being developed with the goal of replacing the high-emission technologies on which we currently depend. The importance of doing so at a more rapid pace is clear.

This report is concerned with the broader sustainability of our economies, and especially the new technologies and infrastructures being deployed to achieve decarbonisation, with particular reference to the critical materials that present both sustainability and resilience risks. It is important to be clear that net zero technology is not the only source – or even in many cases the largest source – of unsustainable demand for these materials. Nor is it the only point at which demand management approaches should be applied. However, in many cases, such as energy and transport transitions, these technologies are forming a foundation of basic infrastructure for the future and as such warrant scrutiny for their environmental impacts beyond their contribution to UK territorial GHG emissions.

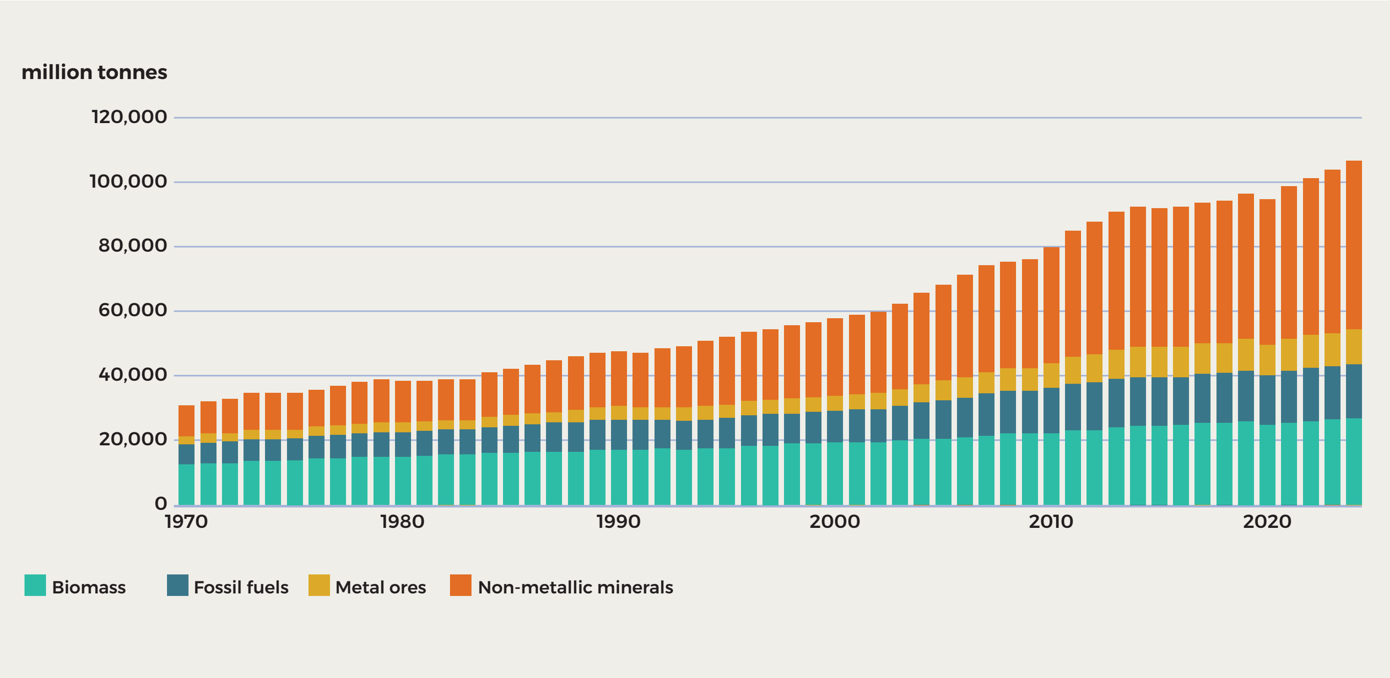


Figure 7 | Global material extraction, four main material categories, 1970–2024.
From Global Resources Outlook 2024. United Nations Environment Programme.

Beyond GHG emissions and the subsequent increase in global temperatures, the habitability of Earth to human societies is under threat from other forms of environmental harms. This is often referred to as the ‘triple planetary crisis’ of climate change, pollution and biodiversity loss, or more granularly described by the nine planetary boundaries set out by the Stockholm Resilience Centre. (See figure 8).

The global economy continues to grow its demand for raw materials to fuel growth, through construction of infrastructure and increasing rates of consumption more broadly. Natural resource extraction has grown by 400% since 1970 and is expected to grow a further 60% by 2060.[57]

The 2024 Global Resources Outlook prepared by the United Nations Environment Programme identified increasing resource use as the “main driver” of this triple planetary crisis. Not only does extraction and processing of material resources account for 55% of global GHG emissions, but also 40% of health impacts from particulate matter (primarily air pollution).[58] The report also forecasts that without urgent and concerted action, resource use in 2060 will be 60% higher than 2020 levels – driving consequences for the climate and planet more broadly. Importantly, the Global Resources Outlook notes that current policy approaches focus almost exclusively on supply-side measures, and says that these must be supplemented with a much stronger focus on demand-side measures that reduce consumption while improving the provision of essential human needs[59] – these are the measures, including demand reduction, reuse and recycling, with which this report is concerned.

The various forms of environmental harm associated with materials are not neatly separable but interlinked with the human activities that cause them, the ways in which they harm the ecological and physical systems that support planetary habitability, and the resulting loss and damage incurred to humans and ecosystems. These interactions can be at global scale, such as rising atmospheric CO_2 levels leading directly to ocean acidification as the CO_2 partially dissolves in global waters. They can also be more local disruptions such as to freshwater availability, which may lead to the loss of land-based ecosystems, as well as the services they provide to local and global communities. Impacts often include reducing the ecosystem’s ability to act as a store

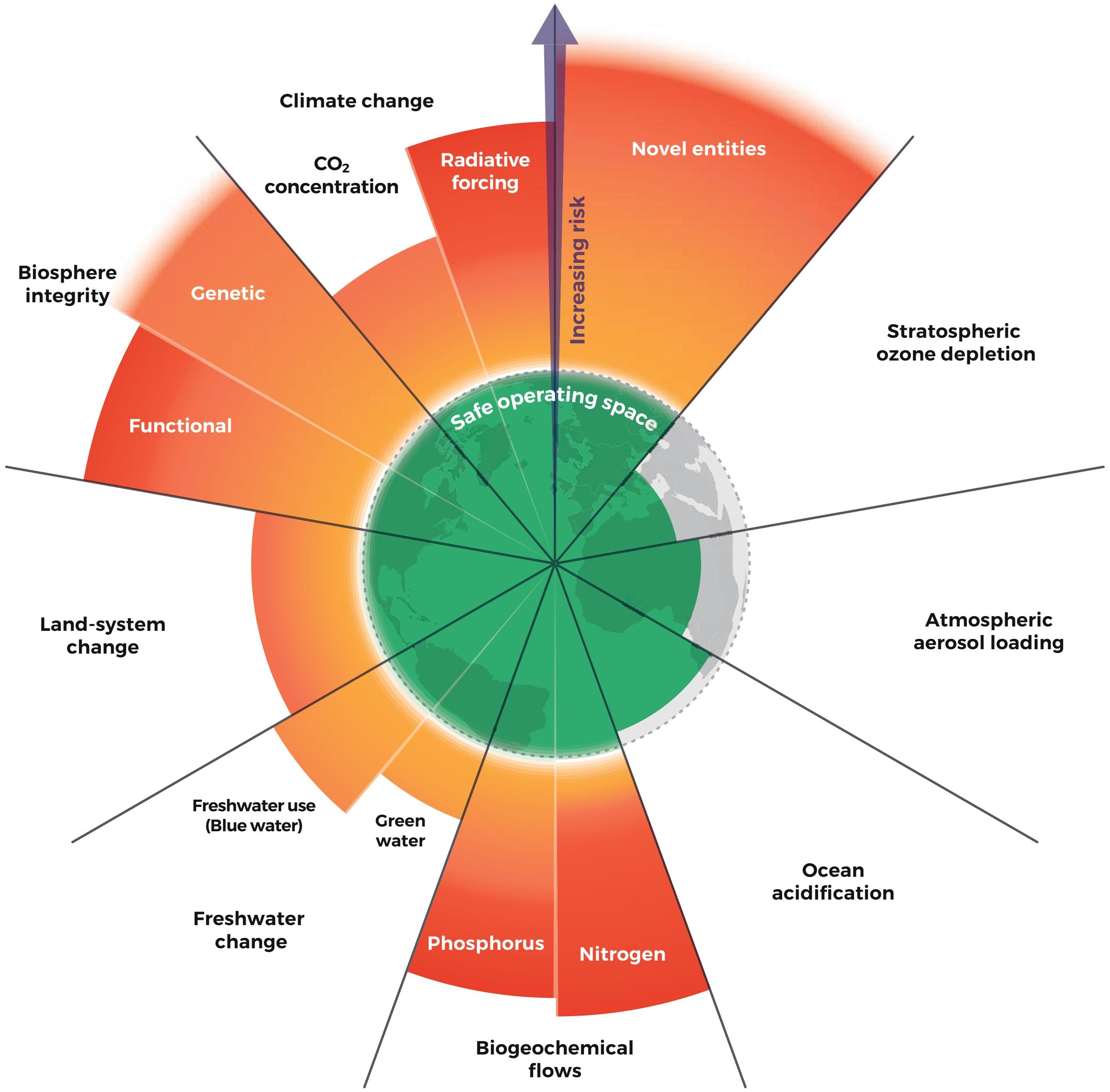


Figure 8 | Planetary boundaries 2023.
Licenced under CC BY-NC-ND 3.0 (Credit: Azote for Stockholm Resilience Centre, Stockholm University. Based on Richardson et al. 2023, Steffen et al. 2015, and Rockström et al. 2009). Novel entities refer to novel anthropogenic introductions to Earth system – this includes synthetic chemicals and substances, and anthropogenically mobilised radioactive materials.

> Natural resource extraction has grown by 400% since 1970 and is expected to grow a further 60% by 2060

> In order to address risks arising from critical materials to the net zero transition and UK economy, as well as to minimise the impacts inherent in their extraction and supply, it is necessary to engage with both demand- and supply-side approaches, and embrace a goal of resource efficiency and managing growing demand

of atmospheric carbon (e.g. through deforestation), as well as reducing flood resilience and decreasing agricultural capacity.

When considering the sustainability of UK infrastructure, the impacts on risk, resilience and global sustainability which arise from the demand produced for materials production and consumption are not visible to decision-makers. The UK policy drivers for decarbonisation, largely the net zero target and system of carbon budgets, are themselves crucial elements, but not sufficient alone to achieve globally sustainable outcomes. This is especially true given the dependence of the UK on imported materials – raw, processed and within components and goods – meaning that:

- The carbon emissions associated with the extraction of critical materials and/or production of the components and goods are not considered to count towards UK carbon budgets.[60]
- The other environmental impacts, especially pollution, land-use change, and freshwater use arising from mining and processing these materials (and manufacturing components and goods) are physically separated from UK decision-making. They are also not considered by local and global GHG emission accounting systems ('carbon accounting'), which drive climate change mitigation policies through the COP process, despite contributing to climate change indirectly.
- Human rights violations associated with material extraction or processing are often poorly recorded, and there are few controls on ensuring ethical sourcing of materials that can be considered at the point of commissioning or procuring infrastructure that will create material demand.

The current need for renewal of swathes of infrastructure as part of the net zero transition is an opportunity to replace high-emission systems with ones that are not only low-emission, but also sustainable in terms of their materials sourcing and their other impacts on people, communities and environments. Failing to take decisive action on material sustainability may lead to our current, unsustainably high, GHG emission infrastructure being replaced with infrastructure systems that are unsustainable in other ways and ultimately becoming themselves a problem that must be solved through policy and engineering. Early action is required to embed material sustainability within our important and wholly necessary efforts to decarbonise.

3.5 Demand-side approaches to achieving critical material resilience

In order to address risks arising from critical materials to the net zero transition and UK economy, as well as to minimise the impacts inherent in their extraction and supply, it is necessary to engage with both demand- and supply-side approaches, and embrace a goal of resource efficiency and managing growing demand.

This is alluded to in the 2023 UK Critical Minerals Strategy, which sets one of its goals as:

"4. Make better use of what we have by accelerating a circular economy of critical minerals in the UK – increasing recovery, reuse and recycling rates and resource efficiency, to alleviate pressure on primary supply.

a. We will promote innovation for a more efficient circular economy for critical minerals in the UK.
b. We will signpost financial support to accelerate the development of a UK critical mineral circular economy.
c. We will look at regulatory ways to promote recycling and recovery."

These commitments are welcome but will not be achieved without a significant change in approach, including a greater focus on resource efficiency. As described below in Section 7, circular economy measures for critical materials – and others with increasing demand – will not be able to reduce near-term primary supply due to the small volume of materials currently in stock or use and the large total growth of demand. A significant supply of recycled materials will only be possible once the decommissioning of infrastructure and assets containing significant quantities of these materials has commenced. With infrastructure lifespans in the range of decades, there will be a significant lag in the capacity for circular economy measures to meaningfully provide for the demand being created.

Increased investment and an uplift in policy efforts are required to plan in a way that reduces our vulnerability, creates incentives for long-term resource efficiency, removes counter-incentives, and develops the UK's engineering capacity for domestic materials management.

This report expands on what it is possible to achieve through demand reduction measures in the UK, setting out an approach to operationalising policy and engineering approaches to demand-side management of critical materials. It provides an overview of the actions that government, industry and regulators can take to reduce the economic and strategic risks posed by critical materials supply in a way that promotes global sustainability, economic resilience, and a just transition.

This report allocates interventions that may be made by government, industry or international bodies into three interconnected categories, which are discussed in turn in the remainder of this report:

Infrastructure and technology planning: choices made in infrastructure planning and technology adoption often drive the sharpest spikes in demand due to the scale of infrastructure deployment. Factoring the critical material requirements arising from different policy and technology choices, in particular in planning future energy and transport systems is the most crucial element of managing demand.

Design and design skills: the right design and innovation choices taken within individual areas of technological development and application can reduce critical-material usage. Often this can achieve the same technological outcomes but with more efficient, or no, critical material use. Design and innovation choices also increase the productive life of materials through longevity and repairability, increase **flexibility in manufacturing** processes to provide resilience, and **enable recovery** of the materials through disassembly and reuse or recycling at end-of-life.

Circular economy: nations can also make better use of their **existing stocks** of materials, for example that which is present in domestic **infrastructure** or which is currently being left in **waste streams**. Planning for **reuse** of these materials in a more **circular economy** of products and assets can reduce our demand for, and dependence on, critical materials. However, due to the projected increase in global demand for critical materials it will not be possible over the next few decades to meet future needs and address unsustainable material use through recycling alone.

4. Infrastructure and technology planning

4.1 Upstream infrastructure and technology governance for critical material demand reduction

Policy, technology options and economics shape decisions for investment in infrastructure and therefore the demand for critical materials. These governance systems need to aim to reduce the critical materials requirement.

Whether infrastructure for mobility, energy or heat generation, storage and distribution, or another form of service, rarely is there only one solution for achieving a particular outcome. The specific infrastructural and technological solutions we implement to meet societal needs are a result of policy and technology choices as well as the surrounding economic structures. These policy and technology choices have the largest impact on critical material requirements of any single decision made. Materials used as part of large-scale infrastructure build-out can increase the demand for its component materials rapidly to the point where a material may become critical. As such, existing infrastructure and technology plans and forecasts are a driver of what materials are currently considered critical and stand to shape consumption and growth in demand.

The choices made now about the make-up of future energy and transport systems will have a massive impact on our material footprint, and different technologies have different critical material dependencies.

- Within the energy system, decarbonisation will change the generation mix and electrification of previously fossil-fuel powered processes (including vehicles and heating) creating new demands, which must be met through upgrading grid transmission and distribution infrastructure. Critical materials are involved in the production of wind turbines (neodymium), solar photovoltaics (primarily silicon but also others), green hydrogen electrolysers (various, but often platinum or nickel), grid-scale battery storage (lithium, nickel and others) and nuclear (chromium and nickel).
- Likewise, transport systems and technologies are early in their processes of transformation, primarily relating to the replacement of personal and fleet vehicles with EVs. Vehicles and vehicle batteries are inherently resource intensive assets, meaning that critical materials requirements are magnified by the scale of deployment required for a 1–1 replacement of internal combustion engine (ICE) vehicles with EVs.
- Similarly, although less typically viewed as traditional 'infrastructure systems', digital and computing systems (including data centres but also distributed digital systems) are a newer and growing type of infrastructure, with new and potentially large requirements for both the critical materials used in the electronic hardware and the energy – and energy infrastructure – used to power the systems.

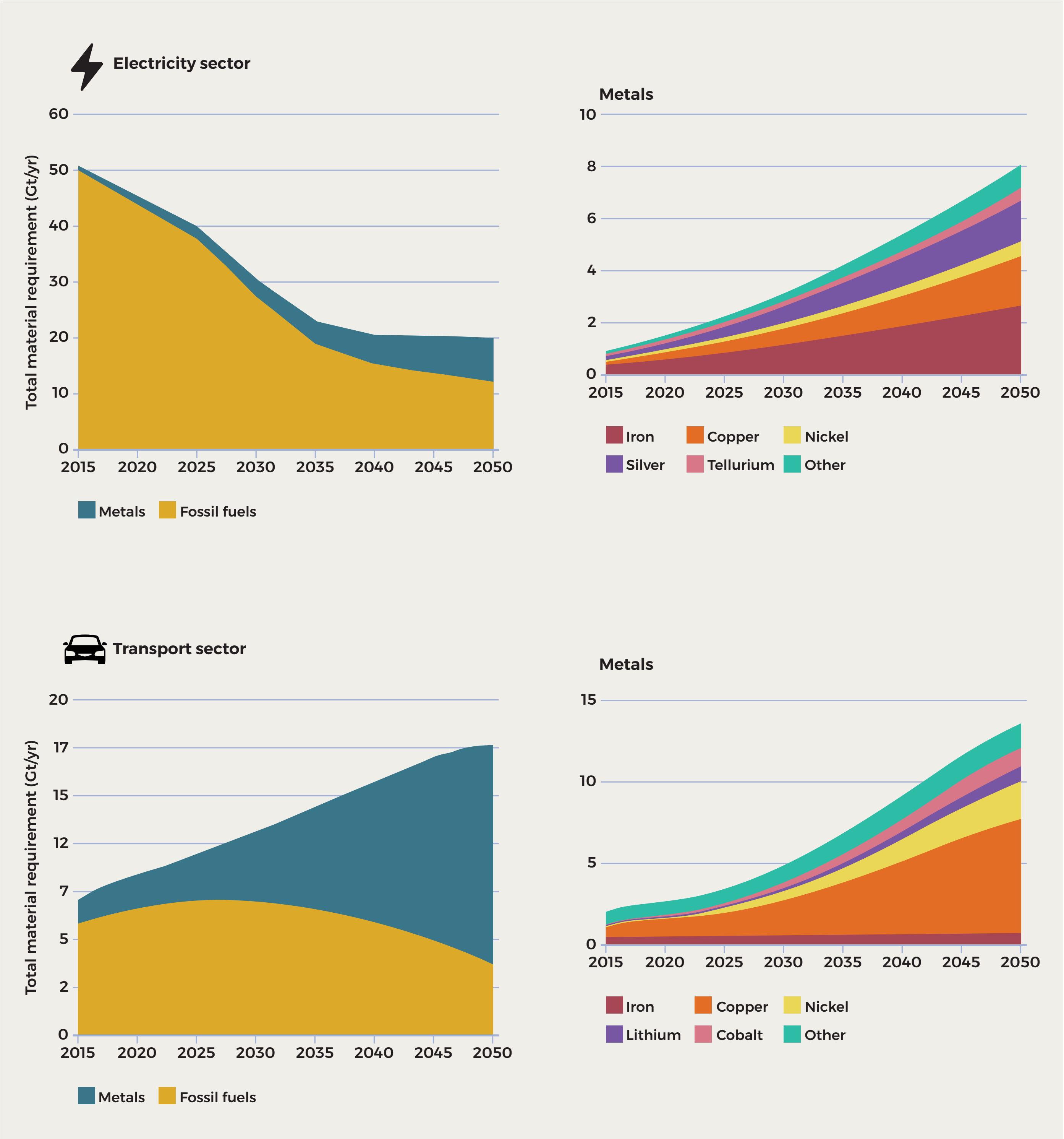


Figure 9 | Estimated total material requirements induced by the energy transition 2015–2050. This scenario is based on the pathway toward keeping the rise in global temperatures well below 2˚C by 2100 compared to preindustrial levels. The concept of total mineral requirement captures all the resource extraction in both used and unused extraction. Used extraction refers to materials that are extracted from the environment and subsequently used in production processes, whereas unused extraction refers to material flows that arise during the course of extraction, but that do not directly enter the economic system (e.g. waste rock and overburden). Adapted from: Watari T. (et al), 2021. Sustainable energy transitions require enhanced resource governance, Journal of Cleaner Production.

Policy choices across these areas will be instrumental in determining the balance of these technologies in the UK, and thus the critical material demand that comes with them. It is essential to anticipate and manage these demands at a system-wide level, and include them in infrastructure and policy planning, to reduce the supply risk and social and environmental impacts of high critical material consumption. This is especially true for materials that have uses in multiple technologies and so may compound risks. This is the case for lithium-ion batteries, which may play a major role in future transport systems, energy storage devices, and digital technologies, meaning that delivery risks associated with the materials may be compounded. However in all of these cases there are technological alternatives to lithium-ion batteries, as we explore further in Section 5.3.

To illustrate the policy and technology choices that shape critical material demands, this section of the report will discuss opportunities for reducing demand in three areas of national policy, which will have significant impact on the critical material demands of the UK as we move toward a decarbonised future – transport planning, energy system transformation and digital technologies. A comprehensive system map of where policymaking decisions are driving resource demands and a framework for incorporating resource use into decision-making is beyond the scope of this work but would be an important basis for incorporating material sustainability into net zero.

Policy recommendation

Recommendation	Intended outcome	Requirements or enablers
7. National infrastructure planning for energy, transport and digital systems should incorporate assessment of critical material requirements of different technology scenarios. **For**: NIC, NESO, IPA, DfT, DBT, DESNZ, CMIC/BGS, others as required.	Capability to assess the critical material demand from infrastructure plans across sectors and risks arising from compounding demands for particular materials Allow for whole-system optimisation which avoids or reduces critical material demands and demand spikes thereby increasing resilience of infrastructure delivery. Enable strategic end-of-life planning for infrastructure to maximise the productivity of critical materials used, and to strategically develop capabilities for the recovery and reuse, or otherwise recycling, of critical materials. Places a value on resource efficiency for individual (critical) materials which could be used to incentivise resource efficiency in individual procurement decisions. Enable contingency planning to increase resilience to supply shocks and pre-figure responses. Identify opportunities for strategic development of localised supply chains to support UK infrastructure and technology needs. Linking domestic manufacturing and end-of-life facilities could reduce costs of whole-life servicing.	Materials Data Hub outputs, and reliable and more comprehensive data on sustainability of current extraction and processing methods. Methodology for assessing long-term sustainability and supply risk of materials and applying a value to reducing their use. Contingency planning capacity and join up with national strategic risk assessment and planning.

> In 2020, 24% of the total domestic GHG emissions came from transport, and of those transport emissions 87% came from road vehicles. The scale of the decarbonisation challenge in this sector echoes the scale and importance of mobility in our lives

4.2 The transport system

As the highest emitting sector in the UK[61], decarbonising the transport sector is essential to meeting net zero targets. In 2020, 24% of the total domestic GHG emissions came from transport, and of those transport emissions 87% came from road vehicles.[62] The scale of the decarbonisation challenge in this sector echoes the scale and importance of mobility in our lives.

Many current efforts to decarbonise UK transport have focused on the direct replacement of ICE vehicles with EVs. The commitment to zero-emission vehicles by 2035 mandates that 80% of new cars and 70% of new vans sold in Great Britain must be zero emission by 2030, increasing to 100% by 2035.[63] However, being an outsized contributor to critical material demands, and the primary driver overall of lithium extraction, decarbonisation driven predominantly via rapid EV uptake would be critical materials intensive.[64]

As an alternative policy focus, a significant reduction in vehicle numbers can be made through 'modal shift' – policies and infrastructure that enable a change from one mode of transport to another. Moving passengers from low-capacity vehicles such as cars into buses or trains allows more people to be transported per journey. This relates directly to a reduction in critical materials – a study of transport in California, US, modelled a 71% decrease in system-wide lithium demand from shifting policies away from a focus on replacing existing vehicles with EVs to e-bikes or e-buses.[65] While this scale of reduction is likely greater than what is achievable in the UK, which starts from a position of relatively higher mass transit use than the modelled US transport system, there is still significant potential for reduction in critical material dependencies to be made from modal shift towards e-buses and e-bikes, and active travel in the UK. Policymakers could also consider transport options that do not use lithium batteries such as electrified tram and rail systems, and active travel.

A key contribution of such studies is to demonstrate that different system configurations, shaped by different policy and technology choices, can be assessed and compared based on their material efficiency – such as 'lithium efficiency'. This could be incorporated into whole-system design approaches and risk assessments of how different system configurations contribute to the supply chain resilience and environmental impact of particular materials, (see recommendations 7 and 10).

New analysis completed for this report, discussed in more detail in Section 5, estimates the total lithium requirements of the forecast UK market for electric vehicles up to 2040 as being 268,000 tonnes (requiring 438,000,000 tonnes of rock to be mined) and estimates the resource savings achievable through design changes such as battery size reductions. While this analysis focuses on design changes within the vehicles themselves, these design choices and their market uptake are often enabled or inhibited by the configuration of the wider transport infrastructure system. For example, a reduction in battery size limits the range of the vehicle, which can lead to range anxiety in drivers – by ensuring that there is an extensive and reliable charging network available throughout the UK, these concerns can be alleviated.

Another potential contributor to reducing overall demand for personal vehicles, and therefore critical materials from EVs, is flexible models of vehicle ownership and use. For example, mobility-as-a-service integrates different modes of transport and transport services into a single mobility service that

Policy recommendations

Recommendation	Intended outcome	Requirements or enablers
8. Reduce reliance on battery-electric vehicles in the future transport system through a widespread modal shift strategy for both passengers and freight. **For**: DfT, NIC, local and combined authorities.	The primary mode of transport is shifted from cars to more sustainable modes of transport. Air pollution, congestion and critical material demand is decreased across the transport system. This includes: – Significant investment in the improvement and expansion of public transport services, with a particular focus on underserved communities such as the north of England to improve equality of access. – Investment in cycling and active transport infrastructure. – Flexible models of vehicle ownership and use such as mobility-as-a-service and car sharing.	Investment in low-carbon transport system options, focused on mass transit but including personal transport solutions which limits a like-for-like replacement of ICE's with EVs. This planning should be joined up with the planning and development of housing, schools, hospitals and business centres to reduce journey requirements and expand mobility options. Efficient multi-modal linkages between ports and rail networks to reduce reliance on road transport, via HGVs, for freight.
9. Ensure a comprehensive, extensive, and reliable charging network, through the expansion and improvement of charging infrastructure throughout the UK. **For**: DfT, DESNZ, NIC.	Equality of access to regular charging points exists across the UK. Range anxiety of battery electric vehicles is significantly reduced, and the use of shorter range, smaller vehicles is increased, in comparison to large vehicle usage.	Widespread decarbonisation of the UK national energy system, including sufficient energy generation and storage technology to support BEV charging infrastructure. Reliable, fast charging technology.

can be used on demand. This enables consumer demand to be pooled into fewer vehicles, rather than each needing a separate vehicle, thus reducing the number of vehicles required and their associated critical material demands. Different approaches to flexible vehicle ownership and use can be taken in rural versus urban areas. In rural areas, car sharing schemes, where a community of users share the usage of a vehicle fleet on a per-trip basis, can allow users to reach destinations otherwise inaccessible by public transport, walking or biking. This is particularly applicable to communities underserved by public transport services, such as the north of England.

With battery-electric heavy goods vehicles (HGVs) expected to comprise a significant proportion of road haulage, freight is also an important sector to consider for modal shift when seeking to reduce critical material demands. System planning is particularly important for creating linkages between port and rail systems, which could reduce dependency on such road vehicles.

4.3 The electricity system

The UK has committed to a fully decarbonised electricity system by 2030, however, there are many potential clean energy technologies that can be combined to form this future system – each with their own specific material requirements. As we will explore further in Section 6.2, current material requirements are subject to innovation which could either increase or decrease their use of critical materials depending on incentives, design trends, and the extent to which the substitution of critical materials is prioritised. Therefore, decisions made now about the balance of technologies for both generating and storing renewable energy will shape the UK's critical material dependencies and material demands across the next decades.

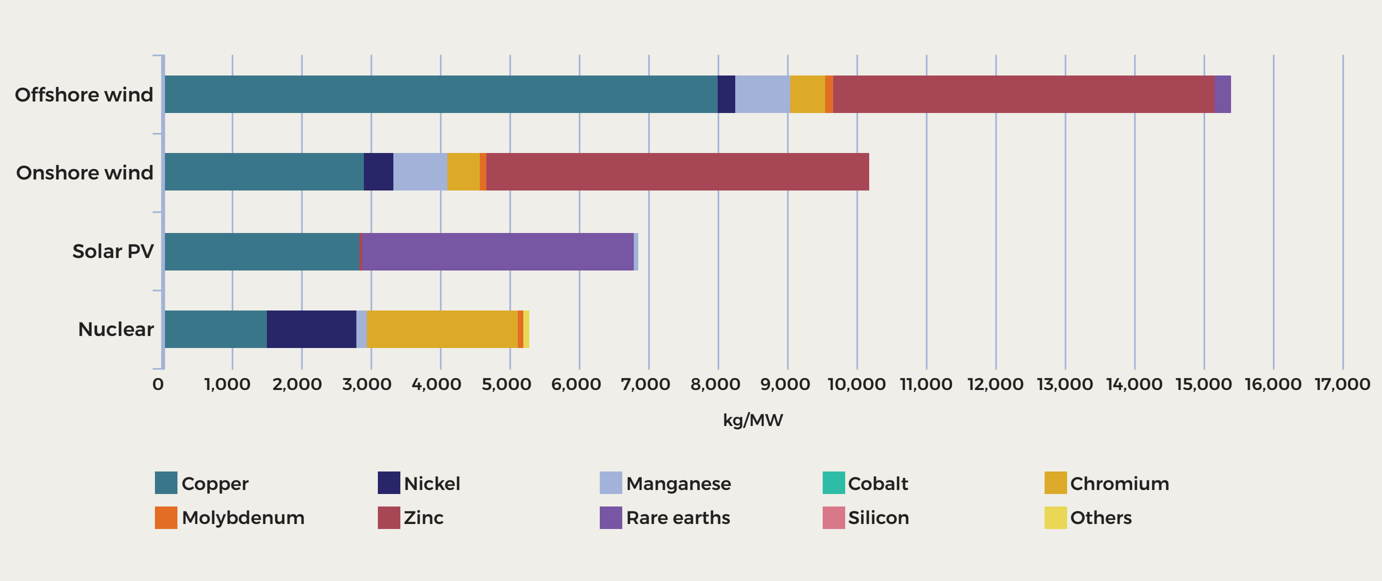


Figure 10 | Minerals used in renewable energy generation technologies.
Adapted from: The role of critical minerals in clean energy transitions, 2021, IEA.

4.3.1 Energy generation technologies and their critical material requirements

There are a diverse range of critical material requirements among energy generation technologies, both in the overall volume of materials per megawatt capacity and mix of specific materials used. At present, solar photovoltaic (PV) and wind energy are predicted to form the bulk of energy generation in the UK, due to their low cost and the high availability of these resources in the UK.[66,67,68] At present, it is unclear what the exact amounts of each generation technology in the future system will be. In March 2024, the Energy System Operator (now National Energy Systems Operator – NESO) published a forecast of the expected GigaWatt capacity of generation technologies in the UK (see figure 11). Such planning should form the basis for assessments of system-wide critical material demands and the risks and harms entailed. Notably however this forecast extends only to 2030, meaning it does not account for nuclear generation capacity, or the infrastructure lock-in represented by choices up to 2030.

In principle, the diverse mix of potential energy technologies to generate electricity provides higher resilience to supply shocks, providing flexibility to upscale or downscale the manufacture of different technologies in the event of a supply shortage of a material required in high volumes for one technology but not for another. However, it is not clear how government would respond to shortfalls in one area of the system, given the sudden nature of supply shortages and the long planning and often decade-scale lead times for new infrastructure.

Alongside the types of generation technologies, the location of energy infrastructure can also be a determinant of material intensity. For example, onshore wind turbines require a lower volume of materials than offshore wind – this is due largely to their smaller size, but their placement onshore can also enable greater use of components with lower critical material intensity, such as hybrid magnets with lower requirements for neodymium and praseodymium.[70] Onshore turbines can also make use of existing power grid infrastructure, if installed on the site of existing power arrays, increasing resource efficiency.[71] However, offshore wind turbines can make use of a larger size and stronger wind currents above the sea to run at much higher

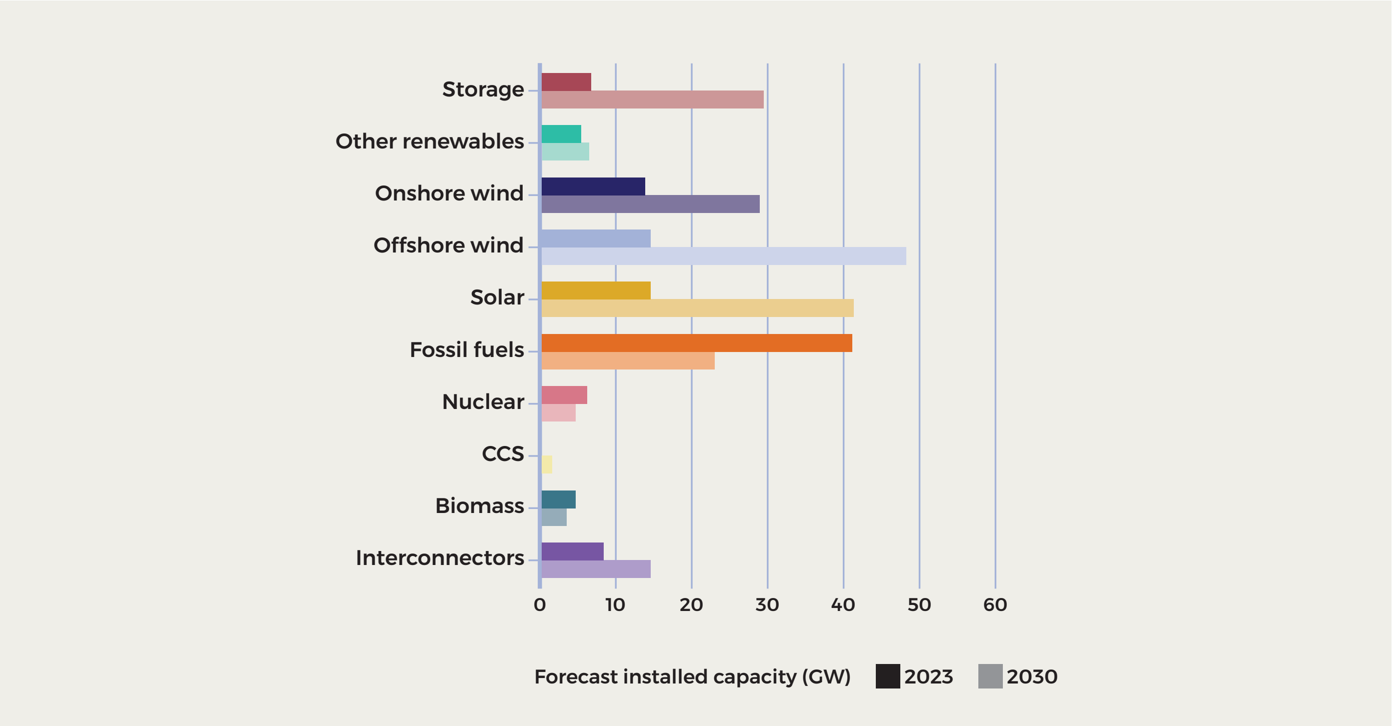


Figure 11 | UK generation mix now and forecast for 2030. Adapted from: Beyond 2030, 2024, NESO.

load factors, and therefore produce a greater power output.

4.3.2 Energy storage technologies and their material requirements

A decarbonised energy system has a range of energy storage requirements, from short-term, rapid grid balancing to interseasonal storage. These needs can be met through a variety of technology options, each with vastly different material requirements.[72]

In a system with high amounts of wind and solar energy generation, short-term energy storage is needed to rapidly regulate voltage and frequency, and to stabilise the electricity system when there are sudden fluctuations. High-efficiency storage from conventional batteries (such as lithium-ion batteries) is considered the most appropriate option for this role[73] however, this storage technology has high costs, and very high critical material requirements.

Long duration energy storage (LDES) will also be required to balance demand and supply over months or years, and to provide electricity when there are seasonal drops in wind and solar energy availability. In the UK, the leading candidate for low carbon LDES is electrolytic hydrogen produced from low carbon electricity, which is then stored in salt caverns – a report by the Royal Society estimates that 60–100 TWh of hydrogen storage capacity would be required in 2050.[74,75,76] The critical material requirements for this form of LDES come primarily from the electrolysers used to produce the hydrogen. There are a wide variety of electrolyser technologies, each coming with their own differing critical material requirements. As with generation technologies, there are trade-offs to be considered with each variation of electrolyser technology depending on the size, location and surrounding infrastructure of the facilities.

4.3.3 Integrating critical material demand management into UK electricity policymaking

The National Energy System Operator (NESO), is, as of autumn 2024, the independent, public corporation responsible for planning and operating Britain's electricity and gas networks and operating the electricity system. It will be a key organisation in determining the future of the UK electricity and wider energy systems and, therefore the UK's critical material demands across the coming decades.

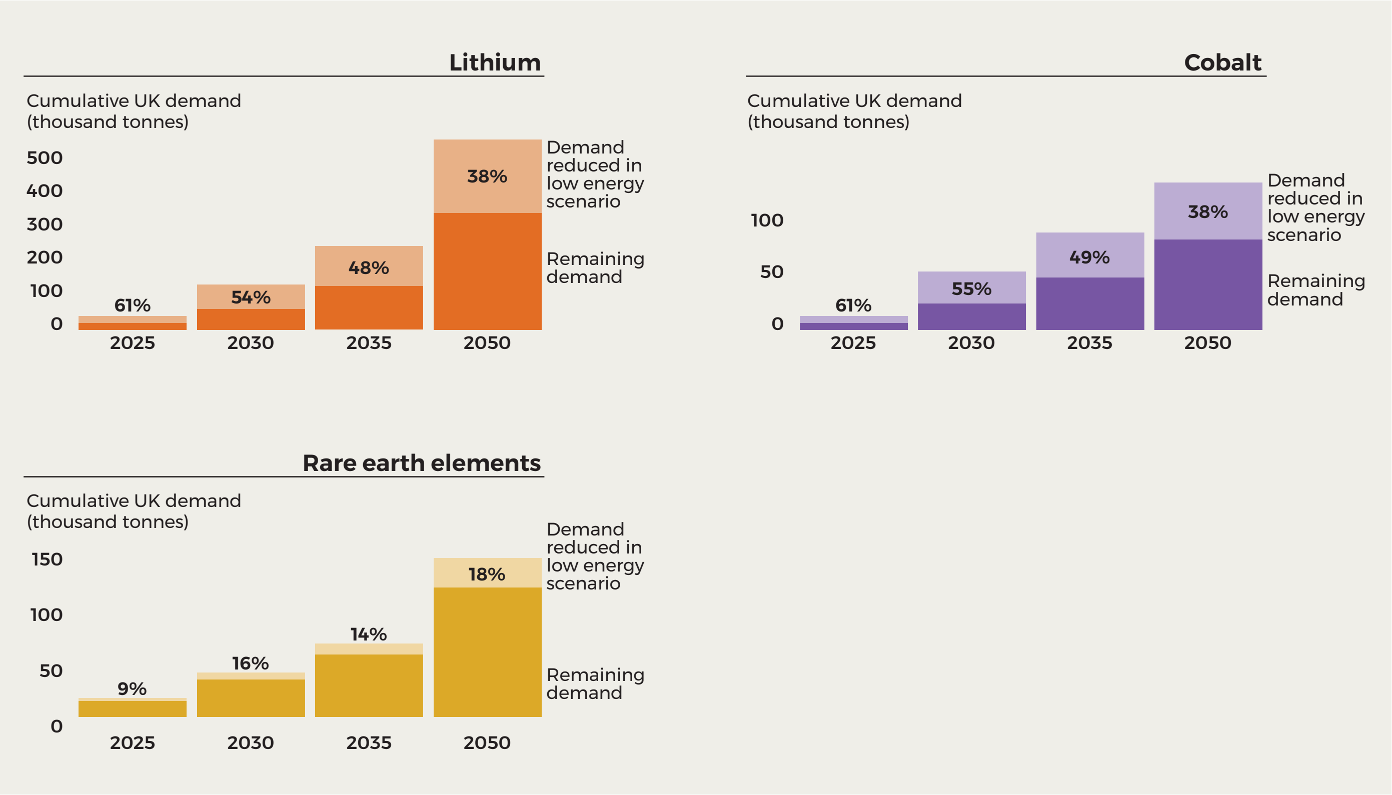
At the time of writing, the NESO has set out three core components of its strategy to decarbonise the electricity system:

1. The Strategic Spatial Energy Plan (SSEP) – a national spatial plan that sets out the capacity, location, and timings of transmission-level energy infrastructure.
2. The Central Strategic Network Plan (CSNP) – which takes the outputs from the SSEP and develops a detailed plan for future transmission networks that will be required across the different energy vectors of electricity, hydrogen and gas.[77]
3. The Regional Energy Strategic Plans – this is where the national and local energy plans come together, ensuring energy networks are regionally coordinated.[78]

Decisions made now by the NESO around technology type, location and size of infrastructure will have a direct influence on UK critical material demands. It is therefore essential that critical material demands are characterised, and that opportunities are identified within planning processes to limit critical material demand and dependencies, when delivering a decarbonised electricity system. This will limit the UK's infrastructure pipeline's exposure to risk from supply shocks as well as reducing the negative impacts of critical materials production and supply.

Policy recommendations

Recommendation	Intended outcome	Requirements or enablers
10. Energy system governance, led by NESO, should include assessment of critical material requirements for energy system future scenarios and delivery risk assessments. See related recommendations (22 and 23) on offshore wind procurement **For**: NESO, OFGEM.	NESO is able to assess the material requirements of future energy system scenarios, the risks these bring in terms of delivery and global sustainability, and, working with Ofgem and government, integrate the mitigation of these in ultimate decision-making and forward planning. This should enable estimation of the efficiency of use of different materials within a future system, as well as enable contingency planning around any delivery risks highlighted as a result.	Collection of data on material requirements of planned energy assets at point of planning permission. NESO and/or government should consider using existing powers to requisition data on material requirements of different energy technologies, to build our ability to forecast material needs and risks and plan accordingly. Methodologies should be established for the estimation of how current material requirements for technologies should be used to estimate future material requirements, to account for potential design innovation.
11. Government should drive the ongoing sharing of data on material usage in different key energy technologies (as well as in other sectors), currently held in the private sector only. **For**: NESO, DESNZ.	Policymakers, planners and other stakeholders are able to assess and respond to critical material requirements of different energy technologies, and identify both areas of risk and system configurations that would minimise them.	Standards are needed for the assessment and reporting of material data for different infrastructure asset types. Trusted data-sharing frameworks enable data sharing and inter-operability. For more information on trusted data sharing, see the Academy's 2018 report, Towards trusted data sharing.[79]



■ **Figure 12 | Projected critical material demand reduction, through energy demand reduction**.
Adapted from: Critical point: Securing the raw materials needed for the UK's green transition. 2021, Green Alliance.

4.4 Energy demand reduction and demand response as critical material demand management

When considering the critical material requirements of the energy system, a crucial factor is the overall scale of the system required. By reducing overall annual energy demand and introducing greater flexibility to reduce the demand peaks, significant system-wide critical material demand reductions can be made across the board through needing to build fewer generation and storage assets, and less transmission infrastructure overall.

Research by the Green Alliance[80] suggests that cutting cross-sectoral energy use could reduce cumulative UK demand for critical materials significantly (up to 55% for lithium and cobalt), compared to a high energy demand scenario. The low demand scenario enabling this reduction is based upon a 'shift' pathway developed by the Centre for Research into Energy Demand Solutions (CREDS), which modelled an "ambitious programme of interventions across the whole economy". This included the rapid roll-out of heat pumps and programmes of retrofit for energy efficiency in buildings and behaviour changes such as a significant increase in the use of public transport and active travel. Other suggested measures to reduce energy demand included increasing freight efficiency to reduce travel distance for heavy goods vehicles and encouraging building refurbishment rather than demolition.[81] Since infrastructure must be built to meet the requirements of demand peaks, there is also a significant opportunity to reduce the material requirements of the energy system by shifting when demand occurs in order to reduce peak demands on the system. 'Demand response' is a strategy that provides flexibility to energy systems by redistributing consumption patterns[82] – this can be used to reduce peak demand by distributing energy consumption more evenly, and thus limit as far as possible the need for material-intensive transmission, distribution and storage infrastructure.[83]

Policy recommendations

Recommendation	Intended outcome	Requirements or enablers
12. Target and achieve whole-system energy demand reduction, in line with the 15% reduction target introduced as part of the net zero strategy. **For**: DESNZ, OFGEM, NESO.	Reducing energy demand can significantly reduce the requirements – in terms of materials, energy and cost – of building the generation, storage and transmission infrastructure required to decarbonise. This would therefore reduce the scale of critical material dependency for those materials that are used in energy infrastructure, reduce the risk of a disruptive supply crisis, and reduce the environmental cost of the materials needed – including those materials not designated critical such as copper.	Whole-system energy demand reduction would be enabled both by addressing the most significant sources of energy waste in our present system, and establishing broader mechanisms and incentives for reducing demand.
13. Reduce peak energy demand, including demand via demand-side response mechanisms.[90] **For**: DESNZ, OFGEM, NESO.	Energy system requirements are particularly driven by the peak demands on the system, so reducing peak demand would have particular impact on reducing the cost and critical material dependency of energy system transformation.	Important enablers for the implementation of demand response include: – Implementation of the Energy Data Taskforce recommendations[91] – The development of economic and regulatory structures that enable demand response. – The appointment of a Flexibility Commissioner, similar to the Electricity Networks Commissioner, and setting national targets for flexibility. – The development of appropriate consumer protection and incentives for participating in energy efficiency and demand response.

Demand response measures can include off-peak energy rebates, which incentivise users to consume energy during off-peak times.[84] To implement such measures, smart grid technology[85] such as smart charging and smart heating would play a key role by enabling users to reduce their peak demand by providing time- and location-specific data for energy systems operators to manage the system efficiently and understand energy-user behaviour.[86] Vehicle-to-grid (V2G) technologies, for example, enable both flexible vehicle charging at times of low electricity demand and drawing on the batteries of EVs connected to the wider electricity system to the grid at times of high demand. By using one battery in a dual role as grid storage and vehicle power, V2G technology could play a role in reducing the standalone battery requirements across the next decades.[87]

Policymakers need to support the development of greater demand-side response to reduce the overall size of the electricity system, including the number of standalone batteries, and thus the critical materials required across the system. There are some notable international successes to learn from, such as in South Korea where a pilot programme was launched in December 2022 allowing smart appliances to automatically respond to demand reduction requests instead of consumers' manual entries, resulting in significant energy savings.[88] In 2022, the European Union also approved its own action plan for digitalising the energy system, which includes requirements and procedures for data access for demand response.[89]

4.5 The digital system

Digital infrastructure is increasing at a rapid pace – internet traffic is growing consistently, companies and nation states are releasing digital strategies, and computationally intensive services such as artificial intelligence could rapidly accelerate this demand even further, in a context where energy infrastructure is increasingly a limiting factor for UK infrastructure development. As the development and adoption of digital technologies increases, so too does demand for critical materials.

Some of this demand is from large-scale infrastructure, such as data centres – whose capacity grew by a factor of 25 between 2010–2018.[92] Data centres require a significant volume of critical materials, such as: platinum (in the media alloy of hard disc drives (HDDs)[93]), silicon (in cabinet for hardware, software and IT systems), copper (for cabling and switch gear), tantalum, and rare earth elements.[94] Data centres are also very energy intensive, require large amounts of water for cooling, and can generate high rates of waste at end of life. In a 2020 survey of 400 data centre managers and IT practitioners globally, only 54% of the respondents reported that they have a decommissioning and reuse policy and that they closely follow it (larger companies reported higher rates, at 77%).[95]

Much of the digital infrastructure that is projected to exist over the coming years is yet to be built, meaning that early policy choices and planning can be highly influential on the sustainability and critical material demand of digital systems. Currently there is little data and evidence with which to make informed planning decisions.

Those policies that do exist – such as the EU 2024 regulations establishing a common rating scheme for data centres,[96] – focus on energy efficiency standards and do not include critical material use and sustainability considerations. Energy efficiencies do not always align with material sustainability. For example, there is a trade-off to be made between resource efficiency and energy efficiency, when considering how often to replace the servers in a data centre. Energy efficiency encourages servers to be replaced as often as possible with the newest technology, as newer technology can store more data and increase energy efficiency. However, replacing older servers and components while they are still functional results in more e-waste and poor material sustainability.[97] Energy efficiency alone without considering material sustainability is therefore not an appropriate overriding goal for sustainability in this case, and could encourage material waste.

Sustainability standards that include material sustainability and the certification of data centres against these standards are therefore urgently needed as a foundation for understanding and evaluating the material composition and demands of digital infrastructure. Sponsoring standard production via the British Standards Institute can be done by industry, or directly by government. Data centres are a source of significant new demand for energy and materials and their growth will also need to be factored into the planning of the wider electricity system, which we advocate should incorporate critical material analysis.

Quantum technologies are another source of materials demand. This emerging area of technology has a wide spectrum of current and potential applications across sectors including finance, health, space, telecommunications, and defence. There are expected to scale-up rapidly in the coming decade with the UK and other countries dedicating considerable investment into the growth of the quantum sector. As this sector scales-up, so too will its critical material requirements. Quantum technologies require several different critical materials for a variety of uses, such as in semiconductors, supercomputers, cryogenics and photonics. For example, gallium (in the form of gallium arsenide) is used for making lasers for wavelengths in atom-based quantum devices, as well as single and entangled photon emitters from quantum dots. Given the expected increase in demand from this sector, it is important that critical material requirements are considered in strategic decision-making on infrastructure investment in support of the ambition for quantum technology in the UK.[98]

Policy recommendations

Recommendation	Intended outcome	Requirements or enablers
14. Government should review and consider policy options for minimising material demands of future digital systems, including through strategic planning and sustainability certification, with a focus on critical material consumption and e-waste management from data centres. This should be part of the foundations of a wider approach to managing the diverse environmental and energy-use impacts of digital infrastructure. **For**: DESNZ, DSIT, DEFRA.	Clarity is gained on the current and expected material costs and dependencies of digital infrastructure in the UK, allowing strategic policy decisions to be made which achieve the desired social and economic aims for digital infrastructure while minimising critical material requirements, energy use and other environmental impacts. Data centres for digital services are built, with the lowest possible carbon and material costs for their instalment, operation and the end-of-life of their equipment. Data centres are considered as part of a wider planning system, and are located optimally to create co-benefits with wider energy infrastructure.	Data gathering on material use in the data sector and a data-sharing approach that ultimately includes full value-chain sustainability data for the materials used, such as through material passporting. Agreed sustainability standards, certification approaches and best practices for data centres, including resource efficiency and end-of-life, as well as monitoring and enforcement mechanisms.
15. Commit to implementing the ban on single-use vapes in England proposed in January 2024 but not implemented prior to the July 2024 general election, and consider policy options for evaluating and monitoring new and existing products that may warrant similar prohibition due to inclusion of disposable batteries without appropriate end-of-life planning. **For**: DEFRA.	Reduced consumption of critical material resources, reduced chemical pollution and environmental harm from improper disposal, and greater availability of recycled materials where this encourages recycling of small electronic devices. Designers and manufacturers are incentivised to develop products that do not lead to disposal of batteries.	Powers available under the Environmental Protection Act 1990. Greater market surveillance and enforcement capacity may be required to review other opportunities to limit critical material consumption and environmental harm through targeted prohibition of disposable digital devices.

Electronics – both personal and those used by industry – such as computer servers, mobile phones, laptops or games consoles – and devices containing lithium-ion batteries also form a significant source of demand. For example, in 2017 over 70% of indium production was used for liquid crystal displays (LCDs),[99] and continues to be used in organic light emitting diode (OLED) displays, which form the screens of most modern mobile phones.[100] This sector is known for its high waste: globally, 62 million tonnes of e-waste was generated in 2022, and only 22% of that waste was formally recycled, with the UK ranking second globally for the highest e-waste per capita.[101] This is due to rapid advancement and adoption of new technologies (and subsequent rapid obsolescence of old technologies), which results in high turnover and consumption.[102] This is compounded by low rates of recycling, with much of the waste being lost to household or commercial mixed waste and residual waste streams meaning that critical materials are not recovered and are lost from the economy.[103] Specific policy choices to reduce the demand from this area can include limiting the sales of single-use items with high material intensities, such as the ban on disposable e-cigarettes in England proposed in January 2024. This has not been implemented at time of writing due to not being taken forwards before the July 2024 general election. Implementing the ban on single-use vapes should therefore be a priority action for the current government (see recommendation 15), and should be the starting point for further disincentivisation of the production and sale of disposable electronic devices that cause environmental harm and are without effective and sustainable end-of-life plans. Policy recommendations surrounding improvements in the reuse and recyclability of e-waste are discussed in detail in Section 6.2.4, and Section 6.4 discusses changes to design practices and legislation to increase material sustainability of products.

4.6 Managing system-wide needs for critical materials

Having considered energy, transport and digital system planning individually, these must also be recognised as interdependent systems that would benefit from some degree of integrated planning. As with other factors that must be considered in system planning, including cost, land use and resilience, optimising each of these systems individually for critical material resource efficiency may not produce the most efficient infrastructure system-of-systems.

While the focus here has primarily been sources of demand from new energy, transport and digital technologies and infrastructure, these are far from the only demands for critical materials. Many significant demands lie elsewhere in the economy, including some high priority sectors such as pharmaceuticals and medical technologies. For example, neodymium is used in solid state medical lasers and cobalt is a primary component in total knee replacements.[104] Therefore, when considering overall demand management across different sources and sectors, it is essential to take a cross-system view of all sources of demand and to embed demand-reduction strategies appropriately.

In the event of a supply shortage of particular materials, a large range of sectors and industries would be adversely impacted. The resource efficiency measures and ambition discussed throughout this report could help prevent such eventualities and provide resilience when supply shortages do occur. Whether in energy, transport or elsewhere, these strategies can only be effective if implemented in the early stages of infrastructure and technology planning. A proactive approach to embedding these critical material resource efficiency strategies early is therefore required. The UK government's approach to managing different shortages should be considered in advance, and in relation to other crisis preparedness planning such as where a likely emergency response, for example vaccine production, is dependent on specific critical materials. Our ability to do this would be greatly enhanced by the collection of data such as described in recommendations 4 and 11.

> Whether in energy, transport or elsewhere, these strategies can only be effective if implemented in the early stages of infrastructure and technology planning. A proactive approach to embedding these critical material resource efficiency strategies early is therefore required

5. Case study: analysis of the effects of demand-side efficiency measures on critical material demands from the UK battery electric vehicle sector

Analysis was conducted by the Royal Academy of Engineering with data and support from Rho Motion, with input from several experts including lead reviewer Professor Paul Shearing FREng. More details of this analysis are available in the separate Methodology supplement.

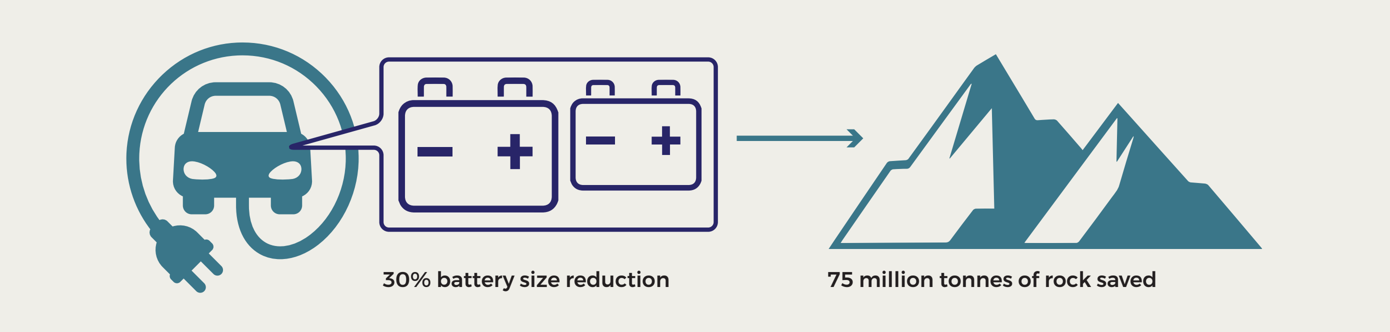


Figure 13 | Illustration of the scale of demand reduction in lithium rock mining that could be achieved through design changes and demand shifts.

- **Without a change in design and policy choices, supplying the UK with EVs would require an estimated 268,000 tonnes of lithium – equivalent to 438,000,000 tonnes of rock mining, based on industry sales projections. This amount of rock would fill Wembley Stadium 40 times, or fill 1 million double-decker buses.[105]**
- **The following analysis illustrates the scale of demand reduction that could be achieved via design changes or shifts in demand in the UK EV sector over the coming decades. It finds that for the UK market alone, a 30% reduction in vehicle battery sizes in the larger EVs by 2040 would save 46,000 tonnes of lithium, the equivalent of 75,000,000 (75 million) tonnes of rock being mined for lithium – a 17% reduction in requirements overall.**
- **These savings are significant, and there are numerous policy levers that could enable them, such as the development of an extensive UK EV battery charging network to reduce battery requirements. However, despite their impact, interventions reducing the impact of EVs through design and demand changes do not do enough to reduce the critical material cost of EVs. Upstream choices around mobility shift are needed as a policy priority.**

Decarbonising the UK's transport sector is essential to meeting net zero targets. As discussed in Section 4.2, EVs have a significant part to play in this transition but are also a highly materially intensive option, representing in many cases the largest single source of demand for lithium (see Figure 3, in Section 3.3., Figure 5 in Section 3.4.1, and Figure 9 in Section 4.1). The expansion of the lithium use in vehicle production is a significant driver of the expansion of lithium extraction and the resulting harms to environments and communities in South America and elsewhere (discussed in Section 3.4.1).[106] Global lithium production tripled between 2010 and 2020, and some projections forecast an 18–20 fold increase by 2050 if current battery chemistry trends continue.[107]

Unless sustainable extraction processes can be adopted rapidly and in all new lithium extraction operations, the environmental consequences of the forecast demand from EVs alone will be severe. Upstream measures such as mobility shift, which reduce the overall number of cars in favour of a more extensive public transport system, should be the priority for transport policy. However, for those EVs that do form part of the UK transport system, it is important to consider their critical material demand and target reduction in it using the levers we will explore. This is necessary alongside ensuring that there is transformational change towards the codification and implementation of sustainable mining practices for lithium.

The following analysis presents a projection (see box) of critical material demand from 2018–2040, based on the current EV sales and future forecasts used by the automotive sector. This is the 'baseline scenario' and represents the future demand for EVs given current policies and market conditions. This baseline is compared to two intervention scenarios:

1. **Reduction in battery sizes**: shifts in demand for smaller vehicles, acceptance of shorter ranges, and design efficiencies result in a 30% smaller battery size.
2. **Alternative battery chemistry**: 30% of the EV batteries are changed from a lithium-ion battery to a sodium-ion battery.

The projections presented in this analysis are forecasts based on trends in EV sales, as provided by Rho Motion Ltd. These projections are intended to illustrate the scale of demand, and the potential reductions that can be made through design changes and demand shift in UK EVs. Detailed methodologies and model assumptions can be found in the Methodology supplement, available online at nepc.raeng.org.uk/critical-materials.

5.1 The projected cumulative critical material demand from UK EVs is high

The projected cumulative critical material demand of UK EVs sold between 2018–2040 totals over 250,000 tonnes,[108] based on industry sales forecasts. This includes an estimated 268,000 tonnes of lithium – or 438,000,000 tonnes of rock mining. This cumulative lithium demand for the UK alone is equivalent to more than 3.5 times the global lithium demand in 2020.[109]

> Unless sustainable extraction processes can be adopted rapidly and in all new lithium extraction operations, the environmental consequences of the forecast demand from EVs alone will be severe

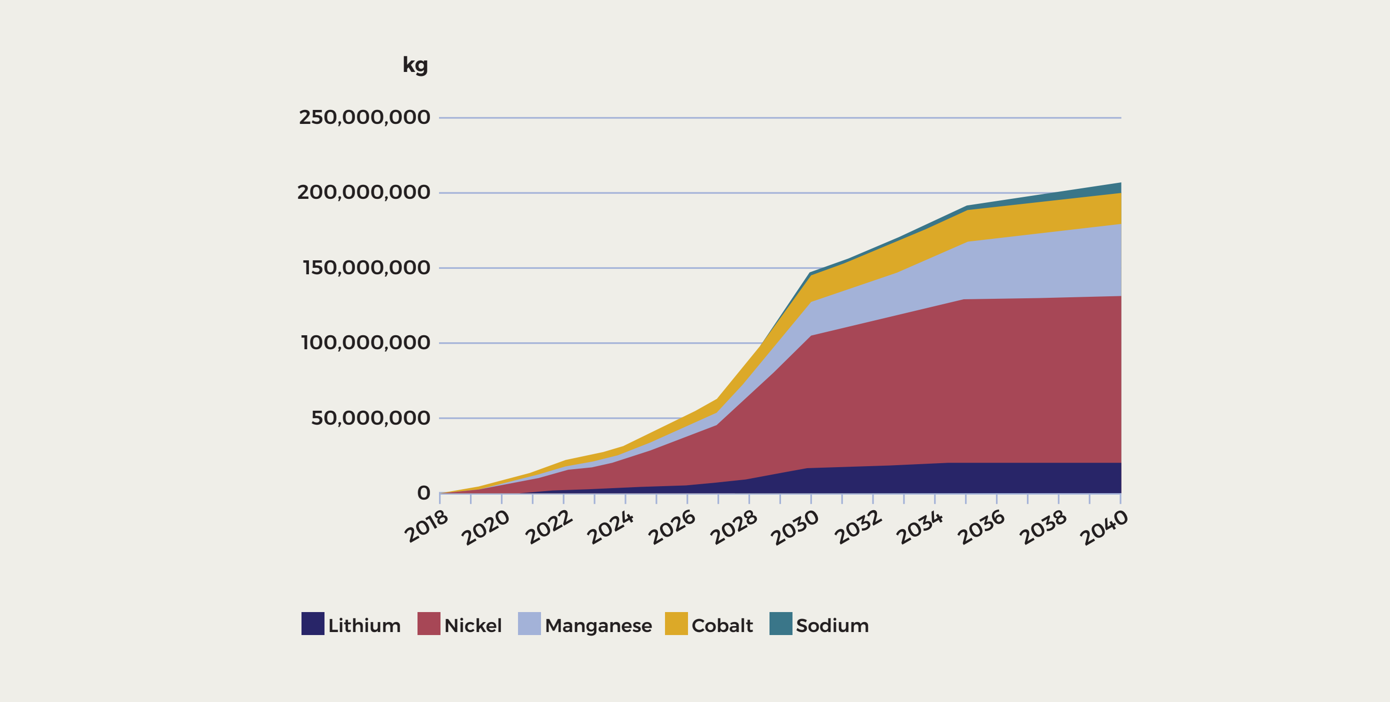


Figure 14 | Projected annual material usage through passenger car and light-duty battery EVs in the UK (baseline scenario).

Element	Cumulative material use 2018–40, baseline scenario (kg)	Rock mining (kg)
Li	268,119,390	438,107,083,260
Ni	1,392,457,959	348,114,489,750
Mn	493,632,569	Unknown
Co	266,649,895	229,052,259,805

Table 2 | Rock mining required to meet these projected demands, using rock-to-metal ratios from Nassar (et al), 2023. Rock-to-metal ratios of the rare earth elements, Journal of Cleaner Production.

5.2 Intervention: reduction in battery size

The larger the battery size, the higher the critical material demand of an EV.

This analysis projects that a **30% reduction in vehicle battery sizes** in the larger EVs by 2040, from the UK market alone, **would cumulatively save 46,000 tonnes of lithium and therefore 75,000,000 tonnes of rock being mined** for lithium by 2040 – nearly 19 Wembley Stadium's worth.[110] This reduction in critical material demand would significantly improve the resilience of the future UK transport system, and reduce its environmental cost.

Numerous policy levers could be utilised to encourage such a trend. However, the size of an EV battery impacts the range and performance

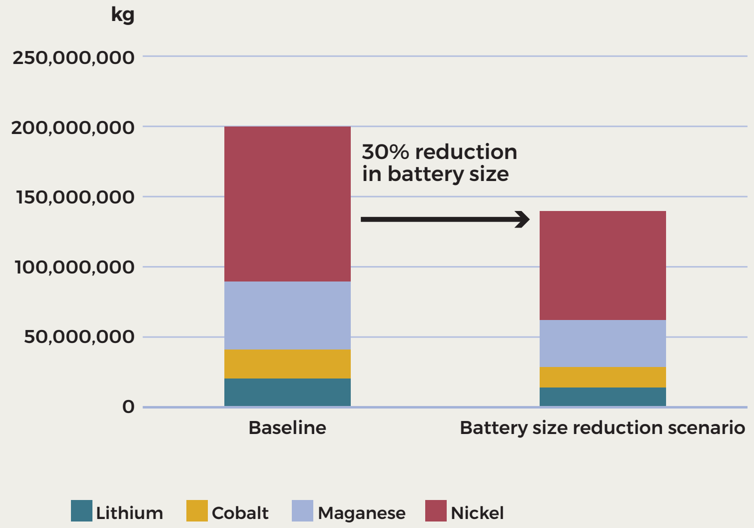


Figure 15 | Impact of a reduction in battery size on cumulative critical material demands arising from EVs projected to be sold in the UK 2018–2040.

of the vehicle – with a larger battery providing more range and higher performance. Therefore, policies encouraging battery-size reduction will need to account for the trade-off with range and performance.

Concerns regarding vehicle range could be mitigated by upscaling and improving the UK's EV battery charging network, thereby increasing the acceptability of smaller battery sizes.[111]

Around half of the projected material savings from the reduction in battery size in this scenario comes from the largest vehicle class examined, despite them only making up less than a third of the sales during that period This indicates that **interventions targeted at the largest electric vehicles** will produce significantly greater benefits to the environment, as well as to resilience and resource efficiency. Regulation and technological innovation will have greatest impact if directed towards this class of vehicle.

Upstream mobility policies are needed to reduce demand further

While the interventions explored in this analysis could make a significant impact on UK critical material demand, there is still an enormous amount of demand left from UK EVs. This remaining demand still represents a significant majority of the demand for critical materials such as lithium and cobalt, which are strategically valuable across a wide range of critical capabilities.

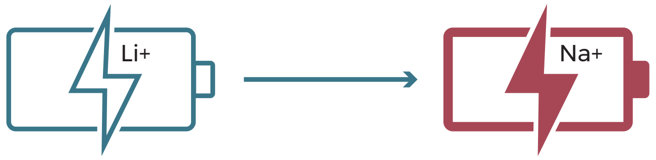
Upstream policy interventions around wider mobility shift (from cars to buses, bikes or electric scooters) will therefore be needed in tandem with policies enabling interventions such as battery-size reduction or alternative battery chemistries, which do not look to reduce the number of cars on the road, as discussed in Section 4.2 of this report.

These upstream interventions are essential to the future of UK transport and the management of critical material demand.

Due to the abundance of sodium, sodium-ion batteries have the potential to be cheaper than lithium-ion batteries, and can utilise existing lithium-ion battery manufacturing equipment, which may provide useful flexibility to increase our resilience to shortages of critical materials used in lithium-ion batteries

5.3 Intervention: alternative battery chemistry

There are a wide range of technologies available to power EVs, many of which are in various stages of research and development, such as sodium-ion batteries, solid-state batteries or hydrogen fuel cells. Some are projected to hit the EV market soon, such as sodium-ion batteries, and some are already in use, such as lithium-ion batteries, which have dominated the market for the past decade. Critical material requirements vary among these types of technologies, and for some are not necessarily required at all. This analysis has focused on sodium-ion battery technology as a replacement for lithium-ion, as sodium-ion is a battery type that is used in EVs at significant rates, especially in China.



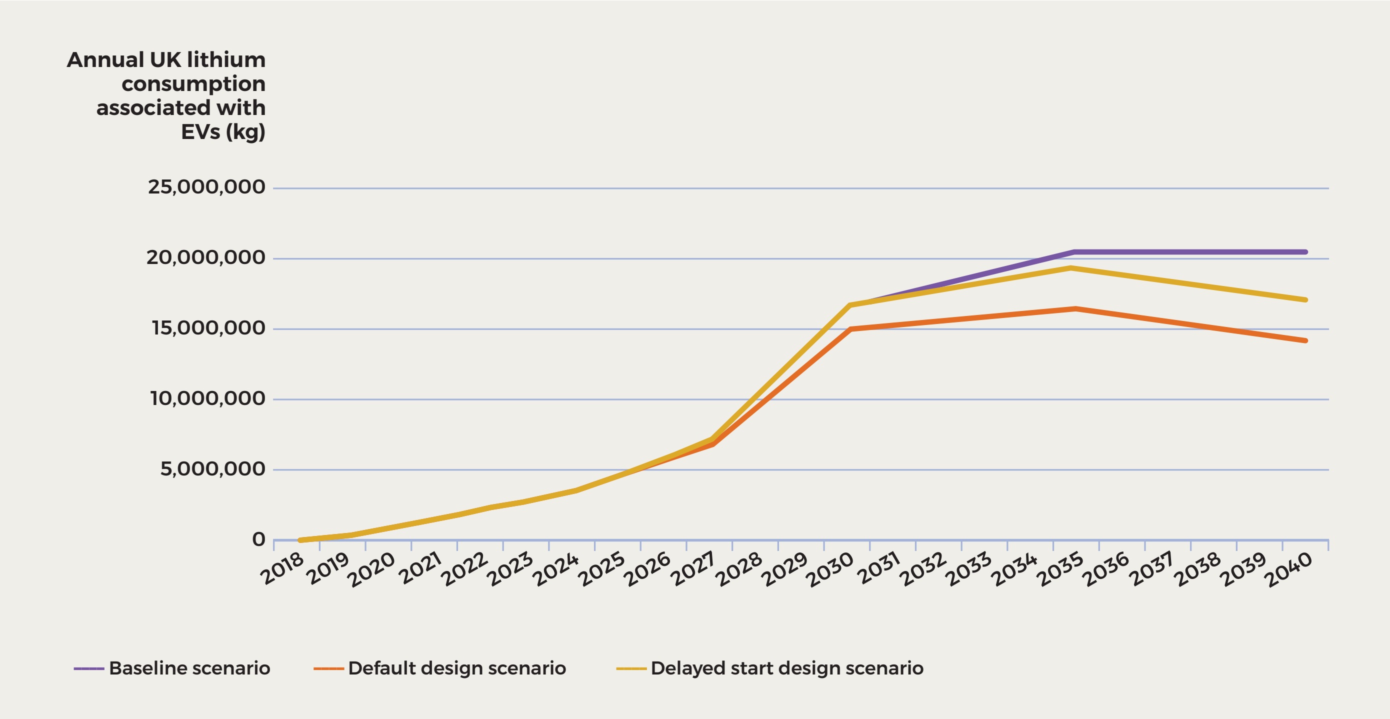
This analysis found that replacing 30% of all the UK EV market lithium-ion batteries with sodium-ion batteries by 2040 would result in a **17% relative reduction in cumulative lithium demand (46,000 tonnes**). In 2023 Swedish manufacturer Northvolt announced a "critical material-free" sodium-ion battery, which can be made using "locally sourced materials".[112] Other innovations are being explored that utilise abundant materials such as the use of waste plastics[113] or recycled permanent magnets.[114] Some current designs for sodium-ion batteries use larger amounts of at least one other critical material than their lithium-ion counterparts – such as manganese or nickel. It is currently unclear which battery chemistries will find market purchase, and critical material-free sodium-ion batteries have yet to be demonstrated at scale in EVs.

Due to the abundance of sodium, sodium-ion batteries have the potential to be cheaper than lithium-ion batteries, and can utilise existing lithium-ion battery manufacturing equipment, which may provide useful flexibility to increase our resilience to shortages of critical materials used in lithium-ion batteries, including nickel, manganese and cobalt. Promoting the development and use of sustainably sourced batteries in the automotive sector and ensuring that battery designs move away from critical material usage are important goals for policymakers, engineers and innovators.

Despite their advantages, sodium-ion batteries have a lower energy density compared to lithium-ion, meaning they typically have a lower peak power and range. Thus, they are currently less suitable for high performance EVs. Consumer demand-shift toward sodium-ion batteries could therefore benefit from shifts in consumer preferences away from vehicles that provide a performance beyond their transport needs.

5.4 Alternative chemistries and end of life

Innovation in battery chemistries must consider the infrastructure capabilities required to safely disassemble and recycle the batteries at end of life. If the UK utilises a range of battery chemistries, it is significantly beneficial for all battery types to be processed using the same recycling infrastructure. For example, both lithium-ion batteries and sodium-ion batteries can be recycled using the same equipment and recycling processes. However, it is worth noting that different batteries must be inputted in separate batches, due to the hazardous combinations of chemicals involved. To encourage recycling, UK industrial strategies should consider prioritising new chemistries and battery types that can utilise the same recycling infrastructure and equipment as existing lithium-ion recycling centres.



■ **Figure 16 | Impact of delayed start on projected UK lithium demand from EVs – annual demand 2018–2040.**

5.5 Starting early is crucial to realise these benefits

This analysis found that a delayed start significantly reduced the effectiveness of demand reduction, due to the long timescales inherent in innovation and production. Assuming the impact of policy changes or new design mechanisms would take time to accrue, starting seven years later would reduce the total benefit by **two thirds**, over the period analysed.

6. Design and design skills

6.1 Product and built asset design for critical material demand reduction

Any technology or built asset or system is a product of engineering, which means it is a product of a process of engineering design. The demand for critical materials in any product, asset or system is therefore also a product of a set of design decisions made from high-level concept and system design and specification, through to detailed design of individual components. Much more can be done to value and prioritise material efficiency and material demand (design for sustainability) throughout the design process. Currently, many material selections are made on cost and the material's properties (such as strength, reactivity, and electrical conductivity) exclusively. Furthermore, many critical materials are used in low concentrations, within intricate components, or in increasingly complex composites and alloys, making them difficult and expensive to recover and reuse.[115]

Reducing critical material demand can be achieved through a wide range of alternative decisions and approaches within the design process. These include reducing the amount of a critical material, substituting it out entirely, extending its useful life by increasing product durability, and extending the scope and ease of reuse. Finally, much more can be done to design in the recoverability of materials at end-of-life.

There are many interventions in material production and product design that may help address these issues (see figure 17). This section will provide an overview of sustainable design, and explore common enablers such as skills, innovation policies, and engineering standards. Different design approaches to resource efficiency will apply within different contexts, for example, in some instances substitution of alternative materials in place of critical materials may be possible. Where substitution is not possible, high reusability might be prioritised, and where there is limited potential for reuse this might mean that designing for a longer lifespan is optimal. In general, it is important to refer to the Waste Hierarchy to understand priorities for resource efficiency. This hierarchy (shown in figure 18) recommends, in order of preference, prevention above reuse, followed by recycling, recovery and then disposal.

Sustainable design frameworks, and the interventions they lead to, are not being adopted at sufficient scale within industry or being embraced as tools for material demand reduction. This is despite such frameworks providing greater resilience to supply shocks. While policymakers in the US and EU are beginning to explore regulatory approaches to encourage or mandate their use in specific sectors, the UK is lacking a unified approach. A 2023 DESNZ consultation on introducing incentives for sustainable design into Contracts for Difference Auctions[116] marks a positive direction of travel for embedding such frameworks in the electricity generation sector. However, Contracts for Difference Auctions occur near the end of the development process for offshore wind projects, and at this stage many of

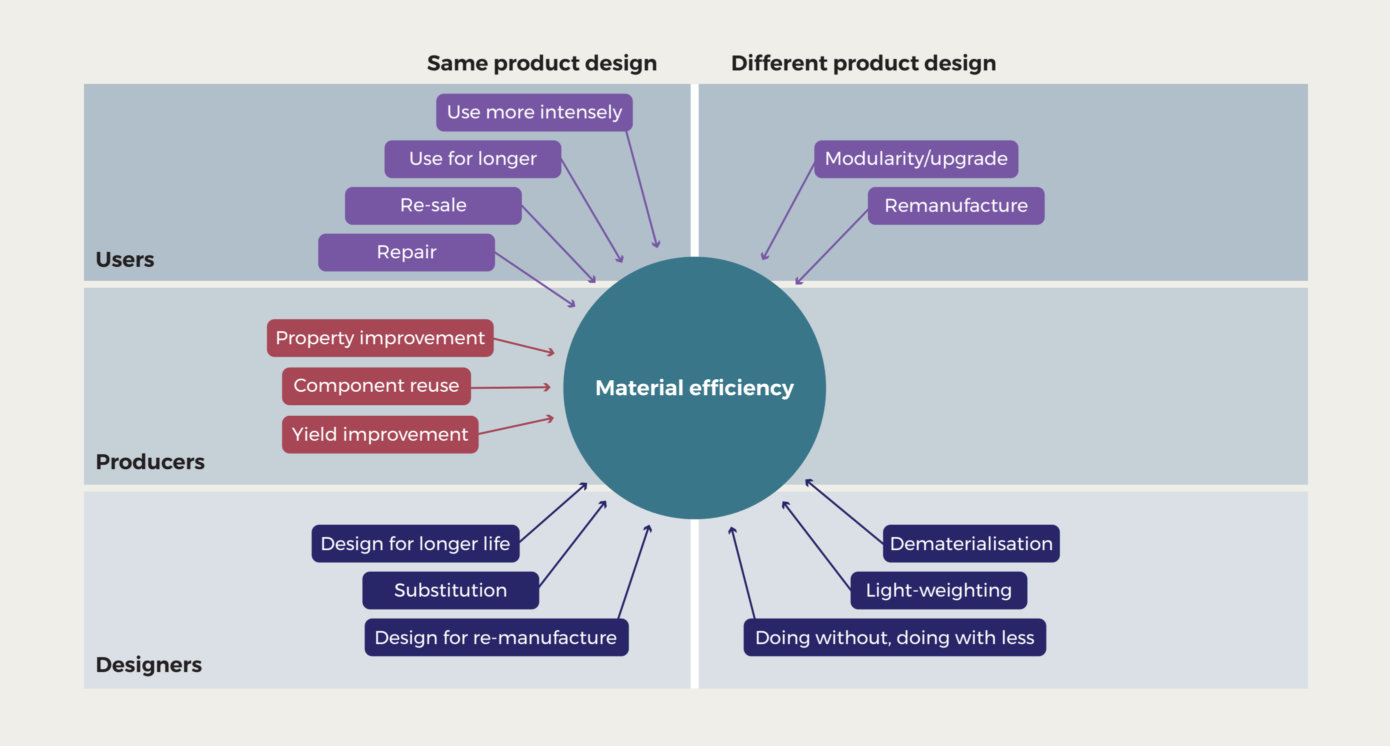


Figure 17 | Range of design interventions that contribute to material efficiency. Adapted from Allwood, J. (et al), 2011. Material efficiency: A white paper, Resources, Conservation and Recycling.

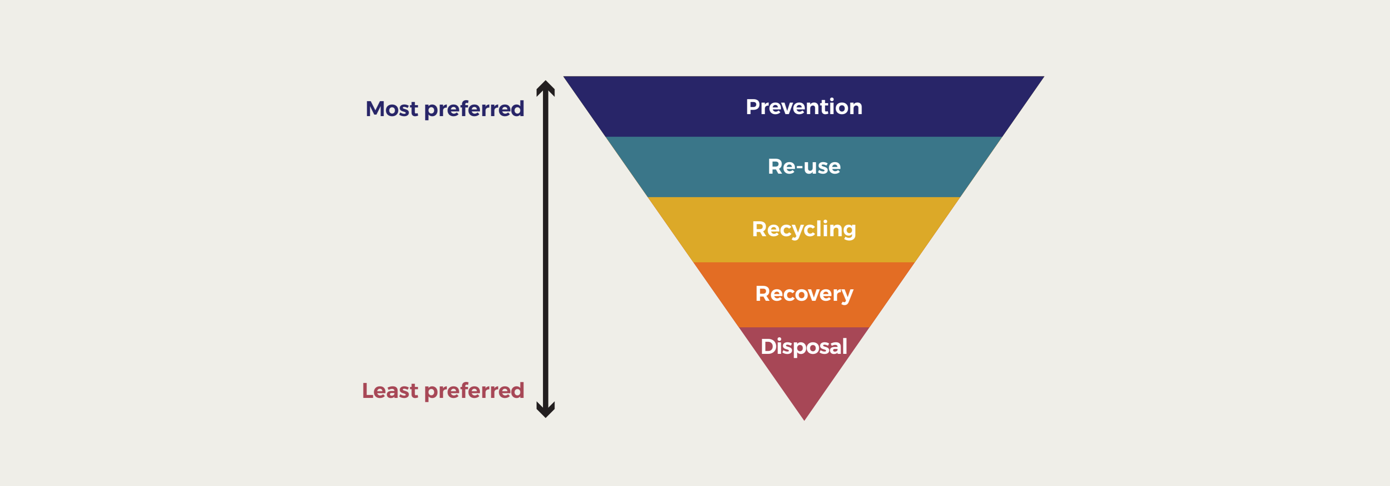


Figure 18 | The Waste Hierarchy. Adapted from: What is the Waste Hierarchy?, [Accessed 16/08/24].

> While policymakers in the US and EU are beginning to explore regulatory approaches to encourage or mandate their use in specific sectors, the UK is lacking a unified approach

the design decisions impacting critical material use have already occurred. Further improvements in sustainable design may therefore be unlocked by incentivising resource efficient design and design-for-reuse at earlier stages in the process of development of offshore wind projects.

As we explore further in recommendations 18–20, both industry and government should consider their role in enabling or requiring the use of sustainable design frameworks for products designed or manufactured in the UK. This should include supporting both pioneering innovation, and developing the design skills and cultures needed to embed design for material sustainability. However, it is important to consider the limitations of the UK's ability to influence, given that many components and products are imported, meaning the UK does not have direct influence on their design. The UK should therefore collaborate with international partners to advance the sustainability embedded in engineering and product standards, encouraging resource sustainability throughout the supply chain.

6.2 Design interventions for critical material resource demand reduction

6.2.1 Material substitution

Material substitution can allow a critical material to be replaced with a more readily available alternative with similar properties. While replaceability is often a factor in the assessment of material criticality, it is a difficult thing to predict and quantify. There are many potential options for substitution of critical materials through innovation in design and materials science. Examples include:

- Magnesium, a critical material, which is a common additive to steel in uses where lightness of weight is an important consideration, such as in aircraft components. Recent research has shown that (highly abundant) calcium can be used as a substitute to achieve the same outcomes. However, this is receiving little uptake, due to insufficient incentive for industry to establish engineering standards and to develop the safety case required.
- Perovskite, is under development as a replacement for silicon in the next generation of solar cells (in particular, replacing crystalline silicon, which has dominated the recent solar PV market – making up 95% of new solar PVs in 2020[118]).
- Sodium-ion batteries have the potential to reduce lithium dependence. These can be produced using the same manufacturing equipment as lithium-ion batteries, but primarily rely on plentifully available sodium instead of lithium. However, sodium-ion batteries have lower energy efficiency and some versions also use other critical materials such as nickel and manganese. Sodium-ion batteries aptly demonstrate the complexity of pursuing material substitutions and the continued need for innovation (See recommendation 16).

While some critical material substitutions or reduction do not have significant performance trade-offs, many will. Critical materials are often included due to their specific properties to deliver a greater output for lower cost. However purely cost-based design does not reflect the system-level risks associated with critical material dependence, or the social and environmental harms associated with them. Understanding how to value these aspects of material sustainability is a key challenge for the green finance sector, to enable appropriate valuation of material savings.

6.2.2 Material reduction

When the unique properties of a material do not allow for it to be designed out of a product, designers can look to reduce the amount of material in their product or asset. Significant critical material efficiencies have already occurred in the development of net zero technologies, such as the reduction of dysprosium from 3–6% to <1% in the permanent magnets of wind turbines, achieved through the optimisation of permanent magnet synchronous generator design.[119] Innovation is ongoing in the sector, such as the development of direct drive turbines that do not use rare earth elements and that reduce copper requirements, instead utilising ferrite magnets and aluminium coils.[120]

> Design for reuse extends the longevity of a product, asset or component beyond its initial lifecycle by allowing it to take on a second use in its existing form. This reduces the amount of primary sourced materials required for the next usage or application

6.2.3 Design for extended product life

Extending the lifespan of a product or asset reduces the number of replacements needed, therefore reducing overall critical material consumption. One approach designers can employ is designing for durability – this can refer to physical durability, to enable damage resistance, or, for consumer products, 'emotional durability', a term used to denote the longevity of a product's desirability or relevance to a user.[121]

Life extension can be especially significant for infrastructure assets; for example it is speculated that there is significant scope for extending the life of existing and new wind turbines as they come to their planned end of life. This can be achieved through strong maintenance procedures, replacing specific components that suffer wear (which itself can be enabled by design for ease of replacement and reparability, see below), and in rare cases replacing turbine components while re-using foundations. At a system level, life extension may sometimes be traded off against the benefits to generation capacity from replacing older and smaller turbines with modern designs which have higher power output. This may be particularly valuable when there is limited space for development or when existing foundations can be reused to speed deployment. This demonstrates the importance of assessing end-of-life options at both an individual asset and a system level.

Designing for modularity and repairability allows broken or obsolete components to be upgraded, self-repaired or replaced without needing to replace the entire asset or device.[122] This is an emerging niche approach among small manufacturers in smartphones and laptops such as those produced by Fairphone. Such modular devices are designed to enable users to disassemble, remove and repair or replace some modular parts by hand rather than replacing the entire product. Another example of modularity is seen in EVs in China, where batteries are designed to be removed and swapped out for fully charged batteries within minutes at charging stations. As the battery is one of the most expensive aspects of current EVs, this approach can reduce the upfront price of the vehicle and enable a 'battery-as-service' model of ownership where drivers pay for the charged battery as a monthly fee or as a pay-as-you-go service. This allows the battery to be separated from the vehicle. Facilities can then closely monitor the removed batteries for defects, and repair batteries early, extending their life, and thus extending the usage of the critical materials within them. However, under this model and for batteries and vehicles to be compatible, widespread standardisation is required across different models and brands of electric vehicles, which is difficult to achieve across consumer electric vehicles. This approach may, however, be more easily implemented in fleet vehicles such as taxis, buses and delivery vehicles, which would benefit from the short time period needed to swap batteries, allowing them to be constantly in use. Standardisation would also benefit the recycling process for EV batteries.[123]

6.2.4 Design for reuse

Design for reuse extends the longevity of a product, asset or component beyond its initial lifecycle by allowing it to take on a second use in its existing form. This reduces the amount of primary-sourced materials required for the next usage or application. For example, lithium-ion batteries from battery EVs have the potential for reuse as electricity storage in solar energy systems.[124] This reduces the total materials demand that would otherwise be needed to provide that energy storage, but such reuse often requires careful planning and design to ensure that the product being used is suitable for use in both or multiple contexts.

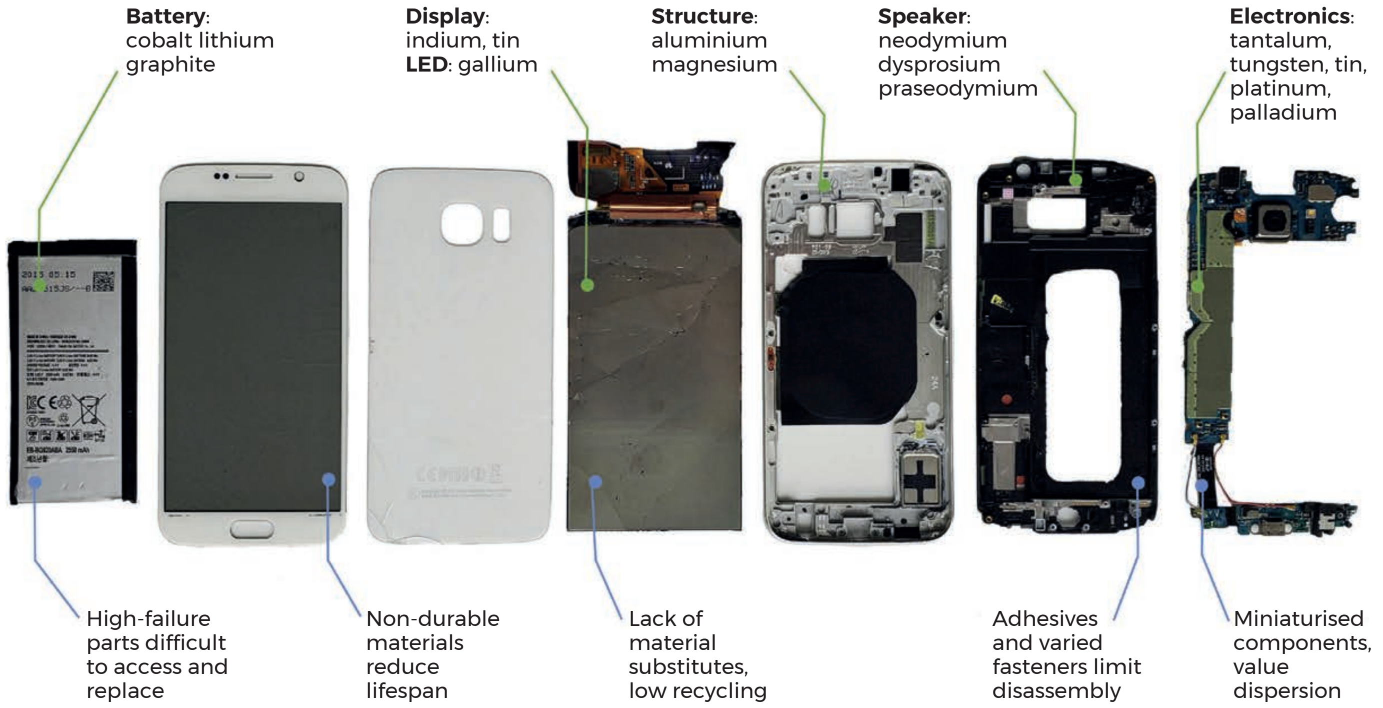


Figure 19 | Illustration of critical material use in a smartphone and the design challenges that limit recovery and remanufacture. Taken from: Babbit, C. W. (et al), 2021. The role of design in circular economy solutions for critical materials, One Earth.

6.2.5 Design for recovery and remanufacture

When products or assets containing critical materials are designed, disassembly at end-of-life is rarely considered.[125] This results in barriers and difficulties in the access, recovery and remanufacture of valuable materials or component parts. Challenges include complex material composites, lack of standardisation, dispersed and low concentrations of critical materials and a lack of labelling or information on the materials present.

Critical materials recovery from current products and assets is reliant on highly intricate and technical processes, which are often prohibitively expensive, and as a result, a significant amount of electronic waste is disposed of to landfill, despite containing valuable materials.

The difficulty of disassembly is a significant barrier to the recovery of critical materials from decommissioned wind turbines, characterised by both design decisions such as the use of epoxy glues which make magnet extraction difficult, as well as in terms of a lack of clear data on the contents and designs of the turbines coming to their end of life. Design for disassembly can help overcome such barriers and allow greater recovery of critical materials at end of life, by reducing time and cost of disassembly, and simplifying the recovery process.[126] These approaches should be applied as a priority within infrastructure procurement and deployment, and other large sources of demand such as vehicles.

6.2.6 Design research needs

While there are many examples of good practice relating to the above approaches, there are a great many materials where there is a limited evidence base for how to approach sustainable design. There are significant gaps in the research base especially related to critical materials and strategies such as substitution and life-extension. This can be addressed via further research and the promotion of best practice.

One initiative to support wider R&D in material substitution is the EU's Critical Raw Materials Innovation Network,[127] an integrated community of industry, academia and policy which looks to support innovation in material substitution for the EU.

Policy recommendation

Recommendation	Intended outcome	Requirements or enablers
16. Government should support facilities to develop and test alternatives to critical materials across a range of uses. An example of this support for research and development in material substitution would be to invest in sustainable battery technologies, and especially sodium-ion batteries, providing additional research funding and manufacturing/testing facilities, engineering standards, and connection to industry to ensure take-up. Investment should prioritise technologies that can utilise existing recycling infrastructure. This is discussed further in the case study analysis in Sections 5.3–5.4. **For**: UKRI, ARIA.	An accelerated pace of development of sodium-ion batteries and use by industries, including but not limited to the automotive sector, to displace lithium-ion and other battery types starting in contexts where the performance of sodium-ion batteries is most appropriate. This research is expected to avoid the use of critical minerals including lithium and cobalt while reducing the demand for nickel, as well as improvements such as better low temperature performance. This may eventually lead to the ability to produce batteries without the use of critical materials, entirely from abundant local materials and waste, with ample reuse and recycling options.	Research funding, engineering standards, skills, industry incentives to invest.

6.3 Research and standards for novel materials

New and innovative materials are vital to enabling the substitution of critical materials or achieving the same technological outcomes through alternative designs. While there can be performance or cost trade-offs associated with designing out critical materials, dedicated research and innovation can minimise or avoid these. Providing investment to research and development to encourage innovations in materials efficiency and substitution is also essential to new developments in sustainable design. In addition, economic incentives and disincentives are a key policy lever to the adoption of widespread sustainable design.[128]

The UK has a strong materials research base, however it is often difficult for new materials to be taken up by industry. More support is needed to remove the barriers to industrial uptake of new materials. For example, the substitution of magnesium for calcium in steelmaking described above has not yet seen take-up within steel manufacturing.

Common barriers include difficulty in scaling up manufacture or accessing funding,[129] delays in development of engineering standards and safety profiles for new materials, and reduced access to insurance. Standards development is currently driven by industry interest and need, and by historical experience for safety cases. More targeted and programmatic approaches to producing standards and safety cases for promising novel, sustainable materials could accelerate their uptake, allowing them to displace critical ones. For some emerging technologies, this could resemble 'innovation guardrails' which are less specific but more widely applicable.[130]

The process for developing standards at national and international levels could be used more strategically to accelerate the development of sustainable technologies and designs, including standards that enable repair, reuse, recycling or remanufacturing of goods. For example, while safety and standards are plentiful for lithium-ion batteries, a relative lack of standards for sodium-ion batteries increases the difficulty of overcoming technological 'lock-in'.

Policy recommendation

Recommendation	Intended outcome	Requirements or enablers
17. Government should work with BSI and relevant bodies to identify priority areas for the development of engineering standards, and directly sponsor the generation of standards, and safety cases and innovation guardrails for priority technologies such as sodium-ion batteries and battery recycling.[131] **For**: Net Zero Innovation Board, DESNZ, UKRI, BSI.	Accelerated deployment of key materials and technologies that displace critical material requirements, by removing barriers to their uptake. Critical material demands are thus reduced, improving resilience and sustainability.	A convening body able to bring together stakeholders from research, regulation, standards production, industry R&D and insurance to identify promising materials or technologies for displacing critical-material-dependent designs/technologies, and funding to fast-track their development and utilisation.

Enabling existing bodies to develop standards is likely to be especially effective at 'pulling through' new materials when linked to technology demonstration labs, where goods can be tested at the level of a small production line. Currently access to this form of testing is a bottleneck for many innovations. Some engineering sectors have seen significant success with centralised provision of such test areas, such as the Advanced Propulsion Centre and the energy- and decarbonisation-focused Flexis Demonstration Area in Port Talbot. There is significant scope for expansion of such models to target needs such as testing designs for circularity – including production, life extension and disassembly for recovery.

6.3.1 Case study: Standards for wind turbine material sustainability

Standards for wind turbines provide a basis for design, as well as addressing resource assessment and operation and maintenance. As such they are highly influential on the development of wind turbine technology.

The UK is the greatest contributor of technical experts for wind energy standardisation at the International Electrotechnical Commission (IEC), an influential global standards body. This includes the production of standards for through-life management and life extension of wind-power assets – an essential foundation for improving resource efficiency in this sector. Other National Standards Bodies, such as in Germany, have published standards for the sustainable dismantling, disassembly, recycling and recovery of turbines, though this has yet to be codified as an international standard.

Germany is an example of active innovation towards resource-efficient and circular-economy-enabling practices, using ideas that should be applied more widely. It is notable however that these are being produced part-way into a long-term increase in wind turbine deployment. As further explored in Section 7.2 of this report, there is an existing challenge arising from the wind turbines already deployed, which are not designed for life extension, nor for easy disassembly, with material recovery at end-of-life.

Great Britain will occupy the chair of IEC Technical Committee 88 from 2024–2030, covering wind energy generation technologies, providing an opportunity to increase the ambition of sustainable wind turbine technologies work and send a clear message on proactive international standards development.

6.4 Sustainable design frameworks

Often referred to as 'ecodesign' or 'sustainable design' frameworks, there are many frameworks and methodologies for integrating environmental sustainability into the design process. These vary from high-level principles to specific tools and decision-making guides for engineers and designers to inform material selection, among other design decisions. However, despite the abundance of good-practice processes, frameworks and tools available, their application is limited and inconsistent.[132]

Ecodesign frameworks range from software tools, checklists, or multi-step methodologies to broad overarching principles. Examples such as the Design Council's 'Systemic Design Approach',[133] and the Ellen MacArthur Foundation's 'Circular design: turning ambition into action'[134] take holistic systems and circular economy lenses to how design choices can impact the sustainability of a product or asset throughout its life cycle. More granular frameworks present multi-step processes, which specify methodologies for incorporating environmental sustainability into different stages of the design process. This can include tools used to guide product designers during the creation of a new design to improve its sustainability, such as parameter optimisation, tools for assessing the sustainability of existing designs, such as carbon-focused life cycle assessments, or tools that help to select the most sustainable design from a range of options, such as multiple-criteria decision analysis.[135] These tools are continuously being updated and are evolving to reflect current best practice and this evolution is increasingly taking into account environmental, social and economic sustainability of materials.[136] Despite the rapid progress however, a lack of accurate and timely data from materials supply chains and standardised assessment approaches remains a substantial barrier.

Sustainable design principles are enforced to varying degrees across different sectors. For example, generally poor material sustainability practices remain common in UK construction. While standards such as the Building Research Establishment Environmental Assessment Method (BREEAM), and the Circular Economy Statements required for building projects by the Greater London Authority[137] provide sector-specific frameworks for sustainable design in the built environment and construction industry, challenges remain. Improvements are needed in their scope, ambition and implementation, as well as in the lack of site-specific consideration for sustainable solutions.[138] The sector has shown interest in transformational improvement in this regard, notably through cross sectoral collaborations on circular economy in the built environment.

Materials exchanges are a structure for identifying current or upcoming opportunities from waste streams and matching them with appropriate customers. There is significant potential to accelerate the role of materials exchanges in creating markets for reused materials and reducing barriers such as logistics of storage and transport. These are being explored most significantly in the built environment sector, and this model could be extended to critical materials.

Also of note is that UK government has recently consulted on the inclusion of sustainability criteria in the auction process for companies wishing to construct offshore wind farms, which would apply a sector-specific ecodesign framework at an appropriate moment in infrastructure planning. This is a positive direction of travel, though the policy specifics will require further development to achieve meaningful impact on material flows.

These examples provide precedents on how policies could impact critical material dependence alongside other material sustainability concerns such as embodied carbon. However, in many common products containing critical materials – such as in consumer electronics,[139] the fashion industry,[140] or the automotive industry[141] – current application of ecodesign is limited and ad-hoc, being led by innovative businesses in the absence of commonly applied standards or policy incentives.[142]

The barriers to ecodesign implementation vary in context, but often include a lack of data, skills, standards and economic or policy incentives. Where standards or incentives are introduced, appropriate systems of enforcement are crucial.

A lack of commonly agreed and enforced standards has led to pervasive 'greenwashing', where companies are able to make misleading, unprovable or false claims relating to sustainability of product designs, which contribute to building a wider scepticism towards truly sustainable products and potentially diluting the additional environmental values that lead consumers to support good environmental practice.[143] The provision of independently verified information regarding the sustainability of a product, such as material use and repairability, via more consistent ecolabelling, has the potential to ensure that consumer demands better incentivise genuine good practice.

6.5 Policy and regulatory enablers

There are several ways in which policy can enable the wide adoption of sustainable design practices. The UK has already made steps to embed Extended Producer Responsibility (EPR), right to repair and ecolabelling within legislation, through 'The ecodesign for energy-related products and energy information regulations 2021'.[144] However, these regulations only apply to a subset of energy-consuming products, namely: welding equipment; refrigeration appliances; household dishwashers; washing machines and washer-dryers; electric motors; and electronic displays. They do not apply to other categories of physical goods. Additionally, while the regulations feature some aspects of right to repair- by mandating that these products must offer repair manuals and spare parts that can be attached by commonly available tools – upgradability, durability, and design for disassembly and material recovery are not included.

EPR has also been used effectively across other sectors, such as in the End of Life Vehicle (ELV) Directive (2000/53/EC), which put regulations in place for manufacturers, including marking plastic and rubber parts for recovery, reuse and recyclability, providing dismantling information, and requiring takeback of their products for reuse, recycling or remanufacture (either directly or via collective schemes) at no cost to the consumer.[145]

EU Ecodesign for Sustainable Products Regulations

What does it replace? This will replace the current Ecodesign Directive 2009/125/EC

What does it apply to? It will enable the setting of performance and information requirements for almost all categories of physical goods placed on the EU market, whether produced inside or outside the EU.

Legislation: The framework will allow for the setting of a wide range of requirements, including on:

- product durability, reusability, upgradability and reparability
- presence of substances that inhibit circularity
- energy and resource efficiency
- recycled content
- remanufacturing and recycling
- carbon and environmental footprints
- information requirements, including a **Digital Product Passport**

Digital Product Passport
This is set to provide information about products' environmental sustainability, including attributes such as durability and reparability, recycled content or availability of spare parts of a product.
The digital passport is intended to help consumers and businesses make informed choices when purchasing products, facilitate repairs and recycling, improve transparency about a products' whole life-cycle impacts on the environment, and help public authorities to better perform checks and controls.

Policy recommendations

Recommendation	Intended outcome	Requirements or enablers
18. Expand the ecodesign for energy-related products and energy information regulations 2021[149] to include material efficiency alongside energy efficiency in the regulations and standards for products currently covered under legislation. The existing list of products covered should also be expanded. This should additionally provide a right to repair, standards around upgradability, durability and design for disassembly, and apply to all categories of physical goods on the UK market. Incentives to encourage the use of ecodesign practices should also be utilised by government – such as subsidies or economic incentives for products or assets that demonstrate good sustainable practice. **For**: DESNZ, Office for Product Safety and Standards.	Products being designed, manufactured and sold in the UK are designed with ecodesign principles at their core. As a result, critical material demand is reduced this contributes to the UK's resilience to supply chain crises. Product owners and users have access to more durable and sustainable products, and get better value for money out of their technology and goods. UK ecodesign legislation aligns to the improvements in EU-wide legislation, introduced in the 2024 Ecodesign for Sustainable Products Regulation.[150]	Applicable and useful ecodesign standards exist across the entire range of UK products, alongside clear guidance on how to apply them in practice. Engineering education and training for sustainable practices and ecodesign are embedded throughout the profession.
19. Expand the ecolabelling standards within the ecodesign for energy-related products and Energy Information Regulations 2021[151] to include more comprehensive sustainability indicators, such as material efficiency, repairability, ease of disassembly and recyclability. **For**: DESNZ, Office for Product Safety and Standards.	Consumers have access to reliable, accessible and comprehensive information on the sustainability of the products they purchase in the UK.	Clear and comprehensive guidance is provided for ecolabelling across the range of UK products. Reliable and standardised data on product and material history is accessible for all UK products.
20. Government should encourage enforcement and monitoring of ecodesign regulations through investment in surveillance networks, stronger disincentives and deterrents for those who do not keep to standards. **For**: DBT, DEFRA, Competition and Markets Authority.	Ecodesign principles are embedded throughout the market, with high rates of compliance with ecodesign standards in all UK products.	Fund and coalesce independent expertise within a regulatory body to evaluate compliance of products.

These targets were upgraded in 2015, requiring 85% of the vehicle (by weight) to be reused or recycled, rising to 95% of the vehicle when including recovery.[146] By setting early targets and defining them in legislation across the EU automotive sector, the ELV directive has used EPR to make significant improvements in the circularity of vehicles[147] and similar policy mechanisms should be utilised across other sectors to achieve these goals more widely. However, it is worth noting that these regulations do not effectively address EV batteries, which are critical material intensive: this is discussed in more detail in Section 7.4.

Importantly, across all sectors, broad targets for recycling a percentage mass of an asset may fail to incentivise the recycling of critical materials, which are generally used in small quantities.

Another example of a policy that aims to create more sustainable design practices include recent EU legislation enforcing interoperability of charging designs for electronic devices aimed specifically to reduce electrical waste and promote more responsible consumption, thus removing design practices that result in consumers needing to purchase multiple unique cables. This will require all smartphones to use USB-C by the end of 2024, and all laptops by 2026. An impact assessment of this policy estimated that excess mobile phone chargers produced or discarded in the EU were responsible for 11,000 tonnes of e-waste, and 600,000 tonnes of CO_2 emissions over their whole life cycle.[148]

More extensive standards for ecodesign practices, coupled with ecolabelling and procurement standards that credit the use of recovered material could significantly improve the sustainability and circularity of products and assets feeding into the UK's infrastructure pipeline and wider market for products.

6.6 Education and skills for sustainable design

Engineering education and skills are crucial to the implementation of more sustainable design practices. As we have seen, both consumer technologies and infrastructure sectors require a huge uplift in skills related to recovery, repair and reuse, with appropriate certification, in order to deliver resource efficient circular economies. The UK faces existing engineering skills shortages related to the transition to net zero,[152] in addition to this there is a large transformation of design skills and practices that must take place to deliver a paradigm shift in design values and approaches towards resource efficiency, resilience, long lifespan, reusability and recyclability in goods, buildings and infrastructure.

Understanding the environmental social and economic aspects of material sustainability is particularly important for the design considerations that determine the demand for critical materials and their recoverability. While a lack of skills is not the immediately limiting factor in the difficulties encountered in, for example, the responsible disassembly of wind turbines created by designs that did not address material reuse (see Section 7.2), earlier focus on these skills and awareness may have avoided this outcome. Addressing the problem requires new skills. This includes interdisciplinary skills that ensure that more engineers are prepared to engage with the holistic considerations of environmentally and socially responsible design.

The UK's Design Council has found that less than half of designers think they have the skills to meet the demand for environmental design, or that their education has equipped them to design for planet, while 71% think that the demand for environmental design is going to grow. At the same time, uptake of design and technology GCSEs fell by 68% between 2010 and 2021.[153] The Council have developed a vision of the skills needs for sustainable design[154] and collated practical resources for designers.[155]

Tackling this gap in skills, as well as unleashing environmental design creativity as a driver of innovation and better practice, requires action at many levels, including all stages of education. There is significant good practice in sustainability instruction within engineering higher education, but not always with consistency nor reaching all the engineers who may benefit.

The National Engineering Policy Centre's Engineers 2030 project,[156] established in 2024, examines what it means to embed sustainability as a core competency in design and engineering education and training. The project seeks to identify what will need to change across UK engineering education and skills systems to attract, educate and support a greater diversity of engineers and technicians in the future and to grow the talent pool of engineering skills that both the economy and the planet urgently need. A series of workshops with Engineers Without Borders UK set out reimagined engineering degree maps to support the flourishing of globally responsible engineering.[157] A core need identified across these pieces of work is designing for resource efficiency and being able to take a global perspective on sustainability and ethics.

A review of sustainability teaching in UK engineering higher education commissioned as part of Engineers 2030[158] found that there was a clear "need for engineering students to clearly see their societal responsibilities as practicing engineers and to challenge existing design paradigms if they are unsustainable… sustainable design is not an abstract concept. It is not one that sits in its own module separate from the technical details of a discipline. It is a core consideration and one that needs to be recognised as an absolutely fundamental concept from the very earliest stages of all degree programmes and repeated at regular intervals right the way through. Far too often it is an afterthought in the design process – something that is checked for compliance at an advanced stage of the design rather than an innate consideration at every stage. In training the next generation of engineers and engineering leads it is beholden on us as educators to rectify this deficient view."

Policy recommendation

Recommendation	Intended outcome	Requirements or enablers
21. Government should work with leaders in the sector to develop and resource interventions to encourage a transformation in UK engineering skills that emphasises resource efficiency, and global perspectives on sustainability. This must ensure that engineers have the training to design the ability to maintain, replace and recover critical materials into future technologies and products.	Sustainable design practices become the norm, with sustainability underpinning design frameworks and guidance across all engineering sectors. All individual engineers and designers are able to assure material sustainability and act as advocates for best practices. Material selection is more likely to include and prioritise the avoidance of use of critical materials, and prioritise design for life extension and responsible end of life, especially enabling the recovery of critical materials. The infrastructure delivered as a result uses fewer critical materials, and those that are used are designed to be recovered and reused or recycled at their end of life.	Accreditation processes such as Engineering Council's Accreditation of Higher Education Programmes (AHEP) are a potential enabler of further progress in this area.

7. Circular economy

7.1 Reuse, recycling and waste management for critical material demand reduction

A circular economy is defined, for our purposes, as one in which materials in the economy are maintained at the highest possible value and as few as possible are used to achieve the ends we want. In practice this means vastly reducing the material wastes shown in Figure 20 and increasing the reuse, recycling, remanufacture, and life-extension of materials thus 'closing the loop' so that very little material extraction is required.

Recovery, reuse, and recycling of critical materials is a crucial element of sustainable resource management in both the short and long term. Material wasted rather than entered back into use is likely to be replaced through additional extraction, increasing supply shortage risk. As critical materials become more prevalent in the UK, the existing stocks of them and available capacity to recover and recycle them will be important for both reducing primary demand and ensuring resilient supply. This requires both investment in capacity for recovery, recycling and reuse of critical materials, as well as changes in design and user behaviour to enable this.

However in the near-term, circular economy levers are highly limited in their ability to manage demand for critical materials. Many critical material stocks are in large infrastructures whose end-of-life is not for decades while demands are accelerating now. Total stocks of critical materials in the UK and global economy are increasing – while this a growth that cannot be offset by efficient use of existing stocks, it is essential to plan ahead and adopt a strategic approach to a circular economy in critical materials that retains these stock in use, in order to plateau demand for these materials and be able to rely on existing stocks for the bulk of demand.

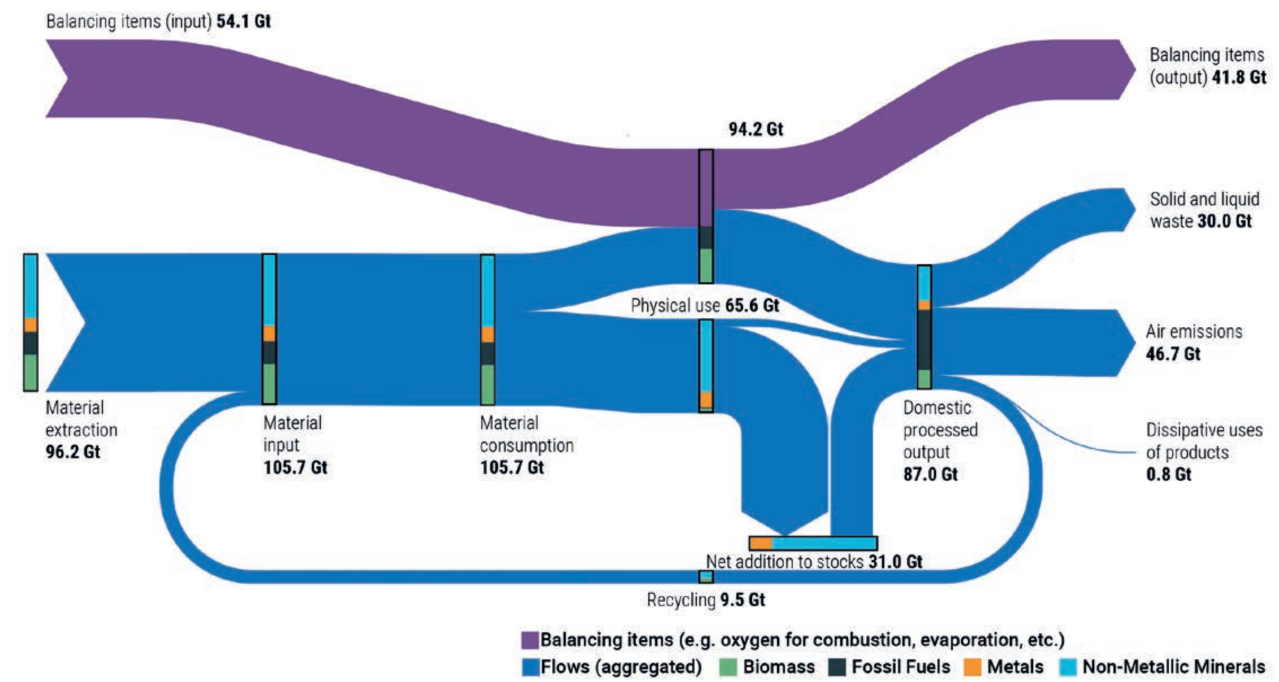
7.1.1 Understanding linear vs circular economies

The global materials economy remains almost entirely linear. The UNEP Global Resources Outlook 2024 estimated that in 2019 recycling provided 9.5 gigatonnes of material input into the global economy, less than a tenth of the 96.2 gigatonnes extracted from natural resources.[159]

While it is important to recognise that a fully circular economy is not possible to achieve in any sector due to residual wastes and technical limitations, zero waste should nevertheless be targeted – especially for materials whose extraction is particularly harmful, as is the case for critical materials.

7.1.2 Circular economy and demand management

While total global material requirements continue to grow and the total stock of critical materials in the UK grows, demand will not be significantly reduced in the near-term by recovery, reuse and recycling and they will not be sufficient alone to manage the risks associated with sharp rises in demand for critical materials. However, as stocks of materials in the UK economy increase, recovery,



Note: Balancing items calculate 54.1 billion tonnes on the input side and 41.8 billion tonnes on the output side.
This accounts for, e.g. oxygen for combustion, evaporation, etc. These elements are needed for the system to be balanced (inputs, outputs).
Source: Global Material Flows Database (UNEP 2023a).

Figure 20 | Global material flows, waste and emissions, 2019, billion tonnes.
Taken from Global Resource Outlook 2024, 2024, United Nations Environment Programme.

reuse and recycling will become increasingly important in reducing material demand as new energy and transport infrastructure reaches the end of its life.

7.1.3 The linear economy of critical materials

Where forms of recycling do take place for critical materials, it is primarily associated with 'closed industrial cycles' when recovery is possible from industrial wastes or products. Rhenium, for example, is primarily used in superalloys and catalysis for specific industrial applications. This means that they are easily recoverable, having never left the factory, and this combined with the high value of rhenium means that total recycling rates are comparably high.[160]

For other critical materials, high value and the specific use-cases mean that certain waste streams are utilised; platinum group metals (as shown below in figure 22) in particular are often recovered from catalysts – including those found in cars – as well as jewellery, electronics and medical technology scrap. Recycled material provided for 23% of total platinum demand in 2010.[161] However this is an outlier among critical materials for its relatively high recycling rate.

For those critical materials that are used primarily in the production of metal alloys, such as niobium, the resulting alloys, often steels, are currently 'downcycled' rather than recycled, becoming mixed with other alloys containing other additives meaning that the critical material additives can no longer be extracted. This not only removes those critical materials from the economy, but also may compromise the quality of recycled steel in the long-term as concentrations grow.

Critical materials that are used to produce electronics, such as indium, are also an endpoint

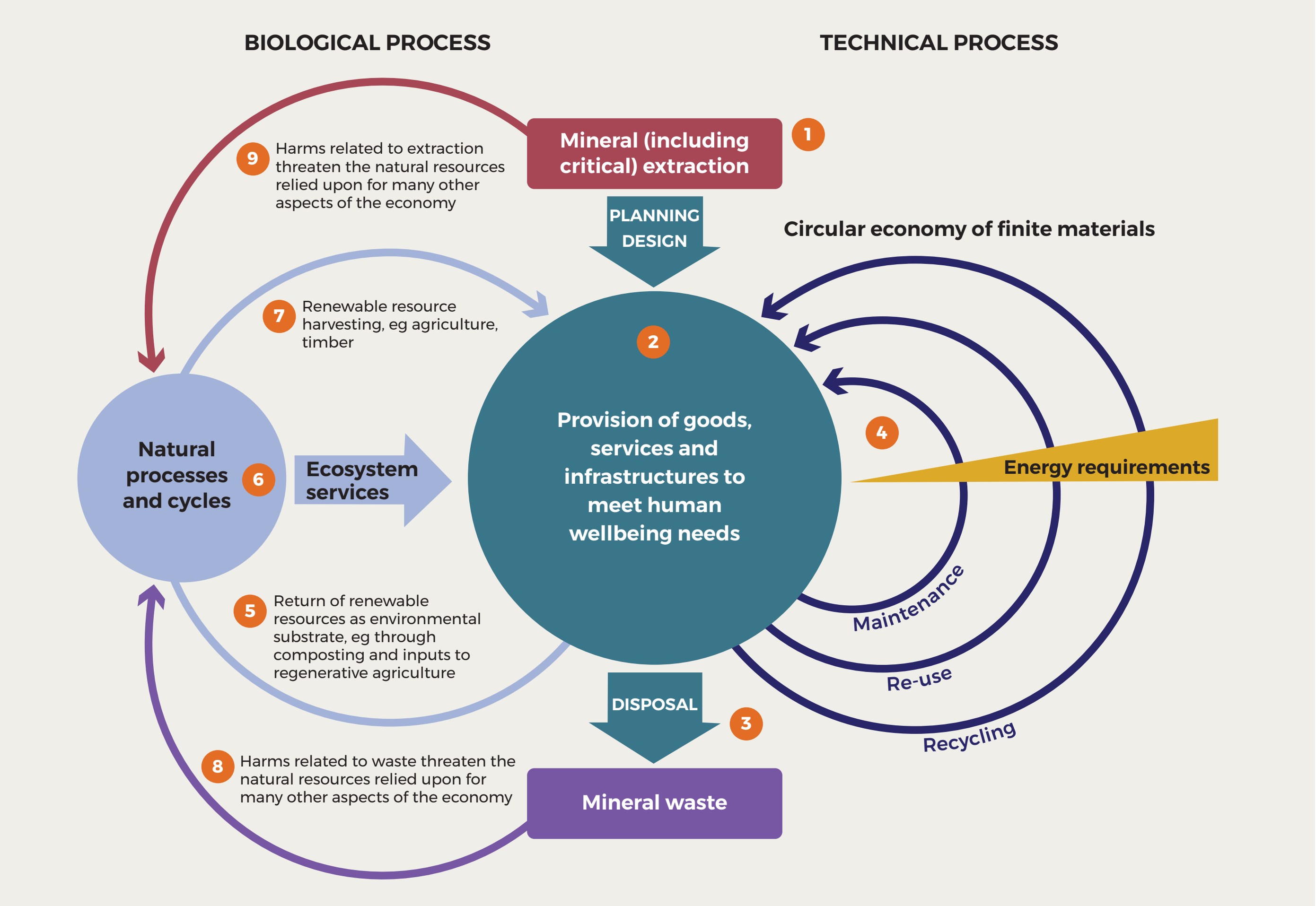


Figure 21 | Butterfly diagram. Modified from Our Shared Understanding: a circular economy in the built environment (2023) who modified it from W. McDonough (2002). Cradle to Cradle: Remaking the Way We Make Things. New York. North Point Press. Numbered processes on the diagram are explained below:

1. Finite resources, including critical materials, are extracted through mining and enter the global economy. In a circular economy, finite material inputs are minimised as far as possible, and more value is gained from fewer resources regardless of the source.
2. Planning and design shape the material needs required to provide infrastructure, goods and services to meet human needs. In a circular economy, these tools are used to reduce the material requirements of meeting people's needs.
3. Materials that cannot be reused, recycled, or fed back into natural cycles are wasted. Currently this is the case for approximately 90% of all materials. In a circular economy, very little material would be wasted.
4. Finite materials, such as metals and critical materials, can deliver more value through life-extension or improvements in performance, or can be reused or recycled to preserve them as part of the circular economy. These options are not equal, with energy and engineering requirements increasing with the complexity involved. In a circular economy, almost all finite materials are either maintained, reused or recycled.
5. Renewable materials, such as food, wood and other biomass can be returned to fuel natural processes such as the carbon cycle, for example through composting or inputs into regenerative agriculture. In a circular economy, almost all renewable resources would be returned to feed natural cycles.
6. Natural (biogeochemical) cycles, such as the carbon cycle, water cycle, and phosphorus cycle, sustain the ecosystems on earth. These ecosystems, besides their inherent value, provide 'natural services' to humans, such as enabling food production, flood controls, capturing carbon emissions from the atmosphere, and reducing pollution.
7. Renewable resources, such as food crops and timber, are harvested from the natural world and enter the global economy. In a circular economy, the renewable resources harvested are minimised, more value is gained from fewer resources, and harvesting is done in such a way that regenerates the natural ecosystems.
8. Pollution from material waste contributes to harm to natural cycles and ecosystems, reducing their capacity to provide resources and services. In a circular economy, minimising waste minimised this impact.
9. Current approaches to material extraction tend to cause harm to natural processes and ecosystems, reducing their capacity to provide resources and services. In a circular economy, minimised material requirements mean that less extraction is needed, and extraction is done in the least harmful way possible.

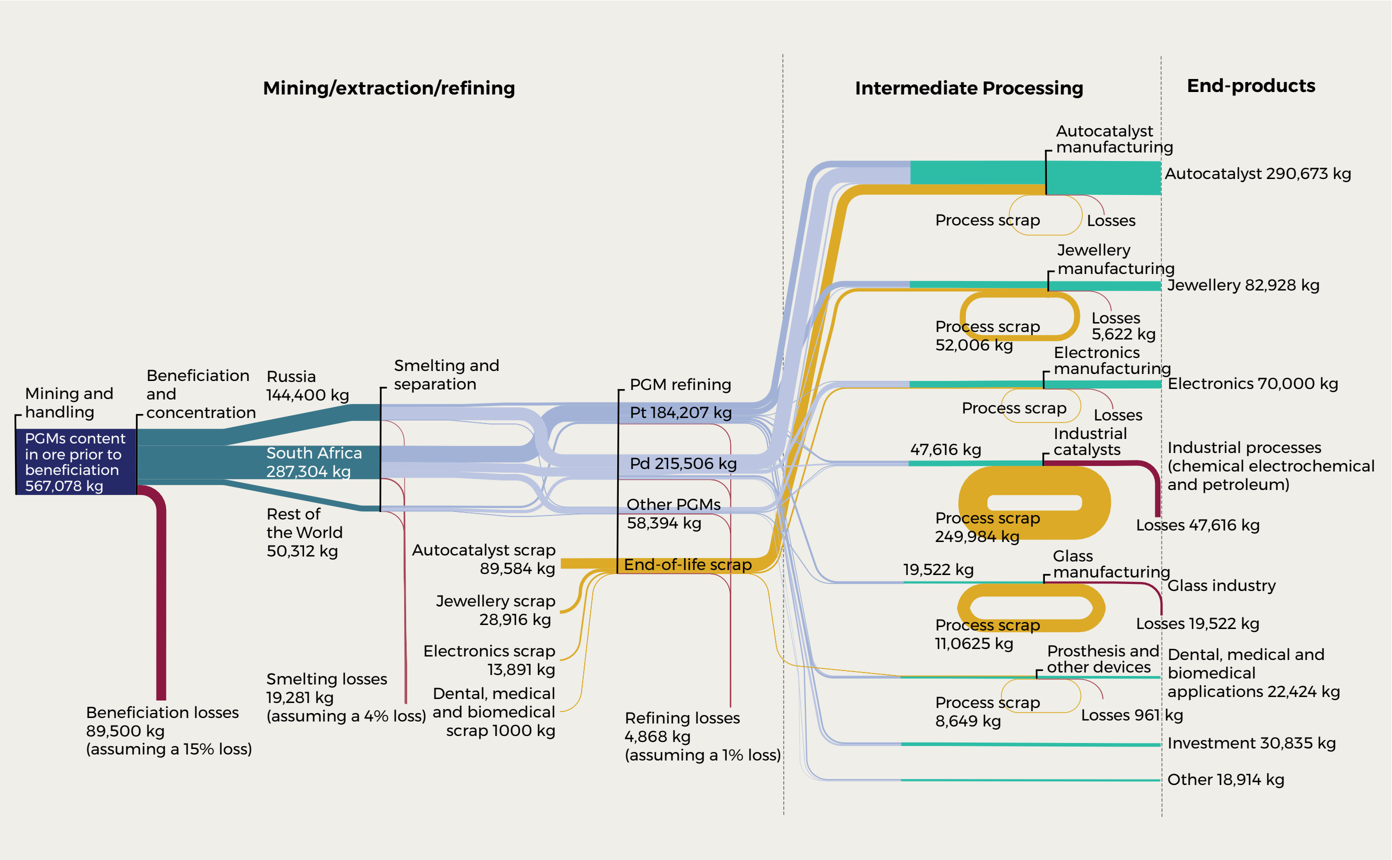


Figure 22 | Global platinum group metals mass flow in 2010. Platinum group metals (PGMs) are mined as primary ores in South Africa, and as by-products of nickel-copper ores in Russia. Some losses occur during beneficiation and concentration (removal of non-PGM materials from the mined ore). There is significant closed loop recycling during manufacturing of industrial catalysts, glass and jewellery, as well as end-of-life recycling especially from catalysts.

for the material as they are spread thinly throughout complex components making them difficult to recycle.

There are significant informal recycling economies for metals such as gold, for which reliable data does not exist. This often involves the shipping – legally and illegally – of electronic waste such as mobile phones from nations in the global North to nations in the global South such as Bangladesh, Nigeria and Ghana, from which it makes its way to 'backyard smelters'.[162] The informal gold recycling sector is thought to be highly inefficient compared to industrial recycling, and poses significant environmental and health risks.[163] However, like many informal waste economies, it constitutes the economic livelihood of many people.

There are many significant areas of waste, especially those associated with more intensive use of critical materials in new infrastructure, which should be prioritised for intervention through a concerted build-up of recovery and recycling. Recovery of materials from the built environment is often termed 'urban mining'. For example, as we will see in the following case study, as early offshore wind turbines are now being decommissioned, many tonnes of critical materials are being lost due, in part, to lack of planning and design for materials recovery in the turbine designs, a lack of disassembly capabilities, and the absence of an economic model for valuing materials recovery. This is despite the highly significant stocks of especially neodymium and copper[164] standing in UK waters – a significant opportunity for 'urban mining' in the UK that will grow considerably over time.

7.2 Case study: reuse and recycling of neodymium from UK offshore wind decommissioning

Offshore wind turbines currently being deployed, such as the Siemens Wind D6 6MW, contain 5800kg of neodymium magnets overall (compared to 2kg in an average electric vehicle motor). These magnets, which are not pure neodymium but in an alloy with iron, could be adapted and reused in the production of electric vehicle motors or crushed and recycled. Currently the full motors are typically exported without controls on the end-of-life of those materials.

Most turbines have an assumed asset life of 25–30 years, though there are options for life extension and/or repowering (replacing turbine parts on their existing foundation), which should be pursued as a priority. Turbines of the type described above are scheduled begin being decommissioned in 2037/38, by which time a total of over 1,000 offshore turbines per year are forecast to come to their end-of-life decisions. No accurate assessment of these assets is available, and the data required may be incomplete, hence the exact opportunity for neodymium recovery presented by North Sea wind turbine decommissioning is uncertain. However it is likely to be significant and of a scale to be of national strategic importance. Despite the scale and value of the opportunity, this resource is mostly not visible to decision-makers.

Off-shore wind assets represent a good example of the potential for urban mining, but barriers to their recovery include:

- existing engineering capacity, in terms of port harbours able to handle turbines, and onshore disassembly yards, and logistics networks for transport and storage of the materials
- difficulties in recovering materials from assets not designed for disassembly such as from the use of epoxy glues
- lack of consistency in, or understanding of, the designs of existing turbines due to market complexities
- safety concerns for people performing magnet removal
- undervaluation of the materials recovered, meaning labour costs of extraction are often higher than those for primary resources
- lack of previous experience with such business models.

In the case of neodymium magnets, these have a high market value, currently estimated at £3–8 per kg but the recycling supply chain is immature and geographically very spread out. Copper is valued at around £6 per kg, but is easier to recover, available in larger quantities, and there are large and efficient logistics networks in place.

Currently there are no sector-wide or national plans to ensure that barriers to neodymium recovery, reuse and recycling are addressed. Rapid action to ensure that turbines installed now are easier to decommission will be of significant benefit. The opportunity to conserve this national resource is reduced with every turbine built without an end-of-life in mind.

As discussed earlier in Section 6 and Section 6.3.1, the UK is a leader in developing engineering standards for circular design in offshore wind, and a 2023 DESNZ consultation on introducing incentives for sustainable design into Contracts for Difference Auctions[165] marks a positive direction of travel for embedding such frameworks in the electricity generation sector. However, Contracts for Difference Auctions occur near the end of the development process for offshore wind projects, and at this stage many of the design decisions impacting critical material use have already occurred. Further improvements in sustainable design may therefore be unlocked by incentivising resource efficient design and design-for-reuse at earlier stages in the process of development of offshore wind projects.

In addition to design-based challenges in decommissioning existing wind turbines, future decommissioning presents challenges for engineering capacity of ports, storage, and decommissioning yards. Competition for scarce facilities may be additionally coming from ongoing deployment of offshore wind turbines as well as decommissioning of oil and gas infrastructure, risking the squeezing out of offshore wind decommissioning. Historic lack of investment and strategic planning may need to be remedied to ensure that the opportunity presented by this decommissioning can be seized. This may consider options for reducing requirements for oil and gas decommissioning, such as approaches that limit the amount of infrastructure being physically removed, which could also be beneficial for the marine ecosystems surrounding them.[166]

Neodymium magnet recovery is contingent a wider regulatory framework to support the reuse and recycling of wind turbines. There is need for clear, well-informed and regionally aligned regulation to enable reuse and recycling. Currently end-of-life components including turbines are classified as waste across the UK and EU. Waste regulation makes movement of components between national borders difficult, which in turn hinders regional supply chain development for reuse and recycling of components. Regional and even international cooperation is needed to align national regulation and enable circular practices across boundaries.

Policy recommendations

Recommendation	Intended outcome	Requirements or enablers
22. Provide dynamic strategic planning for future engineering needs related to deployment and decommissioning of wind assets, and decommissioning of oil and gas assets. This should focus on developing sector capacity and skills for sustainable design, deployment, life extension, and decommissioning. **For**: Scottish government, Welsh government, offshore wind sector, DESNZ, DBT.	UK offshore wind turbines, and potentially others, are disassembled at the appropriate point (after any life-extension actions have been taken), with the critical materials and especially neodymium magnets being recovered for reuse, or failing that, recycling. These could be feedstocks for the automotive sector.	More UK ports with capacity to receive wind turbines, greater capacity of sites able to disassemble them, investment in the engineering skills required to do so, economic incentives to stimulate investment.
23. Build on attempts to consider design and material sustainability in CfD auctions by setting requirements for infrastructure design for end of life, considering the right places to embed this in procurement processes such as planning permission stages or CfD auctions. **For**: DESNZ, HMT, DfT, DEFRA, Environment Agency, planning bodies.	Wind turbine designers and manufacturers are incentivised to build in circular design at the beginning of design processes.	Engineering skills, capacity, data. Changes in design values and processes.
24. Develop a sector-specific approach to improving circular economy for offshore wind to ensure the technical capability exists to more easily decommission, reuse and recycle wind turbines at end of life. **For**: DESNZ, Scottish government, Welsh government, offshore wind sector, Zero Waste Scotland.	Establishing clearly for all stakeholders the requirements for the development of a mature circular economy of wind, including design, finance, logistics, engineering capacities and skills and more, enabling policy and investment to be put in place to ensure a circular economy of wind emerges.	Sectoral collaboration, standards agreement, joined up regulation.

However, regulation that would remove barriers to the decommissioning and valuation of wind turbine components at end-of-life must be crafted carefully to avoid producing a similar situation to other large structure end-of-life economies, in which structures are exported to places where their decommissioning can involve irresponsible practices, which are both environmentally damaging and a driver of human rights abuses.[167]

7.3 Remanufacture/manufacturing capacity

Remanufacture is the process of returning a used product to like-new condition with a warranty to match.[168] This can involve the reuse, reconditioning and replacement of component parts[169] and reduces the need for virgin materials as components, products or entire assets are returned into use. Remanufacture can also often lead to energy and cost savings for the manufacturer when compared to newly manufactured products.[170] Remanufacture therefore has a significant potential contribution to make toward circular economies. UK remanufacture has the potential for significant expansion with many current applications concentrated within fields such as the automotive sector.[171] A report by the Green Alliance in 2019 projected that a 50% increase in remanufacture has the potential for creating 312,000 jobs in the UK.[172]

As discussed in Section 6.2.5, remanufacture should be considered during the initial design of a product or asset, as decisions made early on in this design process can greatly affect remanufacturing efficiency, profitability, and overall viability. For example, products may be difficult to disassemble, difficult to test, or it may be difficult to replace individual components.[173] While not specifically an example of remanufacture, this was demonstrated in this report's case study on reuse and recycling of neodymium from UK offshore wind decommissioning, where the extensive use of epoxy glues presents significant obstacles to the disassembly of offshore wind turbines.

Consumer confidence in remanufactured goods can also impact the success of remanufactured products and this is another area where clear standards are needed to ensure consistent and high quality of remanufactured goods.[174] Ensuring the appropriate education and professional development are in place to deliver the necessary skills for remanufacture is also an important consideration, as remanufacturing processes can involve highly skilled operators requiring advanced problem solving and engineering skills.[175]

7.4 Case study: lithium-ion battery recycling

From portable electronics to EVs, the demand for lithium-ion batteries is increasing at a rapid rate,[176] and by extension, so is the demand for the critical materials contained within them, primarily lithium, cobalt, nickel and manganese. As demonstrated by the analysis presented in Section 5, this demand is predicted to continue to rise across the next decades with the total lithium requirements of the forecast UK market for EVs reaching 268,000,000kg by 2040.

It is important to ensure the UK has the capacity to recycle these batteries and recover their critical materials for input into domestic supply, thus reducing UK demand for primary extraction of raw materials. Recycling also prevents waste batteries from being unsafely disposed of or accumulated at landfill sites at end of life, where improper storage can result in extremely hot fires that are very difficult to extinguish.[177]

Before entering into a recycling stream, the useful lives of lithium batteries should be extended as far as possible. For example, a defective battery might have a mix of faulty and functioning cells – by repairing or replacing only the faulty cells, and maintaining the rest of the battery, the lifetime of the battery can be increased at a lower material cost than replacing the entire battery. Other measures such as optimising charging[178] and avoiding using the battery in extreme temperatures[179] can also contribute to battery life-extension. By extending the time before batteries reach their end of life, not only is the UK's critical material demand from new batteries reduced, but also further time is given to allow recycling capacity to scale up.

Current recycling capacity is not capable of handling the volume of lithium-ion batteries expected to reach their end-of-life in the coming years. In a study looking at European EV recycling capacity, it was estimated that current recycling infrastructure will only accommodate 21% of the expected EV lithium-ion battery waste in 2030,[180] meaning that existing capacity would have to increase by 3.7 times by 2030 to properly process the expected waste.[181,182] While this study was looking across Europe (including the UK), UK capacity specifically would have to be built if recovered materials were to be input into UK manufacture. Some of this capacity is in development, such as Agratas' 40GWh manufacturing factory planned for Bridgewater, Somerset, which is expected to have recycling capability, although the planned capacity is unknown.[183] Safety is also an important consideration here since recycling lithium-ion batteries is hazardous with previous incidents including thermal runaway, battery ignition and explosion.[184] Any new UK recycling capacity should be accompanied with rigorous and appropriate process safety standards. Current EU standards in use are appropriate for this.

The UK does not currently have explicit regulations in place for lithium-ion battery recycling. At present this sits between DEFRA's ELV regulations[185] and Batteries and Accumulators regulations,[186] but is inadequately covered by both: the ELV regulations are set by weight, and therefore do not effectively account for critical materials (which are a small proportion of a vehicle by weight), and the batteries regulations currently class EV batteries as industrial, rather than automotive. Policy to support battery recycling in the UK should address this gap, specifying an end-of-life strategy for lithium-ion batteries explicitly, covering the reuse and recycling of batteries, setting robust recycling targets and planning ahead for future recycling capacity needs. This would align the UK with recent EU regulations in this area, which includes waste collection targets for portable battery producers, targets for the recovery of specific critical materials (lithium, cobalt, copper and nickel), recycling efficiency targets, and a 'battery passport'.[187]

Policy recommendation

Recommendation	**Intended outcome**	**Requirements or enablers**
25. Explore strategic opportunities for the UK in investing in domestic battery recycling capabilities and take an international approach to ensuring all EVs within the UK market have sufficient capacity to be safely and sustainably recycled at end of life. **For**: DEFRA, Scottish government, Welsh government, DBT.	All UK batteries undergo safe and sustainable recycling at their end of life – critical materials are recovered and recycled from this process and input back into the UK economy, reducing the demand for primary mining and extraction.	UK domestic capacity needs to be accompanied with rigorous and appropriate process safety standards.

Afterword

by Professor Joan Cordiner FREng FRSE FIChemE, Chair of the National Engineering Policy Centre Working Group on materials and net zero

We can no longer ignore the unsustainability of our materials consumption, nor the role materials play in addressing climate change. This report highlights that the sharply rising demand for critical materials is in part due to the infrastructure and energy demands created by decarbonisation of the UK. We are not the only country that will be competing for these finite critical materials that are driving environmentally and socially costly extraction. This report recommends that government takes action to have a demand-side strategy and policy framework for critical materials.

This strategy needs to drive:

- Making strategic choices to build infrastructure that is more materially sustainable.
- Reducing needs for fresh extraction and its impacts, by:
  - Lengthening useful life, reuse and recycling of materials.
  - Reducing demand by modal shifts or materials substitutions.
- Ensuring reuse and recycling of critical materials to ensure UK supply resilience.

We need to deliver the following to enable these levers:

- Tracking and understanding where critical materials are in the UK.
- Driving research into step change technologies.
- Building recovery, recycling and reuse infrastructure for critical materials.
- Embracing design methodologies and standards that explicitly consider materials requirements as well as durability, repairability, and reuse or recyclability.
- Upskilling and training with environmental design, new standards, and new technologies.

Journalist Ed Conway's recent book 'Material World' has recently raised the prominence of how material availability has changed the fortunes of countries, jobs and quality of life through history. Despite this learning from history, our plans for decarbonisation have not fully reckoned with their dependencies on certain materials. Decarbonisation is not optional, but we have choices on how we reach net zero; if we get it right, we will build resilience, jobs and wealth in the UK and if not, we risk both failing to meet our goals and doing additional harm to people and the planet. From my perspective as a former risk manager, I am concerned about the potential financial security and quality of life impacts of not acting on the recommendations in this report. Social inequity is already a very significant problem in the UK and a lack of critical materials will only make that worse. If we don't act, the jobs created by the transition to net zero will be overseas with greater sociopolitical risks on our supply. We need a paradigm shift in policy and infrastructure to reduce demand for fresh extraction of critical materials in short order. If we are to reuse and recycle materials, the design processes need to be changed. Research, policy, and values need to drive us in that direction or we will have years of new net zero infrastructure that is difficult or totally uneconomic to reuse and recycle. We need to have a long-term strategy in which materials are not an afterthought.

Strategic management of critical materials for the UK can enable a resilient and sustainable net zero future, through robust economic and technical policy and forward-looking engineering standards. These policies need to work with the international market for critical materials, and the products containing critical materials, to influence design and develop supply chain transparency. Action is needed now to ensure the infrastructure, training, standards and technology is available to meet the UK needs and to improve resilience to supply side shocks and reduce dependence on the few nations and businesses extracting and processing critical materials.

> The future prosperity of the UK, the security of vital infrastructure and the ability to deliver the crucial transition to net zero depends on infrastructure, skills and policy for demand-side management of materials.

After reading this report, consider the materials we depend upon – visibly and invisibly, knowingly and unknowingly – for our everyday lives and for a sustainable future. Remember that they are the product of decades of planning and design work, of a web of global supply chains with a complicated and often harmful impact, and that they are too valuable to waste. Take that knowledge and apply it as we remake the world.

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Methodology supplement

Quantitative analysis of critical material demands from sales of UK electric vehicles

Details of the full methodology of the quantitative analysis of the impacts of electric vehicle battery design interventions on critical material demands, presented in Section 5 of this report are available in a separate document which can be viewed and downloaded at: nepc.raeng.org.uk/critical-materials

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