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Intelligence Centre

Study on future material requirements of the national grid infrastructure to reach net zero

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Open Report

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OPEN REPORT

Study on future material requirements of the national grid infrastructure to reach net zero

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Executive summary

The UK's climate change ambitions are transforming the energy sector. The clean energy transition objective cannot be met without access to energy transition minerals, of which several are identified as 'critical'. The UK's Critical Minerals Strategy identifies the need to establish resilient supply chains and to understand dependencies and future demand trends that may adversely influence which critical minerals are needed to achieve UK net zero targets.

This study assesses the security of supply of aluminium (Al) and copper (Cu) essential for upgrading the electricity grid in Great Britain (GB) to adapt to the decentralisation of power generation driven by renewable energy, and mass electrification associated with consumer technologies, energy storage and distribution. Al and Cu requirements for upgrading the grid based on national forecasts of infrastructure projects are considered.

The scope of this study included those components in the transmission and distribution networks with high Cu or Al content, namely:

- overhead lines
- underground and subsea cables
- interconnectors
- converters
- transformers
- solar connections
- lithium-ion batteries for grid-scale storage

- electric vehicle (EV) charging infrastructure

Assumptions made as part of the study approach were validated by a range of Government and private sector stakeholders throughout the project.

The findings of the study highlight key challenges and bottlenecks within the upstream Cu and Al global supply chains and in the component and product supply chains.

COPPER

There is a forecast shortfall in Cu supply, which means a failure to meet growing demand (driven by global electrification), unless primary production capacity increases. This has resulted in all-time high Cu prices earlier in 2024.

ALUMINIUM

While forecast supply is anticipated to grow in line with demand (as reflected in stable prices), there is high production concentration with China dominant as the producer of 60 per cent of global refined Al. Al production is also very energy intensive, with direct and indirect (from electricity use and transport) carbon dioxide (CO_2) emissions across the Al value chain accounting for 3 per cent of the world's CO_2 emissions, from energy combustion and industrial processes. Emissions reduction needs to accelerate for Al production to reach net zero by 2050.

COMPONENTS

There are multi-year lead times associated with the critical components required for the energy transition, including subsea cables, transformers and offshore wind substations. This is caused by a global race for electricity grid components and market dominance from few suppliers in some sectors, such as high-voltage direct current (HVDC) subsea cables.

Governments and companies have sought to mitigate risk through:

- vertical supply chain integration (for example, cable manufacturers owning rod mills)
- increasing recycling input rate to component manufacture
- centralised procurement strategies
- consideration of direct financing deals between manufacturers and mining companies
- substituting Al for Cu

DEMAND ANALYSIS

The demand analysis in this report estimates that, in total between 2023 and 2050, up to 1.6 Mt Cu and 300 000 t Al will be needed for the planned upgrade projects within GB's electricity grid, when considering the scope of components studied. Across the minimum and maximum demand scenarios, between 50 and 60 per cent of the total Cu and Al requirements between 2023 and 2050 are expected to be needed by 2030 (assuming a power sector decarbonisation date of 2030).

Average annual Cu and Al GB grid infrastructure demand could peak at 0.5 and 0.02 per cent of 2017 to 2021 global supply before 2030. GB Cu and Al needs are expected to be 2 per cent and 0.1 per cent of the global grid requirements, respectively, between 2023 and 2030.

Under the maximum demand scenario considered, approximately:

- 55 per cent of Cu and Al requirements are for the transmission network
- 35 per cent for the distribution network
- 10 per cent for distribution technologies (solar connections, grid-scale storage batteries and EV charging infrastructure)

High-voltage subsea cables (interconnectors, bootstraps and offshore wind export cables) are the group of components with the highest overall material demand, accounting for around 30 per cent of total Cu needs. This may further increase in line with recent Government announcements to quadruple offshore wind by 2030. There is an opportunity for Cu components to be substituted with Al in high-voltage subsea cables, underground cables and low-voltage distribution transformers, although this may require a review of current standards and practices.

The UK is a net exporter of hundreds of thousands of tonnes of scrap Cu and Al, losing significant economic value. There is growing interest from the private sector in developing low-carbon emitting Al and Cu refineries that use recycled scrap material (for example, Alvance and Evolve Metals). There is an emerging opportunity for the UK to unlock economic potential through the circular economy and supply Al and Cu that are produced in the UK.

Requirements for high purity metals in some components may prohibit use of recycled Al in, for example, cables. Recycling of these metals should be considered important as part of a wider circular economy. 'Green' UK manufacturing of recycled material can reduce environmental impact, increase supply chain resilience and capitalise on economic opportunity.

RECOMMENDATIONS

Strategic network planning process

The strategic network planning process (as recommended in the Transmission Acceleration Action Plan (TAAP)) should be accelerated to provide clarity on future material demand. This will improve long-term, anticipatory investment from suppliers and offer clarity on long-term future requirements for the distribution network as part of a whole-system approach.

Understanding the demand for strategic components and materials, such as Al and Cu, should form a key part of the planning process. The TAAP process map should be tested and reviewed considering new Government policy to decarbonise the GB electricity network by 2030. An end-to-end risk management approach is recommended. It is expected that supply risk management will form a key part of this; the demand signal to the supply chain should be initiated at pace and refreshed in lockstep with any future revised network plans.

Procurement

Exploring new procurement strategies to ensure security of supply could include centralised approaches, direct financing deals between manufacturer and mine, and using the Office of Gas and Electricity Markets (Ofgem)'s new advanced procurement mechanism

Supply chain

Companies should share challenges and solutions across the supply chain.

A deep dive into UK supply chain capacity, diversification and security is also needed to identify targeted interventions and initiatives (including investments) that could strengthen supply chain resilience.

Other

- Review design principles and standards for components across the transmission and distribution networks, to consider circular economy principles and material options
- Unlock the UK's circular economy potential through incentivising investment into refinery capacity for recycled scrap Cu and Al
- Perform economic modelling of the UK Carbon Border Adjustment Mechanism (CBAM) to balance risk to supply, cost and completion of grid infrastructure projects, with net zero commitments
- Continue to fund research into the most promising alternative materials (for example, graphene) to ensure future resilience
- Improve data quality across the supply chain through working with data providers
- Review and update the supply and demand model to reflect changes in the global Cu and Al markets and planned GB grid infrastructure projects, and maintain insight

1 Introduction

1.1 THE ELECTRICITY GRID

The electricity grid in GB is a complex network of infrastructure that transfers electricity from power-generating technologies (for example, wind turbines; solar cells; nuclear power stations) to locations of demand (for example, residential and commercial properties; heat pumps; EV charging points), via a series of overhead lines, underground cables and substations.

The grid is formed of two interconnected networks: the high-voltage transmission network and the lower-voltage distribution network. The transmission network consists of onshore and offshore infrastructure and principally operates at two voltages, 275 kV and 400 kV. The lower-voltage onshore distribution network operates at several voltage levels lower than 275 kV (UK Government and Ofgem, 2022). As of 2021, the transmission network was estimated to consist of approximately 20 000 km of overhead lines and underground cables, while the distribution network contained around 800 000 km of lower-voltage lines and cables (UK Government, 2022a).

1.1.1 Transmission and distribution networks

Overall planning for the transmission network is managed by the Energy System Operator (ESO). The ESO is responsible for managing the system balance and operability (Ofgem, 2018). Together with transmission owners (TOs), the ESO develops long-term strategic plans for upgrading the transmission infrastructure. There are three TOs covering GB:

- SP Energy Networks
- Scottish and Southern Electricity Networks
- National Grid Electricity Transmission

Offshore assets are owned and managed by offshore transmission owners (OFTOs).

As the operator of the transmission network, the ESO is legally responsible for ensuring that there is sufficient supply to match the demands of the different parts of the transmission and distribution networks. Six distribution network operators (DNOs) are responsible for planning infrastructure upgrades and maintenance activities across the 14 license areas in the GB distribution network.

Ofgem is the GB electricity markets regulator. In addition to granting distribution and transmission licenses and ensuring compliance, it also oversees the design and implementation of the price control framework, RIIO (revenue = incentives + innovation + outputs). The framework balances investment in the network with company returns and running costs. The current price controls expire in 2028 for the distribution network (RIIO-ED2) and 2026 for the transmission network (RIIO-T2) (Ofgem, 2021).

1.1.2 Future of the grid

Significant infrastructure investment is required to meet the UK Government’s commitments to two key environmental targets: achieving national net zero by 2050 and a fully decarbonised electricity system by 2030, which has recently been brought forward by the new (2024) Labour Government from 2035. The additional infrastructure of cables, lines and transformers required to manage this significant redesign of the grid infrastructure is heavily reliant on Al and Cu, as well as the supply chains relating to these materials and associated components.

This required investment into grid infrastructure is principally underpinned by three drivers:

- increasing geographical distribution of electricity-generating assets
- increasing electrification and peak electricity demand
- increasing need to cope with flexibility

1.1.2.1 Increasing geographical distribution of electricity-generating assets

Historically, the grid was powered by a small number of large capacity (gigawatt-scale), high-emission power stations. However, to meet the UK's decarbonisation targets, there is a need for renewable generating assets such as wind and solar power, which are typically of lower capacity (megawatt-scale or kilowatt-scale if connected to residential or commercial properties). More of these renewable assets are required than traditional power stations, resulting in more connections to the grid and therefore more network infrastructure.

1.1.2.2 Increasing electrification and peak electricity demand

Analysis by the former Department for Business, Energy & Industrial Strategy (BEIS, now split to the Department of Business and Trade (DBT) and the Department of Energy, Security and Net Zero (DESNZ)), suggests that peak electricity demand may increase from 58 GW in 2022 to between 130 and 190 GW by 2050 (UK Government and Ofgem, 2022). This forecast assumes mass electrification of heat and transport (for example, moving from gas boilers and internal combustion engine vehicles to electric heat pumps and EVs.) An increase in network capacity through infrastructure investment is required to cope with this increase in peak demand.

1.1.2.3 Increasing need to cope with flexibility

There is a growing complexity when balancing the grid to ensure supply matches demand. Due to increasing renewable sources of energy, electricity supply is less predictable, resulting in an increase in constraint costs. Where supply exceeds demand, electricity providers may be asked to curtail their supply (reduce or turn off generation). The ESO has planned for a growth in the deployment of grid-scale energy storage technologies (such as battery energy storage systems (BESS)) to help minimise network constraint costs, since excess energy can be stored here rather than curtailed (National Grid ESO, 2022a).

Interconnectors are another solution to manage the balance of the grid. These cables allow electricity to be traded and shared between countries. Ultimately there is a strategic choice between the cost of constraints and cost of investing in infrastructure to reduce these constraints.

1.2 KEY COMPONENTS WITHIN THE ELECTRICITY GRID

An overview of some of the key components within the GB electricity grid, categorised by generation, demand, transmission and distribution, is provided in Figure 1. The infrastructure connecting power generation and demand from end-users includes:

- overhead lines
- underground and subsea cables
- substations equipped with transformers to step-up or step-down the voltage
- converters changing alternating current (AC) to direct current (DC) and vice versa
- interconnectors facilitating the export and import of electricity to and from countries outside GB

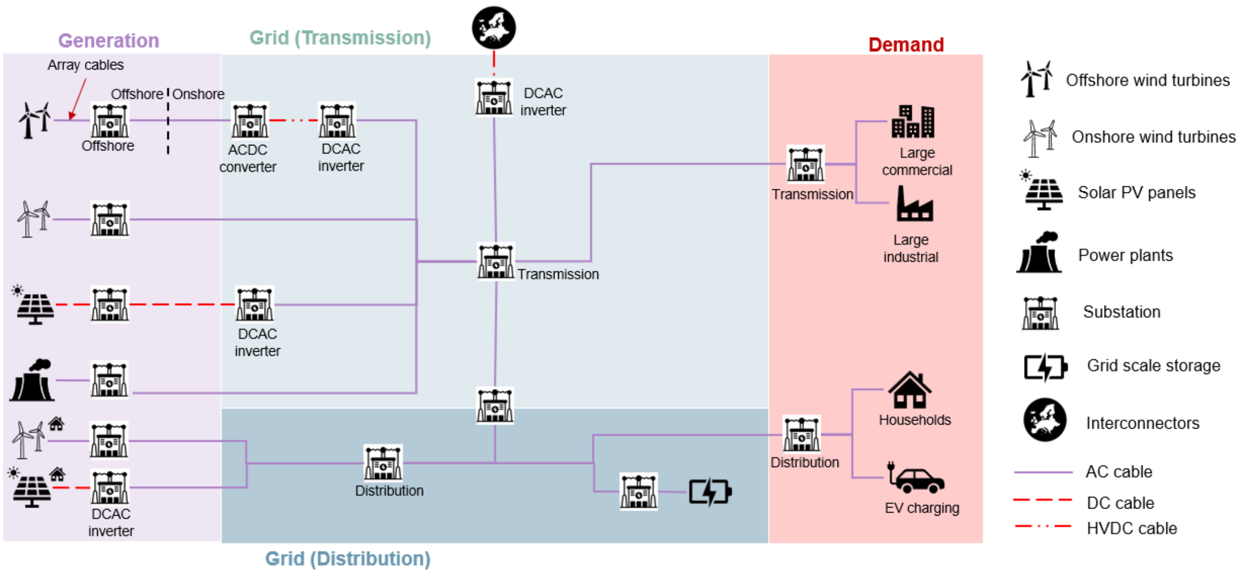


Figure 1 Overview of key components within the GB electricity grid. © Decision Analysis Services Ltd.

1.2.1 Generation

Offshore wind turbines are connected by array cables to an offshore substation or converter station. Export cables connect the offshore station to an onshore substation or converter station, before connecting to the transmission network. Export cables can either be high-voltage direct current (HVDC) or high-voltage alternating current (HVAC). HVDC cables are more efficient over longer distances and so are typically used for offshore wind farms that are located further away from land.

Array cables and export cables are also used to connect onshore wind turbines to the transmission network via substations. For solar panels, which generate DC power, array cables and export cables connect solar panels to the AC transmission network via a DC-AC converter.

Lower-output wind turbines and solar panels (for example, roof-top mounted solar) can be connected to the distribution network.

Step-up transformers within substations connected to generating assets increase the network voltage. A higher voltage results in more efficient long-distance transmission.

1.2.2 Transmission network

The transmission network operates at high voltage levels of 400 kV and 275 kV via overhead lines, underground cables and subsea cables, all of which can be either AC or DC. Subsea cables include ‘bootstraps’, which are HVDC links between different regions of GB, and HVDC interconnectors between GB and six other countries, allowing for the import and export of electricity. The six countries GB is linked with are:

- Belgium
- Denmark
- France
- Ireland
- Netherlands
- Norway

Germany is set to be connected from 2028 (Ofgem, 2024a).

These interconnector cables feed into onshore DC-AC converters, to enable transfer to the AC transmission network. The transmission network typically serves large industrial and commercial consumers.

1.2.3 Distribution network

The high-voltage transmission network is interconnected with the lower-voltage distribution network. This occurs through a series of step-down transformers located in local substations, which reduce the voltage to levels suitable for distribution. The distribution network operates at various voltage levels, including 132, 66, 33, 11 and less than 1 kV. Electrical power is transferred across a series of overhead lines and underground cables. Local substations also connect grid-scale storage solutions (including lithium-ion BESS) to the distribution network.

The distribution network typically serves smaller or individual end users, such as:

- households
- smaller commercial establishments
- public infrastructure, such as schools and hospitals
- transportation systems, such as EV charging stations

1.3 SCOPE OF THIS STUDY

The range and diversity of components within the grid is vast and the quantitative material analysis and scenario demand projections in this study focus on those components with high Al or Cu content. The scope is summarised in Table 1, together with whether subcomponents are typically manufactured from Al or Cu.

Structural components (for example, solar panel racking; electricity pylons, etc.) are out of scope of this study.

Other components out of scope of the study are:

- substation components other than transformers, such as busbars
- power-line components other than conductors, for example capacitors and power-control devices

Table 1 Components within scope and materials.

Component	Subcomponent	Material
Overhead lines	Conductor in cables	Al
Subsea cables (bootstraps and offshore wind export cables)	Conductor in cables	Cu
Offshore wind array cables	Conductor in cables	Cu or Al
Interconnectors	Conductor in cables	Cu
Transformers and HVDC converters	Transformer coil	Cu
Solar connections	Conductor in cables Inverter and transformer	Cu
Lithium-ion batteries for grid-scale storage	Current collector Busbars and wiring	Cu Cu
EV charging cables	Conductor in cables	Cu

Selected key decarbonisation technologies connected to the distribution network are within scope including EV charging infrastructure, solar connections and grid-scale batteries. These technologies are within scope because they provide important additional insight not currently covered within the related decarbonisation critical materials reports and Cu is contained within key functioning components. Note that critical material requirements associated with deployment of large decarbonisation technologies (wind; solar; nuclear, etc.) feature within the relevant decarbonisation foresight reports.

The material requirements in this study focus on announced projects, which are detailed within various documents authored by ESO, the TOs and the DNOs. These are discussed in Section 7). These projects mostly focus on upgrades; since maintenance projects are not publicly available, any additional requirements relating to maintenance activities are beyond the scope of this report.

The time frame of the study covers the period 2023 to 2050.

1.3.1 Northern Ireland

The geographical scope of demand analysed is limited to the GB electricity grid. The electricity grid in Northern Ireland is out of scope for this study: it is part of the Single Electricity Market on the island of Ireland and is regulated by the Utility Regulator, which is accountable to the Northern Ireland Assembly.

2 Supply chain mapping of grid components

Figure 2 shows the different stages of the Al and Cu value chains for components and the material transformations across the mining, intermediate, refining and precursor stages.

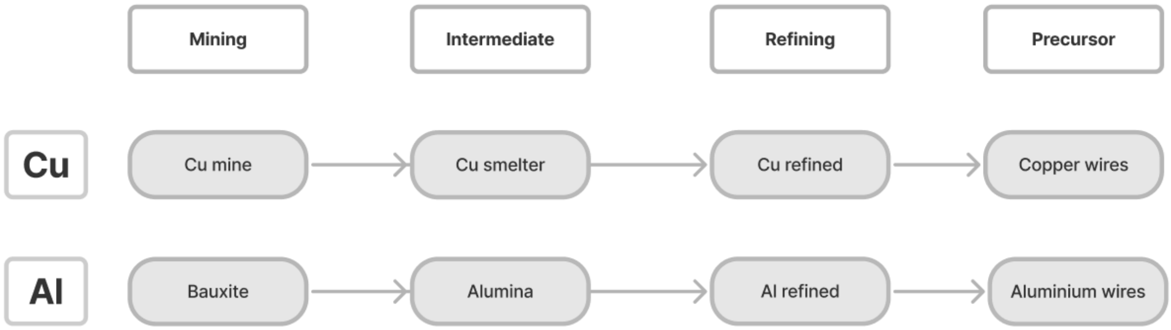


Figure 2 Supply chain mapping of Al and Cu of grid components. BGS © UKRI.

Cu is extracted from low-grade ores, mined from predominantly open-pit mines. The ore is then crushed and ground into a fine powder, which undergoes froth flotation using chemical collectors to make Cu particles hydrophobic. This allows the particles to adhere to bubbles, which are skimmed off the surface. The resulting concentrate then undergoes thickening to remove excess water before being smelted. At high temperatures, the Cu concentrate melts, separating into Cu 'matte' and slag. The matte is further refined in a converter to remove impurities, yielding 'blister' Cu. The blister Cu is purified by heating in a refining furnace to produce 'anode' Cu, which then undergoes electrolysis to form Cu cathodes that are 99.99 per cent pure (University of Arizona Superfund Research Center, 2024; International Copper Association, 2024a). Following purification, the Cu is typically in a rod form, which is then drawn into wire for use in cables and transformers (Eland Cables, 2024a).

Al production begins with the extraction of bauxite ores, which contain alumina (aluminium oxide, Al_2O_3) from open-pit mines. This is refined via the Bayer process. Bauxite slurry is treated with hot caustic soda (sodium hydroxide, NaOH) to dissolve Al-bearing minerals, forming a sodium aluminate solution ('pregnant liquor'). After settling to separate the bauxite residue, the solution is filtered to remove impurities. The liquor is then cooled, causing aluminium trihydroxide ($Al(OH)_3$) crystals to precipitate and grow. These crystals are finally heated in calciners up to 1100°C to remove moisture, yielding alumina powder for smelting to produce Al (International Aluminium Institute, 2023a).

The alumina is processed using the Hall-Héroult process, where alumina is dissolved in molten cryolite within an electrolytic cell, maintained at 960 to 980°C. Large carbon blocks serve as anodes, while the carbon-lined metal container acts as the cathode. A significant direct current splits the dissolved alumina into molten Al and oxygen. The oxygen reacts with the carbon anodes to form CO_2 and the Al collects at the bottom. The Al is then siphoned off to furnaces for alloying and casting into ingots, billets and other products (International Aluminium Institute, 2023b). Like with Cu, Al ingots are drawn into wires for use in lines, cables and transformers (Eland Cables, 2024b).

3 Supply chain bottlenecks

The manufacture of the key grid infrastructure components listed in Table 1 depends upon the supply of raw materials and manufacturing infrastructure, which can be concentrated in certain countries. This concentration can increase the risk of supply disruption and act as a bottleneck. The key countries involved in the mining, intermediate and refining stages of the Cu and Al supply chains are presented in Figure 3. The country flags represent the top three producers of each material.

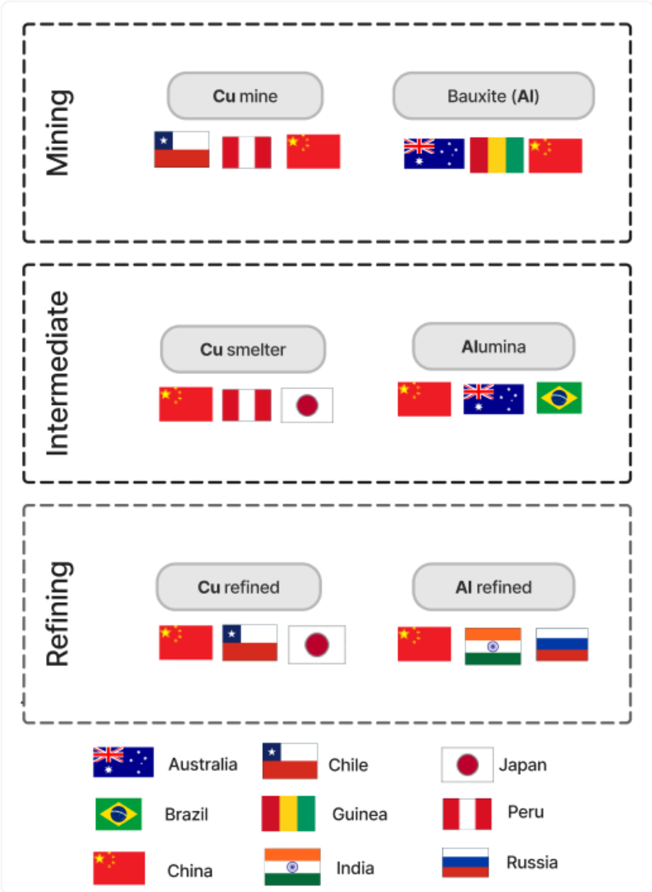


Figure 3 Geographical production concentration in the electricity grid supply chain. The national flags show the top three producers, from left (top producer) to right (third producer), based on a five-year production average between 2017 to 2021 from the BGS World Mineral Statistics Database (British Geological Survey, 2023). BGS © UKRI.

3.1 COPPER

Based upon an average of 2017 to 2021 production data, Chile, Peru and China are the top three producers of Cu ores and concentrates. China appears as the top producer of intermediate and refined Cu, while Japan appears third for both stages.

The production and supply of Cu ore faces challenges from depleting stocks of high-quality ore (Calvo et al., 2016) and vulnerability of supply arising from environmental, social and governance (ESG) issues, blockades and mine closures. Technical issues, strikes, slow ramp-up, weather and declining ore grades have contributed to global Cu disruption rates of 5-7 per cent of the original targeted production since 2019 (International Energy Agency, 2024).

Significant examples include:

- the closure of the Cobre Panamá mine, which accounted for 1 per cent of global Cu output (BBC, 2023)
- a history of stoppages due to protests organised by local communities, most recently in April 2024 (Mining Technology, 2024) at Las Bambas, which produces 30 per cent of Peru's Cu ore supply and 2 per cent of global Cu supply (Mining Technology, 2024)
- strikes in 2017 that resulted in significant disruption at the world's two largest Cu mines, Escondida in Chile (Financial Times, 2017) and Grasberg in Indonesia (IndustriALL, 2017), which respectively contribute to 5 per cent and 3 per cent of global Cu production

3.2 ALUMINIUM

Australia, Guinea and China are the top three producers of bauxite, as presented in Figure 3. As with Cu, China is the top producer at the intermediate and refined stages.

The main Al production and supply challenges relate to environmental concerns. Across the value chain — from mining to refining, semis production and recycling — direct emissions and indirect emissions (from electricity use and transport) accounted for 3 per cent of the world's CO_2 emissions from energy combustion and industrial processes in 2022 (International Aluminium Institute, 2023c; International Energy Agency, 2023a). Broader environmental issues are discussed in more detail in Section 3.3.2.

Bottlenecks in the component supply chain are detailed in Section 3.4.

3.3 MINING, INTERMEDIATE AND REFINING

3.3.1 Production concentration

The global production shares of Cu and Al for the top three producing countries in the mining, intermediate and refining stages are presented in Figure 4.

3.3.1.1 Copper

The top three Cu-producing countries across each stage of the value chain (Chile, Peru, China and Japan) contribute between 45 and 56 per cent of total global Cu production. In the intermediate and refined stages, the second leading producers (Peru and Chile, respectively) accounts for less than 10 per cent of global production.

3.3.1.2 Aluminium

Al has a higher production concentration than Cu, with the top three producing countries across each stage of the value chain (Australia, Guinea, China, Brazil, India and Russia) accounting for over 65 per cent of total global Al production. The concentration is more pronounced at the intermediate and refined stages, with the top producing country (China) accounting for at least 50 per cent of global production.

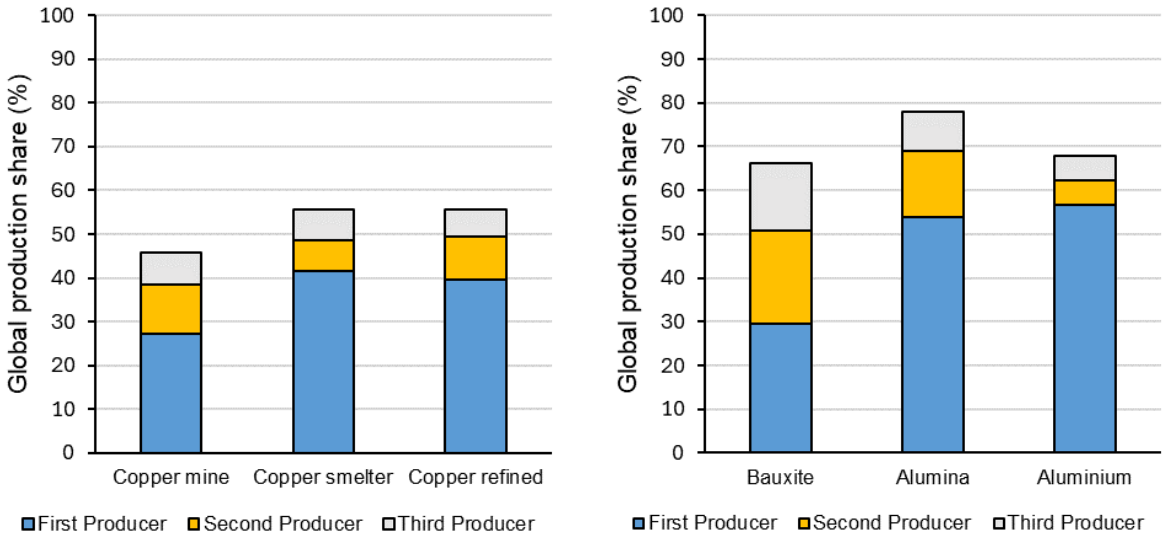


Figure 4 Global mine and refined production of Cu and Al, showing the production shares of the top three producing countries. Data from the British Geological Survey World Mineral Statistics Database are a 5-year average between 2017 and 2021 (Idoine, et al., 2023). BGS © UKRI.

3.3.2 Environmental, social and governance issues

3.3.2.1 Copper

Cu supply faces several ESG-related challenges (ISS Insights, 2022). Open-pit mining operations requires extensive land use, which leads to habitat loss, deforestation and a reduction in biodiversity. The extraction and processing of Cu predominantly involves flotation reagents; however, another way to process the Cu is by heap leaching using acids, which can lead to contamination (Mudd & Jowitt, 2018). The low and declining ore grades mean that more tailings are produced, which must also be stored in embankment dam facilities (Mudd & Jowitt, 2018). These pose a risk of contamination to nearby soil and water bodies with toxic elements like arsenic (As), lead (Pb) and cadmium (Cd). Recent dam failures have also highlighted the dangers to local communities.

As the quality of Cu ore grades has decreased by about 25 per cent in the past decade, more material must be processed to obtain the same amount of Cu, resulting in larger waste volumes (Calvo et al., 2016). Additionally, Cu mines often compete with local communities for water resources, especially in high water-stress areas. This competition can also lead to conflicts, community unrest and production interruptions, with half of the top 20 Cu mines (by capacity) in 2021 located in regions with high or extremely high water stress or arid climates (ISS Insights, 2022).

3.3.2.2 Aluminium

Al production is a major emitter of greenhouse gases, contributing to the release of 1.1 billion t of direct and indirect CO_2e emissions in 2022 (with direct CO_2e emissions accounting for 270 Mt). Over the past decade, the CO_2e emissions intensity of primary Al production (tonnes of CO_2e emitted per tonne of Al produced) has been reducing at a rate of 2 per cent per year. However, for Al production to reach net zero by 2050, the annual reduction rate of emissions intensity needs to increase to 4 per cent by 2030 (International Energy Agency, 2023b).

The International Al Institute has identified three pathways to accelerate the reduction of greenhouse gas emissions (International Aluminium Institute, 2021):

- electricity decarbonisation: using renewable energy to produce Al, and carbon capture utilisation and storage (CCUS) where necessary
    - electricity production currently accounts for over 60 per cent of the sector's emissions
- direct emission: switching fuels burnt in the production process to green hydrogen, and using inert anodes and CCUS
    - direct emissions from fuel combustion account for 15 per cent of CO_2e emissions during Al production
- recycling and resource efficiency: increasing collection rates to near 100 per cent can reduce the need for primary Al by 20 per cent and could lower total (direct and indirect) emissions by 300 Mt of CO2e annually (International Aluminium Institute, 2023d)
    - other sources suggest that adopting a circular economy model could cut production emissions by 40 per cent by 2050 (World Economic Forum, 2020)

The ranked ESG weighted production concentrations of Cu and Al at the mining, intermediate and refining stages are shown in Figure 5. This analysis is based on the indicators recommended in the revised methodology for UK criticality assessment (Josso, et al., 2023). The ranked production concentration is derived from the production shares of the leading producers modified by a factor that reflects the ESG performance of those countries. The higher the score, the poorer the performance in areas like environmental sustainability, social equity and governance practices. A lower score is preferred as it indicates better management and practices in these aspects.

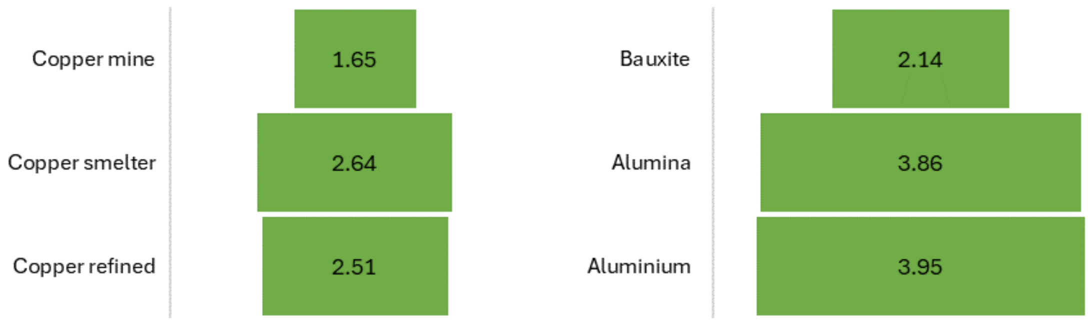


Figure 5 Ranked production concentration scores for key materials (mined and refined) used in electricity grid technologies, based on an ESG-weighted Herfindahl-Hirschman index for each of the top three producing countries. BGS © UKRI.

There are two key observations. Firstly, Al materials have a higher ESG score than Cu materials at the respective stages of the value chain. Secondly, the ranked production concentration score generally increases along the value chain. The highest score – 3.95 for refined Al – is driven by China having an intermediate ESG rating of 5.1. China accounts for over 55 per cent of global production.

3.3.3 Global trade concentration and trade restrictions

Global trade concentration has been calculated using global export and import data from the United Nations Comtrade Database (United Nations, 2024). Exports and imports are categorised under the Harmonized System (HS) of commodity codes, maintained by the World Customs Organization (World Customs Organization, 2022). Table 2 presents a summary of the HS codes used in this study for each element.

For this global trade concentration assessment, import and export data between 2017 and 2021 were analysed. This assessment includes information on trade restrictions, which are sourced from the OECD (Organisation for Economic Co-operation and Development, 2022).

Table 2 Materials included in the analysis of global trade concentration and trade restrictions, with their corresponding HS codes.

Element	Supply chain stage	HS code	Description
Al	Mined	HS260600	Al ores
	Intermediate	HS281820	Al oxide; other than artificial corundum
	Refined	HS760110	Al; unwrought, not alloyed
Cu	Mined	HS260300	Cu ores
	Intermediate	HS740110	Cu mattes
	Refined	HS740312	Cu refined unwrought, wire-bars

As with the production of mined and refined materials, their trade is geographically concentrated and may be subject to restrictions imposed by trading nations. It is important to note that the trade data for intermediate Cu (Cu matte) is excluded due to very limited trade data. The trade distribution for the five selected materials is illustrated in Figure 6.

3.3.3.1 Copper imports

China emerges as the leading net importer of Cu ores, accounting for 57 per cent of global imports. China is also a top net importer of refined Cu refined unwrought wire bars, accounting for 27 per cent of total global imports, placing second behind Qatar, which is a net importer of 47 per cent of global imports.

3.3.3.2 Copper exports

Peru is the largest net exporter of mined Cu with 23 per cent of global exports. It is important to note that Papua New Guinea was excluded from the list of top Cu exporters due to suspected errors in the data, which were orders of magnitude larger than known production values.

In terms of trade restrictions, the second largest exporter of Cu ores, Chile, imposes a 10 per cent fiscal tax on exports.

3.3.3.3 Aluminium imports

China is the largest net importer of bauxite, accounting for 74 per cent of global imports.

3.3.3.4 Aluminium exports

Exports of bauxite and alumina are dominated by Australia, which is a net exporter of 57 per cent and 43 per cent of global exports, respectively.

In terms of trade restrictions, Indonesia — the second largest exporter of bauxite — is prone to imposing export bans. It applied an export ban on bauxite between 2014 and 2017 and introduced one again in 2021. This was driven by a desire to encourage investment in local refineries. However, the Indonesian government is reconsidering this ban due to a local miners' lobby to lift it. The lobby claims that the domestic facilities in Indonesia are inadequate for processing all their output (Reuters, 2023; Liu & Roberts, 2024).

There are no trade restrictions from the top three exporting nations at the intermediate and refined stages of Al and the refined stage of Cu.

Figure 6 The top three importing and exporting countries for mined (ores and concentrates), intermediate and refined stages of Al and Cu, with the share of global trade flows shown for each country. Countries highlighted in red are dominant exporters or importers (where global share exceeds 40 per cent) whilst countries with a cross have active trade restrictions. Compiled from United Nations (2024) and Organisation for Economic Co-operation and Development (2022). Papua New Guinea was excluded from the list of top mined Cu exporters due to suspected errors in the data, which were orders of magnitude larger than known production values.

3.4 COMPONENT AND PRODUCT MANUFACTURE

An overview of companies that are involved in the supply chain of key components is provided in Table 3. Companies highlighted in red have a presence in the UK, typically an office or contact point, to support their operations and customer service. Further insights into the capacity of the UK supply chain, together with risks, are discussed in detail in Section 5.

Table 3 Selected suppliers of key components. Companies with a UK presence highlighted in red. Source: DAS analysis of Baringa (2024).

Overhead lines	Underground cables	Export cables, bootstraps, interconnectors, array cables	Transformers	HVDC converter substations
3M	Brugg Kabel	Hellenic Cables	ABB	GE
Cabelte	Cabelte	JDR Cables	Brush	Hitachi
Garrite	Demirer Kablo	LS Cable	Efacec	Siemens
Lamifil	Hellenic Cables	Nexans	GE Grid	
Tratos	Nexans	NKT	Hitachi	
TFKable	NKT	Prysmian	Hyosung	
Coreal	Prysmian	Sumitomo	Hyundai	
ECN Cunext	Sudkabel	XLCC	Kolektor Etra	
FBE	Tratos	Twentsche Kabelfabriek	Kyte Powertech	
Lumpi Berndorf	Estralin HVC		Ormazabal Cotradis	
Prakab Prazska	Solidal		Schneider	
Quintas & Quintas			Siemens	
Westfälische Drahtindustrie			Tironi	
			Toshiba	

3.4.1 Overhead lines, underground cables and transformers

There is diversity of supply for overhead lines, underground cables and transformers. However, lead times for transformers are influenced by the availability of specialist materials, for example grain oriented steel, which has seen a price surge since 2020, exacerbated by a shortage due to the war in Ukraine (Wood Mackenzie, 2024). Current lead times are estimated to be 15 months, 2 years and 4 years for 32, 132 and 400 kV transformers, respectively (Baringa, 2024).

3.4.2 Subsea cables

In comparison, the market for subsea cables (export cables, bootstraps, interconnectors and array cables) is less diversified, especially for HVDC cables, but growing. There are several subsea cable plants being established in the UK.

- JDR Cables is in the process of establishing a subsea cable facility, which will be operational by 2025 (JDR Cables, 2022, 2024). They have developed and tested Al array cables to mitigate against the growing risk of Cu supply shortages (Financial Times, 2023)

- Sumitomo Electric is establishing a new subsea cable factory in Scotland, to be operational in 2026, which will be able to manufacture HVDC cables (Sumitomo Electric, 2024)
- XLCC aims to enter the UK HVDC cabling market with a facility in Hunterston (XLCC, 2023) ready by 2028 (XLCC, 2024).

HVDC cable shortages are a particular bottleneck, with some suppliers booked out for three to four years, causing significant delays. These have been reflected in the two-year delay on the Viking Link project with Denmark (Ofgem, 2023) and the four-year delay on the NeuConnect project with Germany (4C Offshore, 2022). In addition, European HVDC cable companies NKT (Denmark), Prysmian (Italy) and Nexans (France) currently control over 75 per cent of the market. Some major players are cautious about investing too much in capacity, given the risks around the supply of Cu (Financial Times, 2023). There is additional competition from centralised procurement strategies: Dutch state-owned TenneT secured agreements worth €5.5 billion in May 2023 for 7000 km of cables from Nexans, NKT and others for the development of offshore wind projects (TenneT, 2023).

External analysis suggests that, unless the current global HVDC manufacturing capacity of 4000 km per year increases to 7000 km by 2027, demand will outstrip supply (Financial Times, 2023).

Laying offshore cables requires specialist vessels, capable of laying 4200 to 7200 km of cable per year: only 45 are in operation globally (International Energy Agency, 2023c). More vessels may be needed, but these take three to four years to build, with fewer than 10 shipyards worldwide capable of supplying them (Baringa, 2024).

3.4.3 Converter substations

The HVDC converter substation market is concentrated among major players like GE, Hitachi and Siemens, presenting a higher risk. Siemens Energy has lead times of three to four years for large transformers, exacerbated by competing demand from offshore grids and interconnectors (Financial Times, 2023). Some analysts suggest that there is insufficient manufacturing capacity for key components like transformers and converters (Baringa, 2024).

4 Circular economy

A circular economy can support security of supply and meet decarbonisation targets. Current and potential circular economy policies and initiatives are discussed in this section.

4.1 INTRODUCTION TO THE CIRCULAR ECONOMY

The Ellen MacArthur Foundation defines the circular economy as: 'a systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution. It is based on three principles, driven by design: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature' (Ellen MacArthur Foundation, 2025).

While there may be capital costs associated with implementing circular principles, there are multiple long-term benefits, including:

- reducing emissions
- increasing security of supply for raw materials and products
- reduced landfill waste
- increasing the circulation of recycled materials

National Interdisciplinary Circular Economy Research (NICER)'s circular economy taxonomy (Figure 7) identifies nine stages and six loops that try to maintain the value of materials along the value chain.

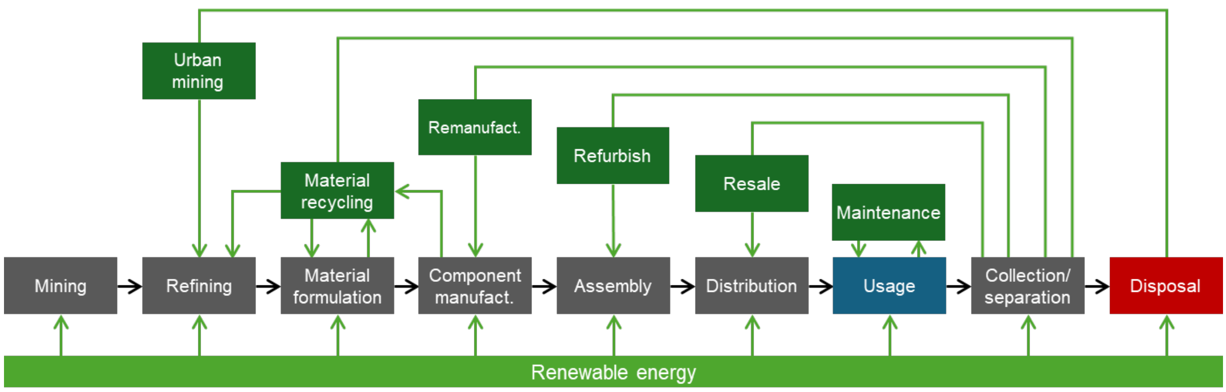


Figure 7 Circular economy taxonomy based on NICER circular economy taxonomy. Adapted from Lysaght, et al. (2024).

This section is split into subsections that are aligned to the taxonomy and consider a circular economy approach in the context of electricity grids across different stages of the value chain. Each subsection explores a view of the current and potential circular economy policies and initiatives:

- mining, refining and material fabrication
- component manufacture
- usage and refurbishment
- end-of-product-life recycling and urban mining

4.2 MINING, REFINING AND MATERIAL FABRICATION

Cu and Al production is an energy and carbon-intensive process. Life-cycle assessments suggest that metal material production rather than component production accounts for most of the embodied emissions in cables and transformers (Jorge et al., 2012a). Typical emissions rates are around 4 t CO_2e per tonne of Cu (International Copper Association, 2023) and 15 t CO_2e per tonne of Al (International Aluminium Institute, 2023e).

Emissions, coupled with higher costs to extract ores in the context of reducing ore quality (Calvo et al., 2016), increasing demand (International Energy Agency, 2024) and vulnerability of mines to blockades, strikes and closures (BBC, 2023), make secondary sources of supply increasingly attractive options.

The primary flows (solid lines) and secondary flows (dashed lines) of Cu and Al are presented in Figure 8. Global data from the stocks and flows model of the International Copper Association (ICA) for the year 2020 were used, as well as data from the International Aluminium Institute (IAI)'s global Al cycle model for the year 2021.

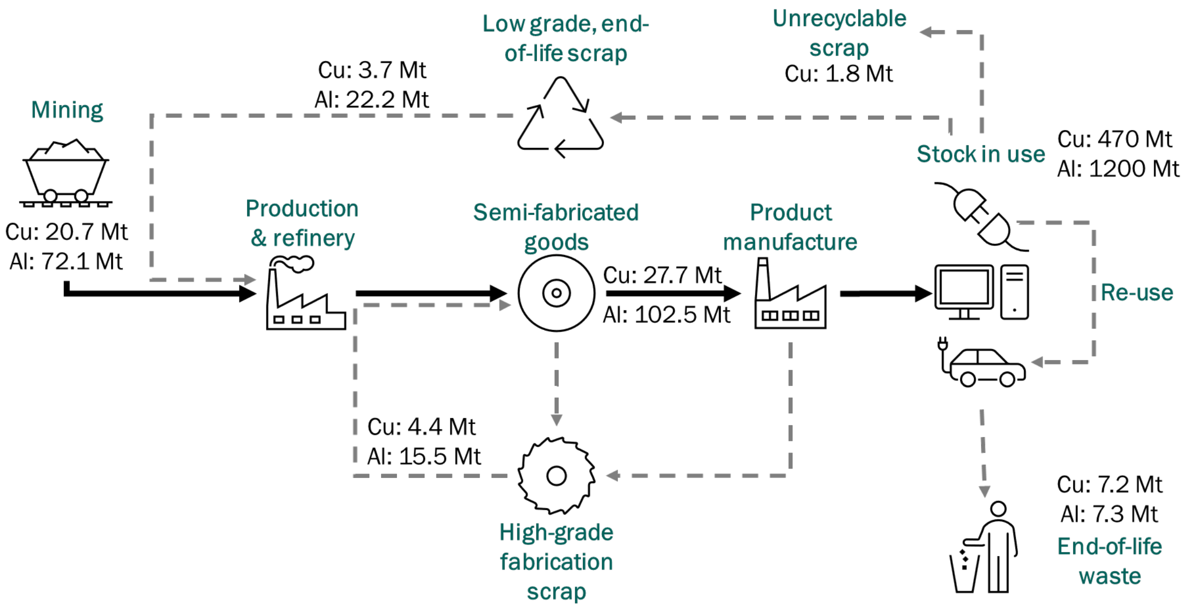


Figure 8 Cu and Al stocks and flows. Solid lines refer to primary flows and dashed lines refer to secondary flows. Units of millions of tonnes (Mt). Source: DAS, with data from International Copper Association (2024a) and International Aluminium Institute (2023f).

International Copper Association (2024a) estimates that globally in 2020, 3.7 Mt secondary, low-grade Cu entered the refinery stage, with primary Cu contributing 20.7 Mt to refineries. An additional 4.4 Mt of high-grade product fabrication scrap (offcuts; shavings, etc.) is estimated to have been added to the production of semi-fabricated goods such as wire, tubing and billets. This is equivalent to a recycling input rate (RIR) of 28 per cent. The RIR is the ratio of secondary (recycled) materials used in the production process of semi-fabricated goods and is one measure of the circularity of a materials system. Similarly for Al, in 2021, 22.2 Mt low-grade scrap and 15.5 Mt high-grade scrap were added to the production process, together with 72.1 Mt primary Al. This results in a higher RIR of 34 per cent.

Cu and Al cables require a minimum purity of 99.9 per cent and 99.7 per cent, respectively. To achieve such high purity, low-grade ore or scrap must be extensively refined or diluted with large quantities of higher-purity metal. Reprocessing methods have been shown to meet these high purity requirements for Cu and Al cable manufacture (Nexans, 2024).

It is forecast that recycled Cu and Al will contribute up to 40 to 45 per cent (The Copper Mark, 2024) and 50 per cent (International Aluminium Institute, 2023g) of the supply, respectively, to meet demand by 2050. Primary sources will therefore still be essential to meet demand. Decarbonising the mining, refining and fabrication stages of the value chain will remain a high priority. Both the Al and Cu industries have highlighted steps to accelerate the path to decarbonisation (International Aluminium Institute, 2021; International Copper Association, 2023).

The UK's only Al smelter, Alvance in Scotland, produces some of the 'greenest' Al in Europe, with emissions of 3.9 t CO_2e per tonne of Al. This is 75 per cent less than the global average and 42 per cent less than the EU average (Alvance British Aluminium, 2024). Alvance uses both pre- and post-consumer scrap and hydroelectric power to minimise carbon emissions. Alvance intends to grow its current production capacity of 42 000 t per year with an additional 100 000 t by 2027 using a mix of recycled Al and primary Al (Alvance British Aluminium, 2024). The UK consumed 800 000 tonnes of semi-manufactured Al products in 2023 (CRU International, 2024) so the output from Alvance could contribute up to 18 per cent of UK demand. BACALL, Hydro and Constellium are other companies that are investing development of reprocessing facilities (BCAST, 2024).

The emerging UK company Evolve Metals aims to develop the UK's Cu refining capacity, using majority secondary scrap as its input (Evolve Metals, 2024).

4.3 COMPONENT MANUFACTURE

For component manufacturers that supply the electricity grid, quality is essential to minimise energy losses and failure rates and maximise useful life (Eland Cables, 2024c).

There are examples of electricity grid component suppliers adopting circular economy principles:

- Nexans and Trimet recently launched Europe's first Al rod containing 10 per cent recycled Al, which has been used to manufacture new cables (Nexans, 2024)
- Prysmian emphasises greater care in supplier selection, both upstream and downstream of the value chain, developing relationships with waste managers that share its vision of sustainability and circularity (Prysmian, 2023)
- circular design principles that consider disassembly and end of life, recognising the benefits available if materials retain their quality through improved end-of-life material separation and, by extension, recycling rate (Hitachi Energy, 2020)

There are also examples of network operators applying circular economy principles, such as through engaging and training suppliers in sustainability best practice (SP Energy Networks, 2024).

4.4 USE, MAINTENANCE, REFURBISHMENT AND RE-USE

The biggest emission driver that transmission and distribution electricity grid operators face is that of energy losses in grid components. Scottish & Southern Electricity reports energy losses of 2 per cent and 5 per cent for transmission and distribution, respectively (Scottish & Southern Electricity Networks, 2019).

Given the UK energy sector is not yet fully decarbonised, energy losses in the grid have associated carbon emissions. Literature on life-cycle assessments estimate network losses account for more than 90 per cent of the carbon emissions over the life of the components (Jorge et al., 2012b). The forecast emissions associated with UK energy generation under different energy scenarios (Figure 9) have been modelled by the ESO[1].

As part of the decision framework on when to replace components, there is likely to be a trade-off between economic and environmental (emissions) costs and therefore a choice whether to prioritise reducing emissions by either replacing components or extending component lifespans through maintenance and repair.

Using recycled materials in grid components is beneficial to reduce embodied emissions and the consumption of new raw materials.

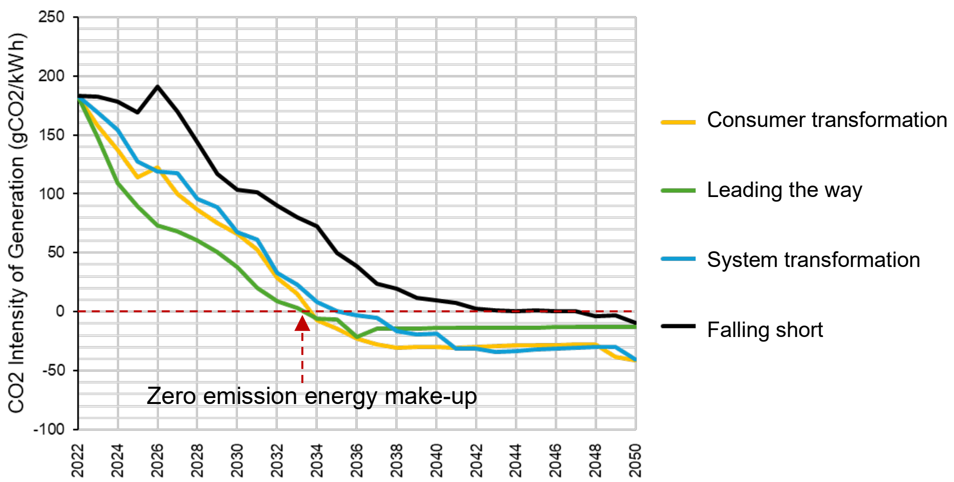


Figure 9 CO_2 intensity of UK energy generation (National Grid ESO, 2023a).

To maintain high-quality grid components, network operators place importance on monitoring and maintenance. Monitoring is essential to understand the state of components and when components should be maintained or replaced. Examples include:

- using real-time sensors in overhead lines to understand sag, deterioration and whether the line can carry a higher capacity (Khawaja et al., 2017)
- remote asset monitoring, using technologies such as thermal imaging and artificial intelligence to assess conditions of assets, can enhance decision making on when to maintain or replace (National Grid, 2023)
- as transformers currently have long lead times, extending their life through repair and preventative maintenance could help to mitigate supply risk; ABB's power transformer group demonstrates an improved maintenance and refurbishment process that can reduce costs and emissions and increase life and capacity (ABB, 2024)
- dynamic line rating (increasing the current-carrying capacity of a line or cable in favourable environmental conditions, such as a cold or windy day) (National Grid, 2023)

[1] The ESO Future Energy Scenarios (FES) describe possible outcomes of the future GB energy system between now and 2050, considering likely demand requirements and the make-up of the energy system to meet this demand

4.5 DISPOSAL, END-OF-LIFE RECYCLING AND URBAN MINING

End-of-product-life disposal and recycling provides a crucial opportunity for reclaiming materials and reducing embodied emissions of new products. Up to 85 per cent of the embodied emissions of Al are in the mining to material refining stage (International Energy Agency, 2023b).

The ICA has identified 7.2 Mt of Cu that were expected to enter recycled end-of-life scrap in 2020 that have not been accounted for (International Copper Association, 2024b). The ICA is undertaking more research to understand this but, if recovered for reprocessing, it could increase the RIR from 28 per cent to 42 per cent.

Similarly, the IAI has identified 7.3 Mt of Al that were not recycled in 2021 (International Aluminium Institute, 2023f). If this re-entered refineries, it would only increase the RIR from 34 per cent to 38 per cent, reflecting the good current rates of Al recycling.

Network operators are required to meet waste-management targets by ensuring that 90 per cent of waste is diverted from landfill and operational recycling rates exceed 50 per cent (National Grid Energy Transmission, 2024). Recycling partnerships enable up to 99 per cent of transformer materials to be recycled (Hitachi Energy, 2020) and above 95 per cent of Cu or Al from cabling to be recovered (Blinová & Godovcin, 2021). RecyCâbles, a European leader in cable recycling and recovery, recovers 18 000 t cable each year for material recovery and re-use to produce new cables, with Cu granules of 99.9 per cent purity (Nexans, 2024).

4.5.1 Hibernating networks

Redundant systems, also called ‘hibernating networks’, could hold significant Cu or Al stocks (Krook et al., 2020). In some EU cities, up to 20 per cent of the current electricity distribution network is deemed hibernating (Krook et al., 2011). However, analysis suggests that the secondary Cu price would have to more than triple before the recovery of materials within obsolete cables becomes economically justifiable (Krook et al., 2011).

4.6 POLICY

Government initiatives to support the transition to the circular economy have been encouraged by The Circular Economy Bill, which passed through the Scottish Parliament in June 2024. The bill requires the Scottish Parliament to have a circular economy strategy, circular economy targets and clear reporting. While this has a particular focus on consumer and household waste, it is a step towards improving and requiring circular economy actions across the value chain in the UK.

CBAM is a Government initiative designed to financially incentivise sustainable supply chains with lower carbon emissions (Department for Energy Security and Net Zero, 2023a). It accounts for the embodied carbon of imported goods by applying a cost based on the difference between the carbon price of the country of origin and the UK carbon price. This mechanism will ensure that the embodied emissions of products are not bypassed by outsourcing supply globally.

5 UK supply chain

There is currently no Cu or Al mining in the UK. However, there are UK mining companies with overseas operations, including Anglo American, Antofagasta, Glencore, Rio Tinto and others. There is a developing presence in UK refining stages, as discussed in this section. The UK has a more established presence at the component stage of manufacture.

5.1 COPPER

While there is currently no Cu refining capacity in the UK, Evolve Metals aims to develop the UK's first Cu refining facility, which will use secondary scrap as its input.

In 2023, the UK exported 240 000 t waste and scrap Cu (using data from the UN Comtrade database: HS code 7404 (United Nations, 2024)). The facility aims to be the first hydrogen-powered Cu refinery, resulting in energy savings of 80 per cent, compared to conventional primary production methods (Evolve Metals, 2024).

5.2 ALUMINIUM

In 2023, the UK consumed 800 000 t semi-finished Al, relying on 1.2 Mt imports (CRU International, 2024) and exporting more than 600 000 t waste and scrap (using data from UN Comtrade database: HS code 7602 (United Nations, 2024)). The UK's consumption of Al is dominated by the transport and packaging sectors, accounting for almost 75 per cent of demand in 2023. Wire and cable demand (of which grid infrastructure is a significant end use) accounts for around 5 per cent of demand (CRU International, 2024).

Due to the UK's limited primary smelting capacity, the country is reliant on Al imports. However, it also exports significant quantities of scrap since there is no reprocessing capability (re-using waste stocks). The UK exports scrap Al at a price worth around half of that which it imports, representing a loss in value worth over £1.5 billion, some of which could be recovered through reprocessing facilities (Innovate UK, 2023).

Alvance, based in Scotland, is currently the only Al smelter in the UK, with a current capacity of 48 000 t per year, which is around 6 per cent of UK's total Al demand in 2023. In 2026 to 2027, Alvance will start operations on a new billet and reprocessing facility, which will have an annual capacity of 100 000 t. A report by the Brunel Centre for Advanced Solidification Technology (BCAST) for the UK Al Federation notes additional new Al reprocessing plants that are being developed, owned by BACALL, Hydro and Constellium (BCAST, 2024).

5.3 COMPONENTS

As indicated by Table 3, there are several companies with a presence in the UK that supply the grid infrastructure market, including:

- overhead lines
- underground cables
- HVDC subsea cables and export cables
- array cables
- transformers
- HVDC converter substations

Companies with a UK presence typically have a UK base or contact point to support their operations and customer service.

There are global supply shortages forecast related to HVDC cables, which are of critical importance to planned UK infrastructure build, the quantities of which are discussed further in Section 6. This bottleneck should be eased slightly by planned HVDC cable plants from JDR Cables (planned production starting 2025), Sumitomo Electric (planned production starting 2026) and, potentially, XLCC (aiming to start production 2028).

5.4 SKILLS SHORTAGE

Although there is a significant component manufacturing presence in the UK, skills shortage is a recognised risk. This has been indicated through news articles (Financial Times, 2023) and Government-commissioned reports (Baringa, 2024). Baringa (2024) indicates shortages across a broad range of professions, including electrical design, test and commissioning engineers, project managers and installation technicians. A board member of Siemens Energy, which supplies transformers and other components for HVDC systems, has said that the biggest bottleneck to implementing projects is skills (Financial Times, 2023).

6 Copper and aluminium demand in Great Britain to 2050

6.1 DEMAND MODEL AND CALCULATIONS

The material demand model for this study is split into three distinct parts, which each estimate the Al and Cu demand of different sections of the GB electricity grid, as described in Section 1.3. These parts are:

- transmission infrastructure: overhead lines, underground cables, subsea cables, interconnectors, offshore wind array cables, transformers and converters
- distribution infrastructure: lower-voltage overhead lines, underground cables and transformers
- distribution technologies: solar connections, grid-scale battery storage and EV charging infrastructure

The model approach is summarised in Figure 10, showing the scope and primary data sources. The subsections that follow discuss in more detail the data sources and assumptions that are related to the three parts of the model. The aggregate of these is presented in Section 6.2, to provide an overarching combined view of total Al and Cu demand between 2023 and 2050.

It should be noted that the model is not producing forecasts; rather it is giving projections, which are based upon a set of assumptions that have been agreed with a reference stakeholder group formed of expert representatives across Government and industry.

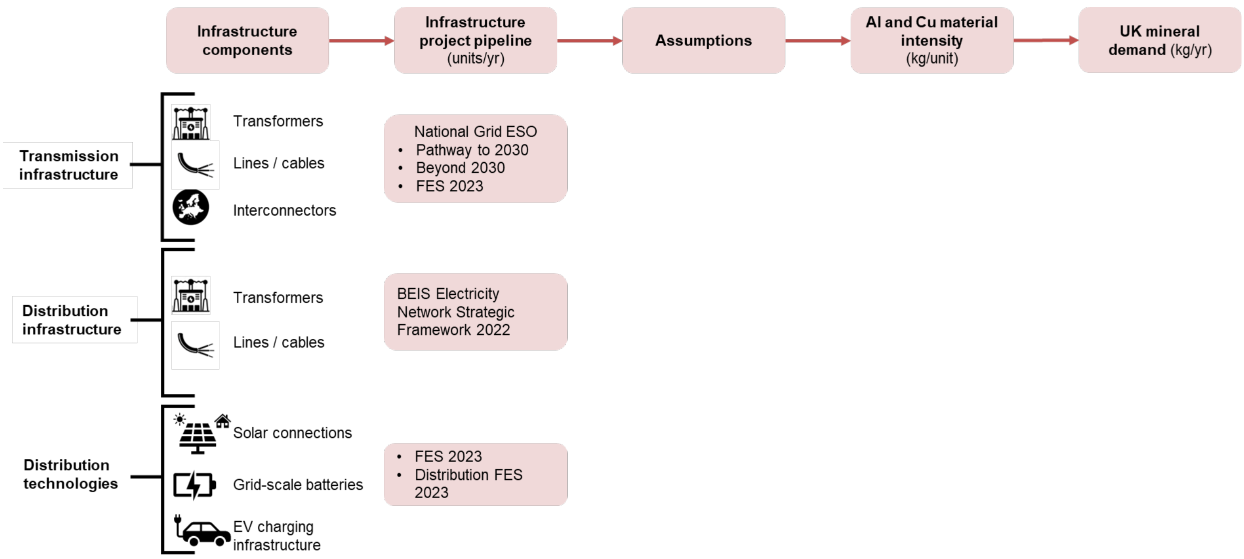


Figure 10 Model schematic showing the stages and data sources for the material demand model. Source: DAS. BGS © UKRI.

6.1.1 Transmission infrastructure

The future Cu and Al material demand in the transmission network is calculated using the following information sources published by ESO:

- Pathway to 2030 (National Grid ESO, 2022b)
- Beyond 2030 (National Grid ESO, 2024a)
- Future Energy Scenarios (FES) 2023 (National Grid ESO, 2023a)[2]

The Pathway to 2030 and Beyond 2030 documents outline planned transmission infrastructure projects. Those with assigned completion dates are mapped against the four FES scenarios. The FES 2023 scenarios describe possible outcomes of the future GB energy system between now and 2050, considering likely demand requirements and the make-up of the energy system to meet this demand. Sufficient infrastructure is undeniably critical to satisfy the requirements of the future system. The key difference with FES 2024 is the more recent document provides a narrower strategic range of pathways, rather than a broader range of possible outcomes under FES 2023.

Where completion dates are not assigned, it is assumed that transmission infrastructure projects under Pathway to 2030 are completed by 2030 and Beyond 2030 projects completed by 2040. It should be noted that projects cited within these publications are announced projects and may not constitute the total required infrastructure build by 2050. Indeed, there are very few projects with explicit completion dates in the 2040s. Additionally, since these documents were published under the previous Government, they do not consider the recent target shift to decarbonise the power sector by 2030 (previously 2035). Therefore, some projects may need to be brought forward to achieve this target.

The following steps and assumptions have been made to determine the future transmission infrastructure needs:

- component requirements (lines, cables and transformers) have been inferred from infrastructure project descriptions in Pathway to 2030 and Beyond 2030 — component mapping to infrastructure requirements are presented in the appendix
- overhead line and underground cable length requirements have been calculated from measuring the point-to-point distance between substations associated with the project and applying a multiplier of 1.15 to account for bends in the route (this ‘bend factor’ is determined from DAS analysis of the ratio of actual line lengths from existing network data with point-to-point distances)
- the split between overhead lines and underground cables is 85 per cent to 15 per cent based on the current split of the network (National Grid, 2015)
- to calculate the array cable length, an array cable multiplier factor of seven times the turbine blade diameter was used (Baringa, 2024)
  - a typical turbine of 14 MW turbine and a 220 m blade diameter was assumed, giving a length of around 1.5 km per turbine
  - a length intensity of around 110 km/GW was used, consistent with other sources (Offshore Wind Scotland, 2024)
  - the total array cable length was then found by multiplying this intensity by the forecast offshore wind capacity in FES 2023 (National Grid ESO, 2023a)
- to calculate the required interconnector length, evidence from the Interconnector Analysis Report (National Grid ESO, 2024b) was used together with FES 2023 (National Grid ESO, 2023a)

[2] At the time of publication, FES 2024 scenarios have been published. However, FES 2023 scenarios are used within this report since delivery dates of transmission infrastructure projects within Pathway to 2030 and Beyond 2030 are mapped against the FES 2023 scenarios.

- subsea export cables for wind farms and interconnectors are assumed to have a multiplier of 1.05 on the straight-line distance to account for bends (DAS assumption)
- dynamic array cables (Cu conductor) connect to floating wind turbines, while static array cables (Al conductor) connect to fixed-bottom wind turbines (Offshore Wind Scotland, 2024)
    - the split between the two types of array cable was determined from the ratio of planned offshore wind capacity of floating to fixed-bottom turbines in FES 2023 (National Grid ESO, 2023a) — 85 per cent fixed-bottom and 15 per cent floating

The calculated overhead line and underground/subsea cable requirement by type is shown in Figure 11. There is a significant demand for array cables, export cables that connect offshore wind farms to the mainland, and high-voltage subsea cables that connect different parts of GB through bootstraps. Under the 'Leading the way' (FES 2023) scenario, the calculated cumulative length requirement for subsea cables to 2040 is around three times that required for onshore lines and cables.

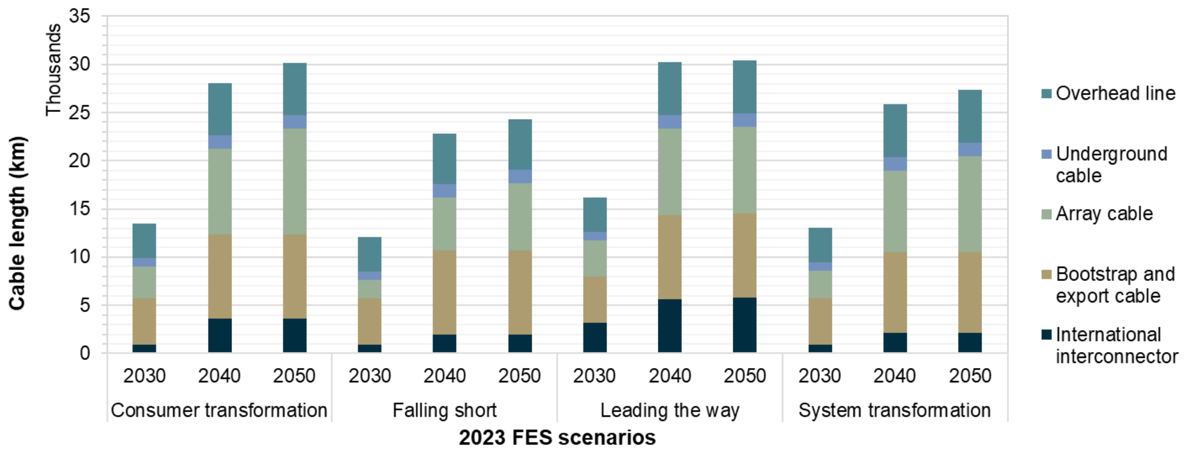


Figure 11 Calculated cumulative line/cable demand of the GB transmission network between 2023 to 2050 by FES 2023 scenario. Source: DAS Analysis. BGS © UKRI.

The requirement for onshore overhead cables is calculated to be around 5000 km to 2040, which is about a quarter of the current onshore transmission network length (UK Government and Ofgem, 2022). Some of this cabling is reconductoring and upgrading networks on existing routes.

Over 90 new substations, converters or substation upgrades are forecast to be required for subsea cable connections. A further 50 new onshore substations or substation upgrades are expected to enable new circuits, improve power carrying capacity or add generation connection capacity.

Cu and Al requirements in the transmission network are calculated through multiplying the forecast quantity of lines, cables and transformers by the component power rating (MW or MVA) and then by the mineral intensity value (kg/MW/km or kg/MVA). The component power ratings and associated mineral intensity values are found in the appendix, together with associated references that were used to source or calculate these values.

The calculated cumulative material demand from 2023 for each of the FES 2023 scenarios is shown in Figure 12. All scenarios are expected to need more than 800 000 t of Cu or Al between 2023 and 2050 to meet the requirements of the GB electricity grid. Mineral demand is forecast to be dominated by subsea cables, including bootstraps, export cables and interconnectors, accounting for around 60 per cent of demand across all scenarios, followed by underground cables and overhead lines. Anticipated demand from substation converters and transformers is dwarfed by cable demand and only accounts for around 5 per cent of total material demand. Despite accounting for around 30 per cent of total required line or cable length, array cables account for around 10 per cent of material demand due to their low mineral intensity.

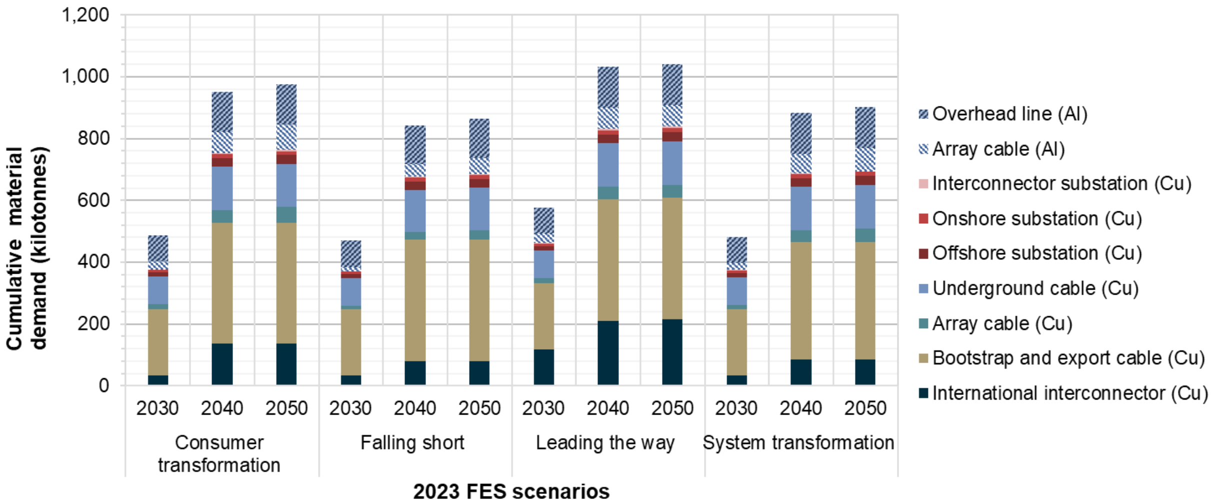


Figure 12 Calculated cumulative Al and Cu demand of the GB transmission network between 2023 to 2050 by FES 2023 scenario. Source: DAS Analysis. BGS © UKRI.

6.1.2 Distribution infrastructure

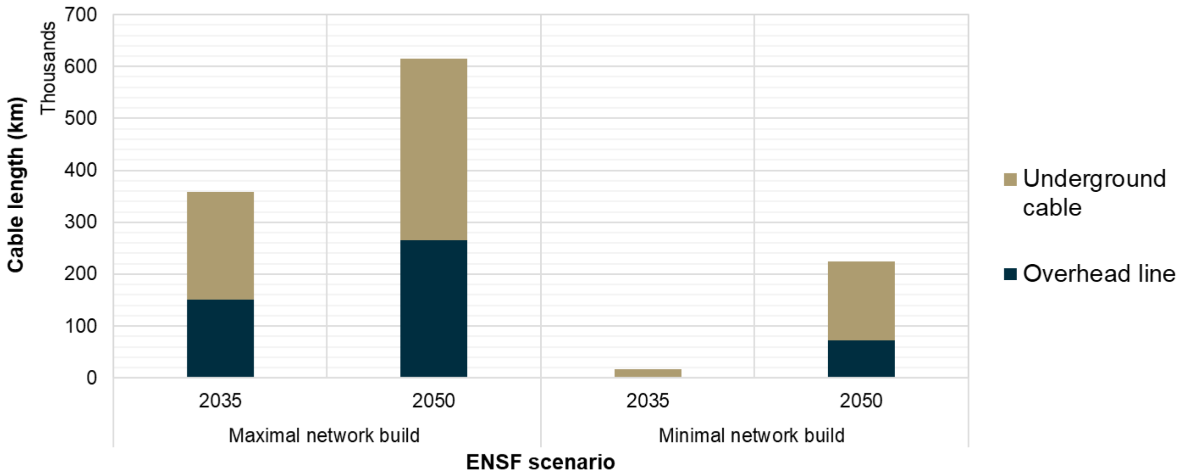
Scenario data to model the distribution infrastructure demand are taken from the BEIS Electricity Network Strategic Framework (ENSF) (UK Government and Ofgem, 2022). The ENSF builds on the UK Government's British Energy Security Strategy and sets out the long-term strategic requirements for the GB distribution electricity network. It uses in-house Government electricity demand and generation models to understand the implications of increasing electrification on the future design of the electricity network between now and 2050. The implications on design are quantified in an accompanying annex to the ENSF.

The ENSF quantifies future infrastructure requirements through two scenarios: a minimal and a maximal network build scenario. The influencing factors behind these scenarios are the level of headroom capacity within the low-voltage network and the pathways of electrification to reach net zero. The ENSF also considers two pathways: a lower-demand scenario, driven by less electrification of heat and transport, and a higher-demand scenario. In both cases, net zero is achieved by 2050 and the commitments within the UK's sixth carbon budget (2033 to 2037) are upheld.

The maximal network build scenario considers the case where the low-voltage network is most constrained (least headroom capacity) and the higher electrification pathway is taken. The opposite cases are considered for the minimal network build scenario.

The ENSF also considered two time horizons: overall UK net zero by 2050 and decarbonisation of the energy sector by 2035. Note that the new UK Government has announced plans to bring this target forward to 2030.

The cumulative GB overhead line, underground cable and transformer requirements from 2023 to 2050 are presented in Figure 13, as stated in the ENSF. These are additional infrastructure requirements on top of the existing network. The maximal network build scenario forecasts that around 600 000 km additional network lines will be required to 2050, which is over 70 per cent of the existing network length (estimated to be 840 000 km within the ENSF). This increase consists of 560 000 km of underground cables and 280 000 km of overhead lines. Within the same scenario, 900 000 transformers are required by 2050.



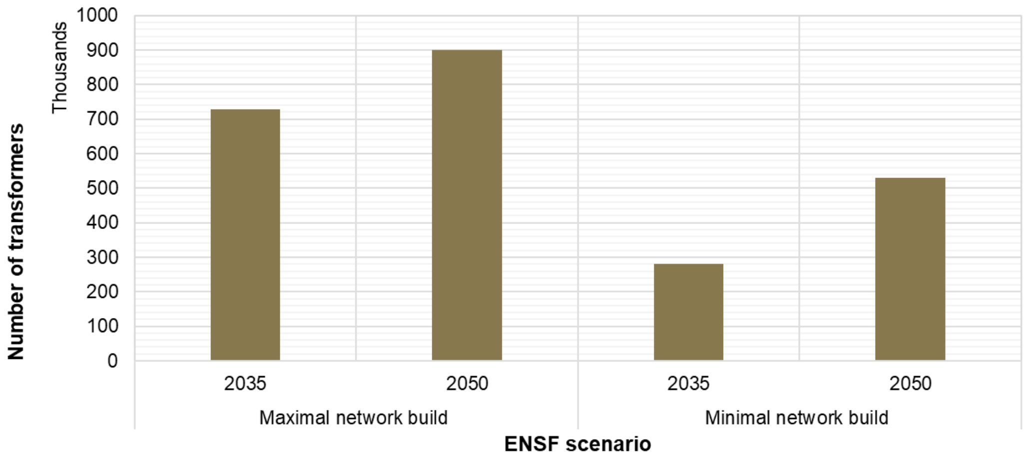


Figure 13 Cumulative line, cable and transformer demand of the GB distribution network from 2023 to 2050 by ENSF scenario. Source: DAS analysis of ENSF. BGS © UKRI.

To calculate the required Cu and Al, the following steps and assumptions were made:

- the future split of the different voltage levels of required overhead lines, underground cables and transformers is based on the current voltage level split of the network, using evidence within the ENSF and from Ofgem and the Energy Networks Association (Energy Networks Association, 2015)
- the power ratings (in MW and MVA) of the required overhead lines, underground cables and transformers were determined using average power ratings of the existing network, using publicly available DNO datasets
- material intensities (in kg/MW/km for lines and cables and kg/MVA for transformers) have been estimated using design information provided through websites of manufacturers of overhead lines and underground cables, and though transformer nameplates or environmental product declarations
    - power ratings, material intensities and associated references are given in the appendix for lines and cables, and transformers
- the conductors in overhead lines are typically made of Al; historically, Cu has been used for the conductors in underground distribution cables and the windings of lower-voltage distribution transformers, and the demand calculations assume these material attributions
    - opportunities for replacing Cu with Al in underground cables and distribution transformers are discussed in Section 8.4.3

The cumulative material requirements of Cu and Al from 2023 are presented in Figure 14. The appendix presents a more detailed breakdown of the demand by the different voltage levels. Under the maximal network build scenario, 450 000 t of Al and Cu are required by the energy sector decarbonisation target (previously 2035) and 680 000 t by 2050. Of this, around 100 000 t Al will be required for overhead lines and 580 000 t Cu for underground cables and transformers. The minimal network build requirements are around half those of the maximal build scenario.

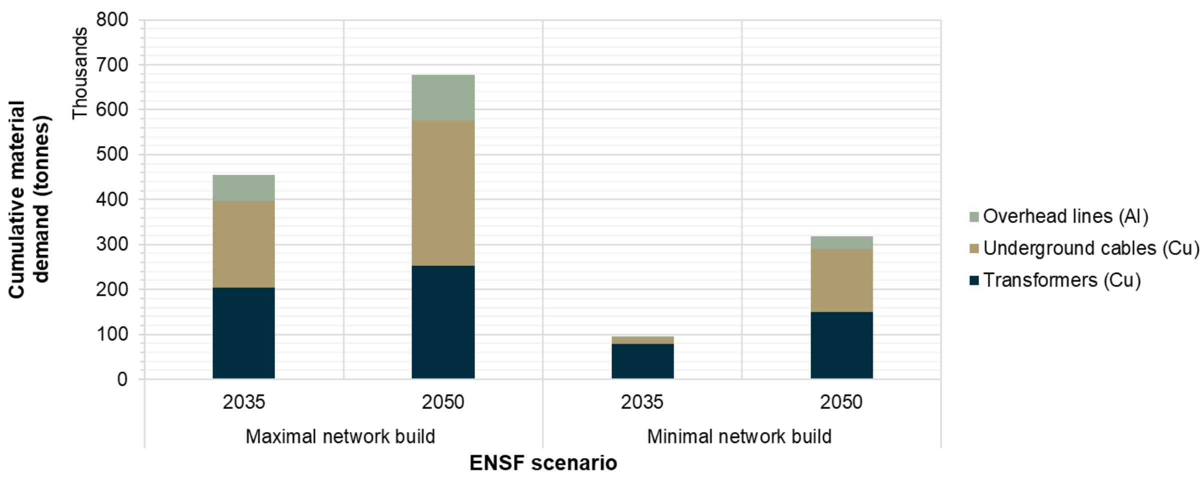


Figure 14 Calculated cumulative Al and Cu demand of the GB distribution network between 2023 to 2050 by ENSF scenario. Source: DAS Analysis. BGS © UKRI.

Bringing the power sector decarbonisation target forward will have a significant effect on the average annual material requirements. Assuming the same quantities of materials will be required in 2030 as they were in 2035, this is expected to cause the average annual Cu and Al requirements to increase by over 60 per cent in the maximal network build scenario, shown in Table 4.

Table 4 Average annual distribution network material requirements before and after power sector decarbonisation target year for the maximal network build scenario. Source: DAS analysis.

Power sector decarbonisation target year	Average annual material requirements between 2023 and target year (kilotonnes/year)	Average annual material requirements between target year and 2050 (kilotonnes/year)
2035	35	14
2030	57	11

6.1.3 Distribution technologies

Scenario data to model the distribution technology material demand are determined using FES 2023 and the distribution FES (DFES) 2023 documents. DFES documents are published by each of the six DNOs and outline the range of credible futures for the growth of the distribution network, aligned to the national FES scenarios. The website address of the data sources used for each DFES is provided in the appendix.

To calculate the material requirements, the following steps and assumptions have been made:

- grid-scale storage battery capacity forecasts were determined from aggregates of data across the different DFES documents
- for the purposes of this analysis, storage batteries are assumed to be lithium-ion, which contain Cu in the current collectors and to connect electrodes
- material requirements for solar connections and EV chargers vary by subtechnology (for instance, large ground-mounted, commercial roof-top and domestic roof-top solar connections, and three levels of EV chargers)
- for solar connections and EV chargers, the level of data required to reliably determine material requirements was published by some DNOs but not others. To bridge this gap for solar connection estimates, subtechnology ratios were estimated using complete DFES datasets, which were then applied across the aggregate distributed solar capacity reported in the FES 2023 dataset
- EV numbers are typically reported instead of forecasted charging capacity, so the forecasted ratios (2020 to 2050) of EV charging capacity per EV from complete DFES datasets were multiplied by EV numbers within FES 2023 data to get EV charging capacity
- the 2023 split of EV chargers by level was applied to the forecast EV charge capacity to estimate the capacity makeup by level — these data are provided in the appendix

The forecast capacity increase of the distribution technologies within scope by 2050 is shown in Figure 15. Large, ground-mounted solar connections are forecast to have the highest capacity, broadly followed by grid-scale storage batteries and level 3 EV chargers.

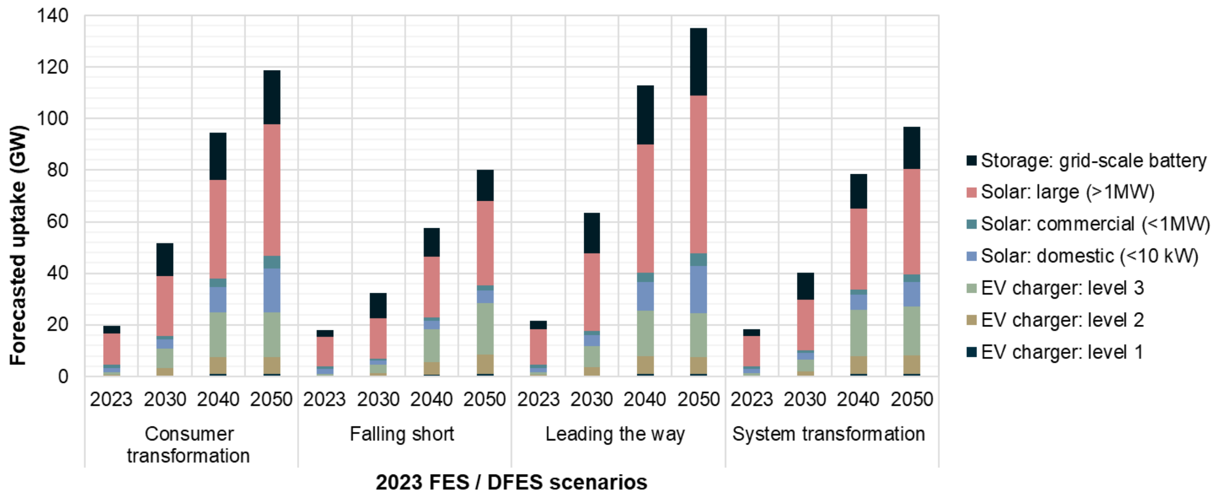


Figure 15 Uptake of GB distribution technology between 2023 baseline and 2050. Source: DAS Analysis BGS © UKRI..

The material intensities of technology types used (and the relevant sources) are given in the appendix. These were multiplied by the forecast capacity to estimate the future material demand. Al does not feature in this section of the model, since it is mostly used as a structural material in the context of these technologies. Structural components are out of scope of this study.

The cumulative forecast Cu demand from 2023 is shown in Figure 16. The cumulative Cu demand for all distribution technologies reaches 230 000 t in the 'Leading the way' scenario. Solar connections account for around 80 per cent of total Cu demand in the distribution technologies, across all scenarios. EV chargers have a negligible Cu demand compared to other technologies, requiring a maximum of 1000 t by 2050. This is due to low material intensities across all EV charger types when compared to battery storage and solar connections. Grid-scale battery storage cumulative Cu demand varies between 20 000 t and 45 000 t by 2050.

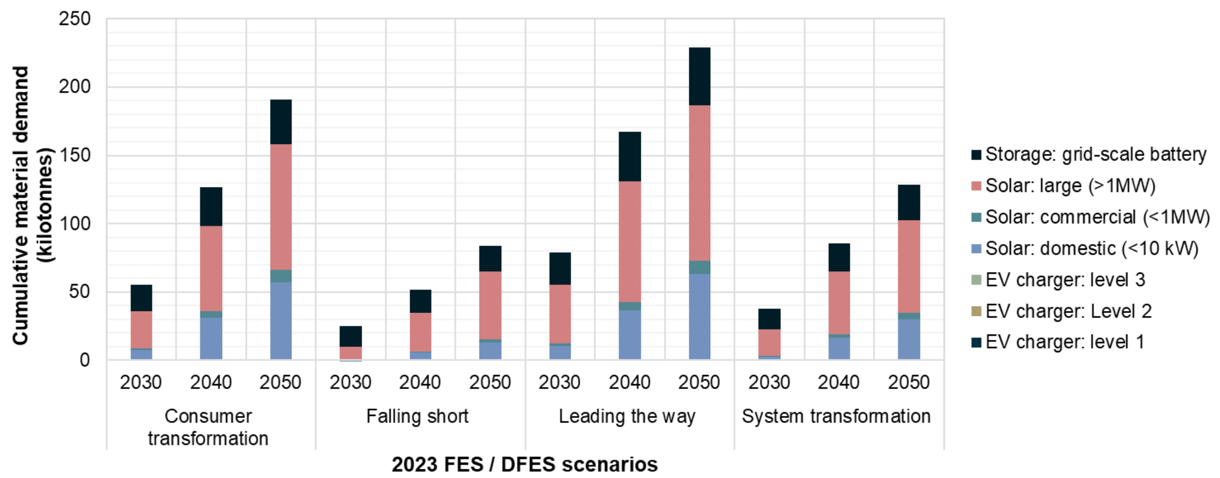


Figure 16 Cumulative Cu demand of GB distribution technology from 2023 to 2050. Source: DAS Analysis. BGS © UKRI.

6.2 AGGREGATE DEMAND FOR GREAT BRITAIN

The calculated material demands within the three subsections of the model are compared in Figure 17. The cumulative Cu demand between 2023 and 2050 in the highest demand scenario is approximately:

- 800 000 t for transmission infrastructure
- 600 000 t for distribution infrastructure
- 200 000 t for distribution technology

This aggregates to 1.6 Mt.

The aggregate Al demand between 2023 and 2050 in the highest demand scenario is 300 000 t, comprising 200 000 t for transmission infrastructure and 100 000 t for distribution infrastructure.

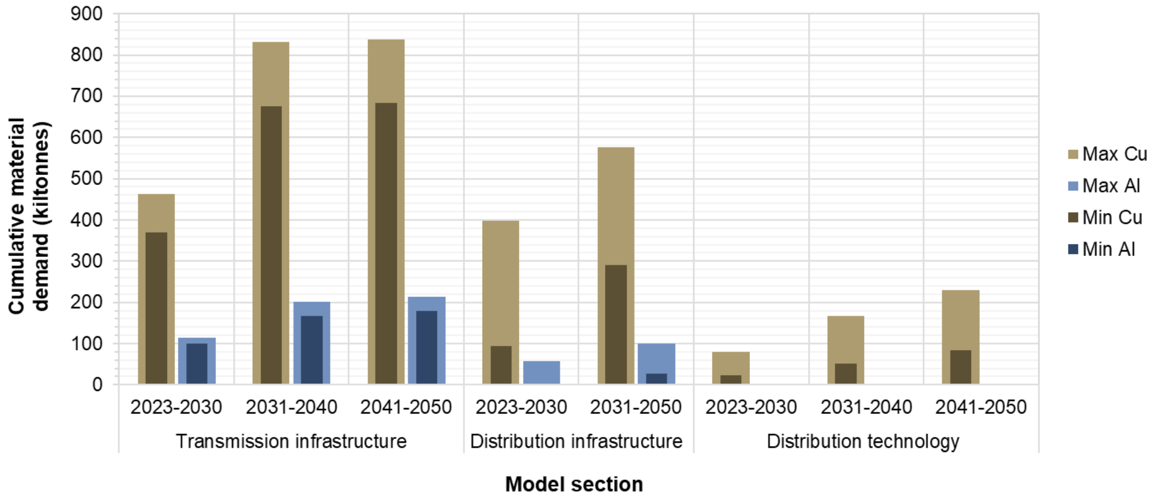


Figure 17 Cumulative GB material demand between 2023 and 2050 for the transmission and distribution network and distribution technologies. The minimum and maximum values represent outputs of the different scenarios. DAS Analysis. BGS © UKRI.

Global refined production values in Table 5 were used to compare the GB material requirements with global supply (including secondary production).

Table 5 Global primary and secondary production of Cu and Al.

Element	Global primary production (5-year average) (tonnes)	Global refined production including secondary (5-year average) (tonnes)
Cu	17 064 904	24 302 950
Al	64 360 000	106 900 000*

Figures from British Geological Survey (2023) except * from International Aluminium Institute (2023f) .

The average annual GB demand is compared to global production of the material in Figure 18. Assuming the power sector decarbonisation target shifts to 2030, the maximum average annual demand as a percentage of global production will occur between 2023 and 2030: 0.5 per cent for Cu and 0.02 per cent for Al.

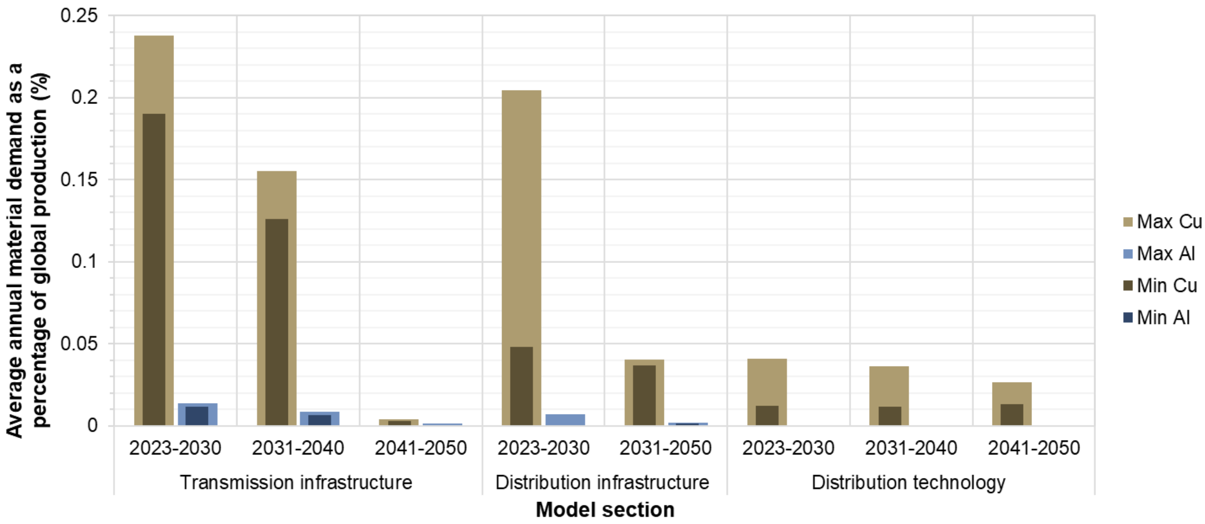


Figure 18 Average annual GB demand as a percentage of current global metal production (five-year average, 2017 to 2021). The minimum and maximum values represent outputs of the different scenarios. DAS analysis. BGS © UKRI.

6.3 GLOBAL GRID DEMAND VS DEMAND PROJECTIONS FOR GREAT BRITAIN

The International Energy Agency (IEA) forecasts for the average annual demand of Cu and Al for global electricity grids are presented in Figure 19. The values exclude Cu use in generation capacity and focus on the conductor cables and wires and transformer components. The IEA scenarios developed are:

- 'Announced pledges' scenario (APS), which includes recent national announcements as of August 2023 for long-term net zero targets
- 'Net zero emissions by 2050' scenario (NZE), which describes a pathway to achieve net zero CO_2 emissions by 2050 and aligns with limiting global temperature rise to 1.5°C

The UK accounts for between 1.0 per cent and 1.5 per cent of the global Cu demand for transmission, distribution and transformer equipment requirements between 2023 and 2030, the UK's most mineral-intense year range, and 0.3 per cent of the Al requirements. This places the UK in significant competition with the global market for supply chains and products, particularly Cu-intensive cables.

Globally, millions of tonnes of Al and Cu will be required in electricity grids to reach net zero targets and meet global electrification requirements. Figure 20 presents average annual Cu and Al demand for electricity grids as a fraction of 2017 to 2021 global refined production. The Al requirement increases from 15 per cent of average annual global refined production to 25 per cent in the maximum (NZE) scenario by 2050.

Global grids will require around 25 per cent of 2017 to 2021 refined Cu production between 2022 and 2030, rising to over 45 per cent in the 2030s and 2040s for the maximum (NZE) scenario.

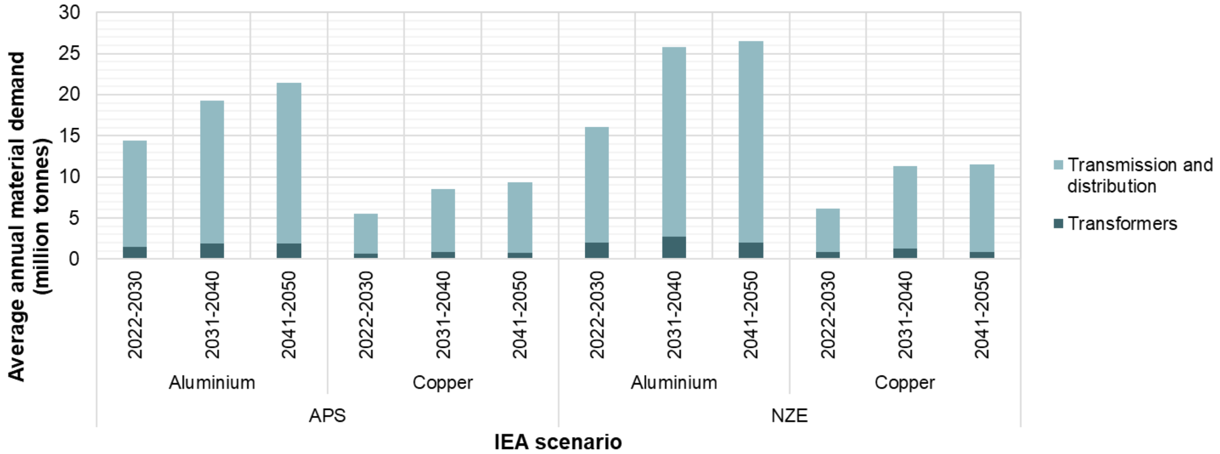


Figure 19 Global electricity grid average annual material demand. Source: DAS analysis of International Energy Agency (2023c). BGS © UKRI.

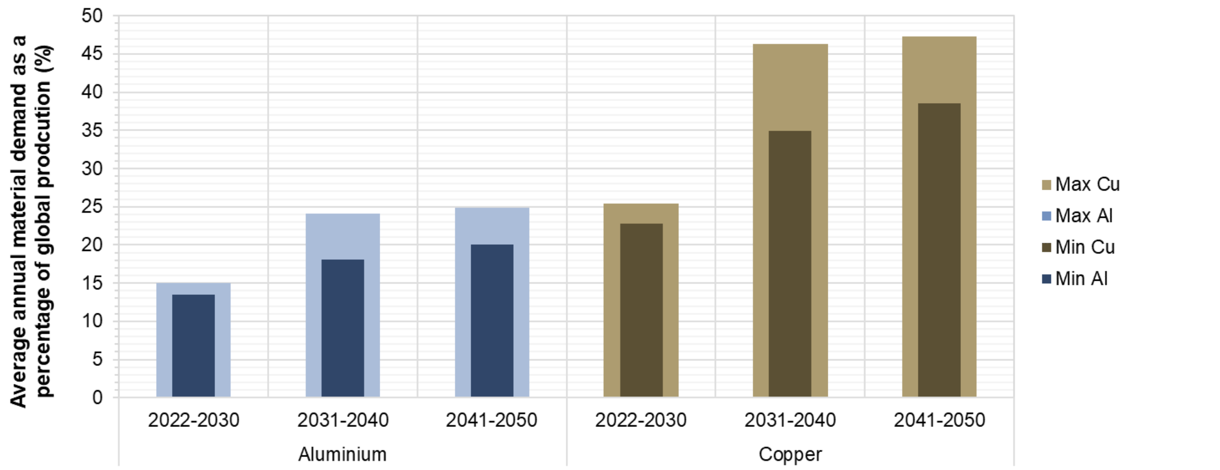


Figure 20 Global electricity grid average annual material demand as a percentage of 2021 global refined material production. Source: DAS Analysis of International Energy Agency (2023c). BGS © UKRI.

7 Discussion and conclusions

Security of supply of Cu and Al is critical to energy transition, achieving UK's net zero ambitions by 2050 and decarbonising the power sector by 2030. The analysis in this report forecasts that a cumulative total of up to 1.6 Mt Cu and 300 000 t Al will be required to enable this by 2050. These national energy transition ambitions, which are replicated internationally, will place unique and acute pressures on the global supply chains of Cu and Al.

The main analysis conducted in this study focused on those components in the electricity grid with high Al or Cu content. At the infrastructure level, the scope of analysis included transformers, overhead lines, underground and subsea cables, interconnectors and offshore wind-array cables, and export cables. At the technology level, component analysis included solar panel connection cables, EV charging cables and grid-scale storage batteries.

7.1 DEMAND BY GREAT BRITAIN

The cumulative material demand between 2023 and 2050 for upgrading the GB electricity grid is expected to be 1.1 Mt Cu and 200 000 t Al in the minimum demand scenario. In the maximum demand scenario, this increases to 1.6 Mt Cu and 300 000 t Al. In line with UK targets to decarbonise the energy sector, between 50 and 60 per cent of total Cu and Al needs to 2050 are required by 2030, in a rapid expansion of capacity and offshore cable additions to the network.

Securing supply chains for this rapid expansion poses a significant challenge. GB's electricity grid Cu demand peaks at 0.5 per cent of current global supply between 2023 and 2030, equivalent to 2 per cent of global Cu needs for grid infrastructure networks over the same time period. Al demand for GB grids is expected to reach 0.02 per cent between 2023 and 2030: GB accounts for just 0.1 per cent of global grid Al needs in the 2020s.

The UK is competing with a rapidly expanding global market in a diverse Cu and Al supply chain. Specific component supply chain challenges such as those of transformers and HV subsea cables with long lead times are expected to drive capacity pressures.

7.2 GLOBAL COPPER SUPPLY AND DEMAND

Cu production is currently sufficiently diversified to result in low-ranked production scores across three stages of the upstream supply chain: mining, intermediate and refined (1.7, 2.6 and 2.5, respectively). The ranked production score is derived from the production shares of the leading producers modified by a factor that reflects the ESG performance of those countries, out of a maximum value of 10 (Josso, et al., 2023).

Based on the current mining commitments, the supply of mined Cu is expected to peak in 2026, followed by a reduction, partly due to the declining quality of ore grades. Chile is currently the main supplier of mined Cu (supplying close to 30 per cent of mined Cu production). The Democratic Republic of the Congo (DRC) is forecast to be the second-largest producer of Cu ore through to 2040 (International Energy Agency, 2024). DRC has a particularly poor ESG score, which will contribute to a growing supply risk.

ESG issues have been particularly prominent in Latin America and Cu supply is vulnerable to blockades and mine closures. This was demonstrated by the closure of the Cobre Panamá mine in Panama in 2023 due to protests around environmental concerns and protests at Las Bambas in Peru in 2022 due to workers conditions. Technical issues, strikes, slow ramp-up, weather and declining ore grades have contributed to global Cu disruption rates of 5 to 7 per cent of the original targeted production since 2019 (International Energy Agency, 2024).

At the refining stage of the supply chain, the IEA forecasts that China's share of the refined market will increase from 40 per cent to 50 per cent by 2030 (International Energy Agency, 2024).

Together with the growing supply risk, this analysis forecasts that demand for Cu will increase from 26 Mt per year in 2023 to 36 Mt by 2040, as shown in Figure 21. The increase in demand is primarily driven by growth in the renewables, EVs and electricity networks sectors. When considering Cu supply, the output from committed mining projects, forecasted recycled production and demand shows a Cu shortfall, which is anticipated to emerge over the next one or two years, unless primary production capacity increases (International Energy Agency, 2024).

These increasing supply chain pressures have pushed Cu prices to an all-time high this year (2024), reaching $11 000 per tonne in May 2024 on the London Metal Exchange (London Metal Exchange, 2024). Record prices have also been driven by increasing capital and operating costs incurred by mining companies, caused by reducing ore quality, longer permitting times, inflation and sustainability requirements (Financial Times, 2024). Prices have reduced slightly since May 2024 due to lower-than-expected demand from China so far this year. China is starting to substitute Cu wire for Al, possibly due to price pressures (Mining.com, 2024).

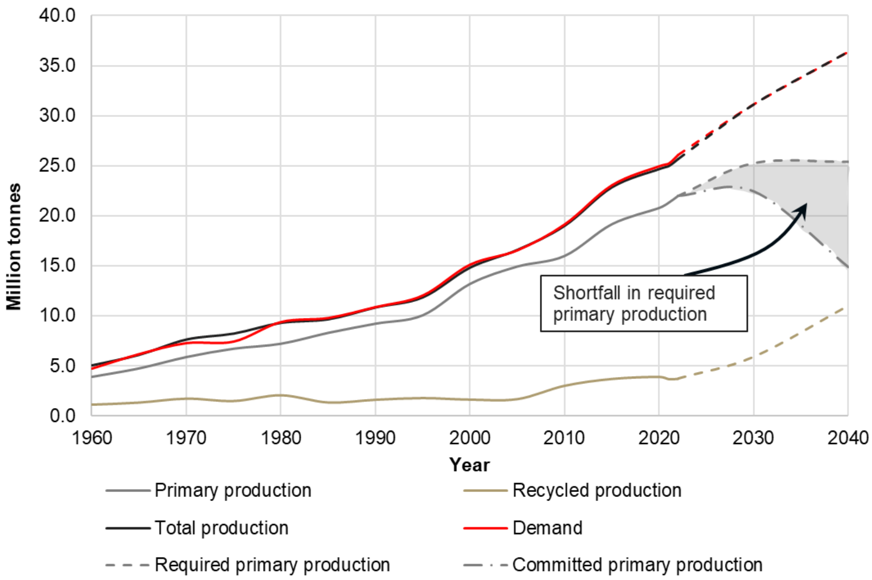


Figure 21 Global Cu supply and demand forecasts. Source: DAS analysis of International Copper Study Group (2023) and International Energy Agency (2024). Solid lines refer to measured data from the ICSG and broken lines refer to forecast data from the IEA. BGS © UKRI.

There are several solutions emerging and under consideration in the global supply chain to overcome the Cu supply challenges:

- direct deals between cable manufacturers and mining companies, so that mines are financed in return for security of supply
    - this is precedented in the EV manufacturing sector, as Stellantis (owner of Jeep, Fiat and Peugeot) has a direct financing deal with McEwen Copper (Stellantis, 2023)
- greater supply chain integration — for example, Nexans owns rod mills, which is helpful to ensure security of supply

- Nexans is also looking to increase its recycling rate from 5 per cent to 30 per cent by 2030, partly to improve security of supply, in addition to meeting decarbonisation targets (Nexans, 2024)
- material substitution, as is being demonstrated by China's shift to Al cables (Mining.com, 2024)

7.3 GLOBAL ALUMINIUM SUPPLY AND DEMAND

While Al is a key primary and potentially a substitution material within the electricity grid sector, its supply is less diversified than Cu across the mining and refining stages, representing a potential supply risk. Australia and China account for 30 per cent and 60 per cent of the mined and refined market, respectively. The higher production concentration than Cu leads to greater ranked production concentration scores across three stages of the upstream supply chain — mining, intermediate and refined (2.1, 3.9 and 4.0, respectively).

The dominance of Australia and China in the bauxite supply chain is reflected in global trade flows. Since smelting capacity in Australia is less than its bauxite production rate, it is a net exporter of bauxite, accounting for 57 per cent of global bauxite exports between 2017 and 2021. Since Chinese smelting capacity is higher than its bauxite production, it is a net importer of bauxite, accounting for 74 per cent of global bauxite imports over the same time period.

Emissions from greenhouse gases are the key ESG issue for the Al value chain, with 1100 Mt of direct and indirect CO_2e generated in 2022. Over the past decade, the emissions intensity of primary Al production (tonnes of CO_2e emitted per tonne of Al produced) has been reducing at a rate of 2 per cent per year. However, for Al production to reach net zero by 2050, the annual reduction rate of emissions intensity needs to increase to 4 per cent by 2030 (International Energy Agency, 2023b).

The International Aluminium Institute has identified three pathways to accelerate the reduction of greenhouse gas emissions (International Aluminium Institute, 2021):

- electricity decarbonisation: using renewable energy to produce Al, and CCUS where necessary
- direct emission: switching any fuels that need to be burnt in the production process to green hydrogen and using inert anodes and CCUS
- recycling and resource efficiency: increasing collection rates to near 100 per cent can reduce the need for primary production, thereby reducing emissions

Manufacturing plants that employ some of these initiatives have reduced emissions by a quarter, from around 16 t to 4 t of CO_2e per tonne of Al (World Economic Forum, 2023). The Alvance plant in Scotland is an example of this.

Demand for Al is expected to experience significant growth, with global requirements forecast to increase from 86 Mt in 2020 to 120 Mt in 2030, a rise of 40 per cent as shown in Figure 22 (International Aluminium Institute, 2022). This will be met by a forecasted increase in primary production and recycled supply. It is anticipated that, by 2050, recycled production will match primary production, with around 80 Mt contributed from each source (International Aluminium Institute, 2023g). Confidence in the Al supply chain is reflected in the price of Al, which has remained stable between $2000 and $2500 per tonne since June 2022, around a quarter of the price per tonne of Cu.

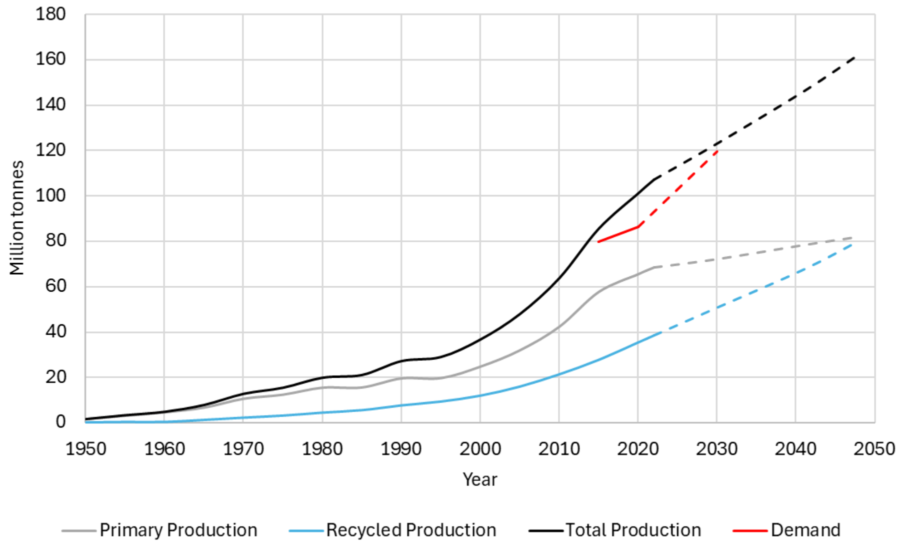


Figure 22 Al and Cu supply and demand forecasts. Source: DAS analysis of International Aluminium Institute (2022, 2023g). Solid lines refer to measured data and broken lines refer to forecast data. BGS © UKRI.

7.4 LEVERS TO DE-RISK SUPPLY AND ACHIEVE NET ZERO

7.4.1 Accelerating the planning process and clarifying demand

Transmission and distribution network planning recommendations provide several opportunities to improve demand foresight and assist security of supply. There is currently no whole-GB energy system view of the infrastructure plans and requirements across both the transmission and distribution networks from which to build a clear view on materials demand.

Transmission and distribution network planning is separate. Consequently, several planning documents were used in this study to produce realistic estimates of the holistic demand for the GB energy grid to 2050. There are several planning documents and frameworks owned across DESNZ (for example, the ENSF), Ofgem (for example, RIIO Price Control Framework) and ESO (for example, FES scenarios; Pathway to 2030; Beyond 2030) that currently feed into the broader grid infrastructure planning system.

TAAP is the Government's response to 2023 recommendations made by the UK's electricity networks commissioner to accelerate the construction of major transmission projects (Department for Energy Security and Net Zero, 2023b). The recommendations centre around the development of a new planning roadmap that reduces overall plan and build time for new transmission infrastructure from 12 to 14 years to seven years. This requires the creation of a strategic spatial energy plan (SSEP), which will 'bridge the gap between government policy and infrastructure development plans', and centralised strategic network plans (CSNPs), which will 'support the connection of all transmission connected generation and demand, and seek opportunities to coordinate connections, reducing the amount of network infrastructure needed.'

Reducing the plan and build time beyond the 50 per cent reduction outlined in the TAAP is likely to be required to meet the new Government's target to decarbonise the power sector by 2030. The SSEP and CSNPs will need to be developed at pace so that the supply chain can be informed and primed early, considering current lengthy supply chain delays in HVDC cables, transformers and other key components (Section 3.4). We refer to the analysis in this report that indicates that approximately half of the total Al and Cu requirements between now and 2050 are needed by 2030.

It is, however, currently unclear how the recommendations in the TAAP will support the acceleration of the plan and build of the distribution network, which also has significant material requirements prior to the power sector decarbonisation target date. There is a risk that, if the distribution network plan and build is not accelerated in line with the transmission network, there will be a mismatch in rollout and delivery between the two parts of the electricity network and the benefits of energy transition to end users will not be fully realised.

7.4.2 Exploring new procurement strategies

New approaches to procurement strategies are now being applied across the Cu, Al and grid infrastructure component supply chains to ensure security of supply. Examples of successful supply chain strategies include the centralised procurement approach being used by Dutch state-owned TenneT to secure a €5.5 billion contract for 7000 km of subsea cables. Direct deals between cable manufacturers and mining companies have also been successful in securing supply, as demonstrated in the EV sector.

The TAAP recommendations included establishing a supply chain forum, which was launched in January 2024 and will help to 'identify cross-industry supply chain challenges and remove barriers to investment and greater domestic manufacturing capability' (Department for Energy Security and Net Zero, 2023b). In addition, in order to support security of supply, Ofgem plans to roll out an advanced procurement mechanism by 2025 to allow companies to secure supplier capacity ahead of final determinations that can also be used during RIIO-ET3 (Ofgem, 2024b).

7.4.3 Providing choice for material substitution

Record high Cu prices are encouraging companies and grid operators to consider substituting Al in cables, lines and transformers. There is evidence that China is shifting towards using Al cables instead of Cu cables in its grid infrastructure rollout (Mining.com, 2024). Al is less conductive and less dense than Cu, with around 60 per cent conductivity and 30 per cent of the density of Cu (MatWeb, 2024a, b). This means that around half the mass of Al is required for the same current-carrying capacity. The superior conductivity-to-weight ratio of Al is a key reason why Al is the preferred material for overhead lines.

There is external evidence to suggest that there are opportunities to substitute Al for Cu in the components listed here (International Aluminium Institute, 2022). Some companies already offer Al variants of these components or, in the case of subsea cable manufacturers (such as XLCC), are in the design and development phase:

- underground cables (Thorne and Derrick International, 2021)
- distribution transformers (Maddox Transformer, 2022)
- subsea cables (Financial Times, 2023; XLCC, 2024)

The decision to use either Cu or Al in components will be driven by factors and design considerations, including:

- regulatory limits: whether British Standards (or other key design standards) allow the use of materials other than Cu
- capital expenditure: including the price of Al and Cu and associated insulating material
- operating expenditure: the anticipated cost of maintaining the component through a life-cycle assessment. Cu has historically been used for underground and subsea cables where weight is not a major concern and superior technical properties such as corrosion resistance and tensile strength are required, resulting in lower maintenance costs (International Energy Agency, 2021)
- physical size: since the conductivity of Cu is around 60 per cent greater than Al, the cross-sectional area of an Al cable would need to be 60 per cent greater, equivalent to a diameter that is 30 per cent larger than that of the Cu line, cable or transformer windings

7.4.3.1 Graphene

Historically, materials substitution has focused on Al as a substitute for Cu. In terms of more advanced alternative materials, however, graphene is a form of carbon that has exceptional electrical, thermal and physical properties. The electrical conductivity of graphene is higher than Cu; it is also stronger than steel and less dense than Al. There is growing evidence from research that graphene could be a key composite material in the ability to increase the power transferred through electrical transmission and distribution cables (Gwalani, et al., 2024; Graphene-info, 2023).

The key barrier to commercial readiness is the ability to manufacture high-quality graphene at large scales. Processes such as chemical vapour deposition can produce high-quality graphene, but it is challenging to manufacture 3D samples such as wires (Gwalani, et al., 2024). The price of graphene can be up to $2000 per kilogram, which is around 200 times that of Cu (National Graphene Institute, 2024).

However, KEPCO, the utility responsible for electricity generation, transmission and distribution in South Korea, is completing a research project into the development of composite cables, which include graphene fibres. Graphene fibre-based Al cables can have over three times the power transmission capacity of Al cables. Part of the project will include developing the required technology and a pilot facility that can manufacture the graphene fibres at scale (Graphene-info, 2022).

7.4.3.2 Superconductors

Superconductors are materials that have no electrical resistance when cooled to extremely low temperatures. These can be manufactured into superconducting cables for electricity transmission using materials called high-temperature superconductors (HTS). The temperature is high relative to absolute zero.

HTS cables contain a thermally insulated cryogenic envelope containing liquid nitrogen to cool the cable to required temperatures. They have several advantages, including high current-carrying capacity, high power relative to diameter (a 17 cm-diameter cable can carry 3.2 GW) and no production of heat or electromagnetic fields (Nexans, 2022). There are examples of applications of HTS cables for short (less than 6 km) distances in urban areas or data centres where high power transfer is required in a low-voltage system (European Network of Transmission System Operators for Electricity, 2024). The key challenges relate to the cost of operating and maintaining the cryogenic cooling system, together with thermal losses.

7.4.4 Increasing material efficiency and reducing material requirement

In this report, material efficiency is considered synonymous with material intensity (units of kg/MW/km for cables and kg/MW for transformers) based on material efficiency as the quantity of a material required to achieve its function. In the case of lines, cables and transformers, this is to transfer electrical power safely. There are opportunities to improve overall material efficiency that have been explored.

There are three key variables properties of a cable or line that contribute towards the material efficiency:

- load (or current) carrying capacity
- voltage rating
- whether the line or cable carries AC or DC

7.4.4.1 Current-carrying capacity

The higher the current-carrying capacity, the more electrical power that can be transferred. However, the greater the current, the greater the resistive losses, which manifest as heat. Therefore, the current capacity is limited by the ability of the cable, line or transformer to dissipate heat. This is in part driven by the physical properties of the cable, but also a function of the environmental conditions in which the component is operating. Heat is more easily dissipated in air than underground, which is why overhead lines have a greater material efficiency than underground cables. Material efficiency could therefore be increased by focusing on building more overhead lines, where appropriate. This would need to be considered together with additional infrastructure requirements relating to pylons and other ancillary equipment.

Smart grid techniques, such as dynamic line ratings, can be used to improve material efficiency, by increasing the current-carrying capacity of a line or cable in favourable environmental conditions (such as a cold or windy day). Recent advances in conductor design have shown that using Al conductors together with composite cores made of carbon fibre and ceramics allow higher operating temperatures and therefore higher current flow (Kramer, 2024).

Energy loss as heat generation is a primary factor when considering the cross-sectional area of cabling, since too much heat generation can result in thermal degradation and compromise the safety of the cable. While a smaller cross-sectional area requires less material, it will have a higher resistance and generate more heat losses if carrying the same current. This is why cables carrying higher currents have a greater cross-sectional area. Underground cables and subsea cables require more insulation to protect the cable cores, resulting in poorer heat dissipation, greater cross-sectional area and higher mineral intensity.

Cables and associated infrastructure will need to be resilient to climate risks intensified by climate change, including storms, floods and global temperature variation (International Energy Agency, 2023c).

7.4.4.2 Voltage rating

Since electrical power (MW) is a function of current and voltage, increasing the voltage for the same current results in an increase in transfer of electrical power, meaning that more power can be transferred for a similar quantity of material.

7.4.4.3 Alternating current and direct current

HVDC lines and cables are very effective at transferring electrical power over long distances with minimal power losses. This is because DC systems do not require reactive power, which is a significant portion of non-useful work within AC systems. This also allows HVDC systems to operate effectively at very high voltages over long distances, with recent HVDC systems operating at 800 kV. Losses across 1000 km are approximately 3 per cent compared with 7 per cent for AC lines. The material intensity for HVDC lines is approximately half of that for HVAC lines. Therefore, adopting more HVDC lines and cables can increase material efficiency.

Additionally, analysis by the IEA indicates that that deploying HVDC transmission lines more widely in global electricity networks has the potential to shrink their material demand by 3 per cent in 2030 and 10 per cent in 2050 (International Energy Agency, 2024).

7.4.5 Unlocking the circular economy

A circular economy can support security of supply and meeting decarbonisation targets. The global transition to net zero is contributing to unprecedented demand for Cu and Al as well as critical raw materials (UK Government, 2022b). Increasing the secondary supply of Al and Cu is essential to meet forecasted global demand.

7.4.5.1 Refining and recycling

The UK has very limited Al smelting capacity to produce primary Al (48 000 t per year through the Alvance plant in Scotland) and no refining capacity to produce primary Cu.

There is growing UK capacity for reprocessing scrap Al into products. A report by BCAST for the UK Aluminium Federation highlights several new developments in this space, including new plants by Alvance (100 000 t per year capacity planned for 2027), BACALL, Hydro and Constellium (BCAST, 2024). Evolve Metals aims to develop the UK's Cu-refining capacity using secondary scrap as its input (Evolve Metals, 2024).

Despite growing secondary Al production capacity, the UK is a significant exporter of scrap Cu and Al. In 2023, the UK exported 240 000 t and 600 000 t waste and scrap Cu (HS Code 7404) and Al (HS Code 7602), respectively (United Nations, 2024). A 2023 report by the Circular Economy Innovation Network estimates that yearly imports of Al are worth around £3000 per tonne, while exports are only worth £2000 per tonne, partly driven by the lower value of scrap (Innovate UK, 2023). This represents lost economic value, which could be recovered through the development of reprocessing plants of scrap Al and Cu.

As well as boosting economic value, expanding the UK's reprocessing capacity can support security of supply and contribute towards decarbonising material production. Alvance, Evolve Metals, BACALL, Hydro and Constellium will all use 'green' methods to reduce emissions.

While grid infrastructure components, such as cables, require high-purity Cu and Al, there is a precedent of recycling material and reprocessing it into new cables. Nexans is partnered with RecyCâbles, a French company that recycles and recovers thousands of tonnes of Cu and Al each year, some of which is then used to produce new cables (Nexans, 2024). There is an opportunity for the UK to invest in recycling and reprocessing facilities that can recover high-purity Cu and Al for use in cabling and transformer windings.

7.4.5.2 Maintenance and transmission Losses

Energy losses in the network can account for more than 90 per cent of CO_2e emissions over the operating life of the components (Jorge et al., 2012a, b). Advanced monitoring methods and technologies (sometimes called 'smart grid' technologies) are being developed and used to reduce energy losses and safely extend component life and network capacity, thereby reducing material requirements and investment costs. These methods include:

- static synchronous compensators (STATCOMs): devices that enable real-time control of power flows and voltage levels and can regulate the reactive power element in AC networks, meaning power transmission capacity can be enhanced (International Energy Agency, 2023c)
- remote asset monitoring: using technologies such as thermal imaging and artificial intelligence to assess conditions of assets, for more informed decision making about component maintenance (National Grid, 2023)
- dynamic line rating: increasing the current-carrying capacity of a line or cable in favourable environmental conditions (such as a cold or windy day) (National Grid, 2023)

From a maintenance perspective, safely extending the life of components through new methods and technologies may also be able to mitigate the risk to supply of some components with long lead times, like transformers. The timing of when components will be replaced will be a trade-off between economic and environmental costs.

7.4.5.3 Policy

There are laws in the UK (and elsewhere) that mandate the implementation of circular economy principles. In June 2024, the Circular Economy Bill passed through the Scottish legislature, allowing ministers to introduce measures to help develop a circular economy, such as setting recycling targets. The EU's Critical Raw Materials Act (European Commission, 2024) includes requirements on recyclability and recycled content in certain products that contain critical materials.

CBAM is an emissions tariff to be introduced in 2027 that will promote the sourcing of low-carbon Al, since the tariff will be higher for Al if it is produced using carbon-intensive methods. It presents an opportunity for UK production, which is lower carbon than the global average. It could encourage the UK to further develop its Al production capacity based on circular economy principles. Economic modelling of the CBAM will be required to balance sourcing of low-carbon Al with cost and supply risk that may affect infrastructure project delivery.

8 Recommendations

This foresight study provides an overview of the Al and Cu requirements for key electricity grid infrastructure components to support the UK's transition to net zero. The study has provided a view as of autumn 2024, but it will require regular updates to ensure that the complexity and dynamics of the global market are captured.

Based on the findings in this report, there are several areas where additional development could support security of supply and delivery of the UK's grid infrastructure requirements.

8.1 ACCELERATE THE STRATEGIC NETWORK PLANNING PROCESS

Acceleration of the strategic network planning process for the transmission and distribution networks (as recommended for the transmission network in TAAP through development of the SSEP and CSNPs) should be undertaken at pace, This will provide clarity on future material demand that will improve long-term, anticipatory investment from suppliers, while also offering clarity on long-term future requirements for the distribution network as part of a whole-system approach.

Understanding the demand for strategic components and materials such as Al and Cu should form a key part of the planning process. The seven-year TAAP process map should be tested and reviewed considering the new Government policy to decarbonise the GB electricity network by 2030. Meeting this target date may require further reduction in planning time as outlined in the TAAP.

Analysis in this report suggests that around half of Al and Cu material requirements before 2050 (within announced projects) will be required by 2030. An end-to-end risk management approach is recommended. It is expected that supply risk management will form a key part of this; the demand signal to the supply chain should be initiated at pace and refreshed in lockstep with any future revised network plans.

The planning process should consider a holistic, whole-system approach across the transmission and distribution networks since there is currently no whole-system view across both. There is a risk that, if the distribution network plan and build is not also accelerated in line with the transmission network, there will be a mismatch in rollout and delivery between the two parts of the electricity network.

8.2 EXPLORE NEW PROCUREMENT STRATEGIES

New procurement strategies for both Government and the private sector should be explored. In the context of multi-year lead times for HVDC cables, converter stations and transformers, it is critical that supply of these components is secured early to meet the 2030 target. Government could consider centralised procurement approaches with the ESO, TOs and DNOs to secure bulk supply.

This approach has been successfully applied by other European countries (for example, Dutch state-owned TenneT). For the private sector, this could include direct financing deals between component manufacturers and mining companies to provide demand confidence and secure supply, in the face of increasing Cu prices.

By 2025, TOs will be able to take advantage of Ofgem's new advanced procurement mechanism to secure supplier capacity ahead of final determinations that can also be used during RIIO-ET3.

8.3 SHARE CHALLENGES AND SOLUTIONS ACROSS THE SUPPLY CHAIN

Supply chain resilience could be enhanced through the supply chain forum established in January 2024, as recommended in the TAAP. The forum aims to identify cross-industry supply chain challenges and remove barriers to investment and greater domestic manufacturing capability.

8.4 DEEP DIVE INTO UK SUPPLY CHAIN CAPACITY AND SECURITY

While this report has sought to spotlight areas of greatest supply risk (for example, HVDC subsea cables), a detailed needs-based assessment to identify targeted interventions and initiatives, including investments, is recommended. This would strengthen the resilience and performance of companies in the supply chain that depend upon the Al and Cu value chains and on whom the rollout of grid infrastructure is critically dependent.

8.5 REVIEW DESIGN PRINCIPLES AND STANDARDS.

As part of the TAAP recommendations, ESO will convene a working group with relevant stakeholders to progress a set of electricity transmission design principles. One aim will be to standardise infrastructure and equipment design across the grid, which could result in reduced lead times. Together with extending this review to include all components within the distribution network (including EV charging cables, solar connection cables, etc.), several other aspects should be considered as part of the design review, including whether future design standards contain:

- circular economy principles, including designing for disassembly and recycling
- clarity on material options, such as whether Al (or other materials) can be used as the key conducting material

8.6 UNLOCK THE UK'S POTENTIAL IN A CIRCULAR ECONOMY

Incentivising investment for UK Al and Cu refineries for recycled Al and Cu could:

- reduce environmental impact
- increase supply chain resilience
- capitalise on economic opportunity, since the UK currently exports hundreds of thousands of tonnes of scrap Cu and Al

8.7 CARBON BORDER ADJUSTMENT MECHANISM

Government should undertake economic modelling of the CBAM, from the perspectives of risk to supply, cost and completion of grid infrastructure projects, while balancing net zero commitments. This should be undertaken before the CBAM comes into effect in 2027, once the demand side is clarified, in consultation with relevant supply chain stakeholders.

8.8 FUND RESEARCH

Continuing to fund research into the most promising alternative materials like graphene will ensure future resilience in a global market that is set to become more competitive as countries scramble to secure supply to meet decarbonisation targets.

8.9 IMPROVE DATA QUALITY ACROSS THE SUPPLY CHAIN

Reliable estimation of supply and demand risk depends upon good-quality data. Working with data providers to improve supply chain data quality will ensure that there is greater confidence in the calculation of supply chain risk to underpin investment and policy decisions.

8.10 REVIEW AND UPDATE THE SUPPLY AND DEMAND MODEL

The model described in this report to make supply and demand projections should be kept under continual review to reflect changes in the global market and the GB and global demand projections.

Appendix

TRANSMISSION INFRASTRUCTURE DEMAND

The component mapping to infrastructure requirements inferred from the ESO Pathway to 2030 and Beyond 2030 documents is presented in Table 6.

Table 6 Recommendation categories and associated components.

Category	Example description	Associated components
New network/wind farm/ high-voltage link	'New circuit between *A* and *B*' 'New *offshore* network'	New substation transformer/ converters at start and finish New cable (single or double)
Reconductor cable/uprate cable	'Replace conductors on existing circuit between...'	New cable
Upgrade substation/new substation	'New substation in *area*'	New substation transformers
Other network components	'Add PCD to existing circuit'	N/A

Line, cable and substation power ratings and material intensity for the transmission networks are outlined in Table 7and Table 8, respectively. For the purposes of material intensity estimates, it was assumed that all subsea export cables, bootstraps and interconnectors are DC.

The average component ratings and associated mineral intensity were determined from sources that include:

- the ESO Electricity Ten Year Statement (National Grid ESO, 2023b) and TO open network data
- wind farm leasing information (Department for Energy Security and Net Zero, 2024)
- the interconnector register (National Grid ESO, 2024c)
- DNO open data
- environmental product declarations for transformers

Table 7 Transmission line and cable power ratings and mineral intensity. Source: DAS analysis of industry data.

Component	Material	Power rating (MW) capacity	Mineral intensity (kg/MW/km) [3]	Mineral intensity (tonnes/km)
Interconnector (DC)	Cu	1300	30	39
Bootstrap (DC)	Cu	1500	30	45
Export cable (DC)	Cu	1500	30	45
Static array cable (AC) [4]	Al	N/A	N/A	9
Dynamic array cable (AC) [4]	Cu	N/A	N/A	30
Overhead line (AC)	Al	2400	10	24
Underground cable (AC)	Cu	1250	100	62

Table 8 Transmission transformer power ratings and mineral intensity. Source: DAS analysis of industry data.

Substation	Firm capacity rating (MVA)	Mineral intensity (kg/MVA)	Mineral intensity (tonnes/unit)
Grid supply point	1500	150	225
Interconnector transformer/converter substation	1250	250	312
Wind farm transformer/converter substation	1250	250	312

[3] International Energy Agency (2023a)
[4] Offshore Wind Scotland (2024)

DISTRIBUTION INFRASTRUCTURE DEMAND

Line and cable and substation power ratings and material intensity for the distribution network are outlined in Table 9 and Table 10, respectively.

Overhead line and underground cable power ratings and material intensity for the distribution network are presented in Table 9. Power-rating capacities were determined from open-source National Grid energy distribution circuit data[5] and assumed to be representative across the GB distribution network. An average winter current rating was taken across the circuits at the same voltage level. Some voltages were grouped together for consistency with the ENSF dataset. Material intensities were then determined using manufacturing datasheets[6] and the previously calculated current ratings.

Table 9 Distribution line and cable power ratings and mineral intensity. Source: DAS analysis of industry data.

Component	Material	Voltage level (kV)	Power rating (MW) capacity [5]	Mineral intensity (kg/MW/km) [6]	Mineral intensity (tonnes/km)
Overhead line	Al	132	95	13	1.24
		66 & 33	26	40	1.04
		20, 11 & 6.6	3	85	0.26
		<1	0.1	720	0.07
Underground cable	Cu	132	95	45	4.28
		66 & 33	26	132	3.43
		20, 11 & 6.6	3	230	0.69
		<1	0.1	1620	0.16

Transformer power ratings and material intensity are presented in Table 10. Distribution transformer power rating capacities were determined from open source DNO datasets[7]. Material intensities were separately estimated using transformer product declaration datasheets and equipment nameplates

[5] https://connecteddata.nationalgrid.co.uk/dataset/circuit-data
[6] https://www.elandcables.com/electrical-cable-and-accessories/cables-by-standard/dno-approved-cable; https://tratosgroup.com/products/energy/dno-approved-cable-bs/
[7] https://connecteddata.nationalgrid.co.uk/dataset/nged-network-capacity; https://connecteddata.nationalgrid.co.uk/dataset/distribution-substations; https://northernpowergrid.opendatasoft.com/explore/dataset/substation_sites_list/information/

Table 10 Distribution transformer power ratings and mineral intensity. Source: DAS analysis of industry data.

Voltage level (kV)	Firm capacity rating (MVA)	Mineral intensity (kg/MVA)	Mineral intensity (tonnes/unit)
132	68	100	6.8
66 & 33	18	175	3.2
11	0.3	250	0.08

The following graphs and tables break down Cu and Al demand within the distribution infrastructure by voltage level.

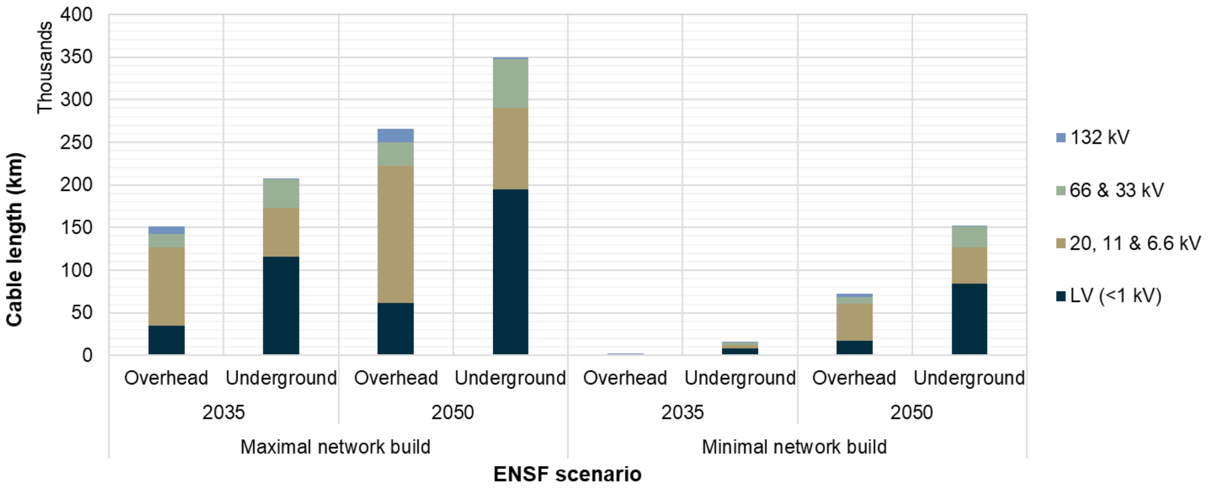


Figure 23 Cumulative overhead line and underground cable demand of the GB distribution network from 2023 to 2050 by ENSF scenario. Source: DAS Analysis of BEIS ENSF, assuming current voltage split of network is maintained. BGS © UKRI.

Table 11 Required cumulative transformer numbers of the GB distribution network from 2023 to 2050 by ENSF scenario and voltage level. Source: DAS Analysis of BEIS ENSF, assuming current voltage split of network is maintained.

Scenario	Year	11 kV	66 kV & 33 kV	132 kV
Maximal network build	2035	713 601	12 180	2394
	2050	882 441	15 062	2961
Minimal network build	2035	276 247	4715	927
	2050	519 066	8860	1742

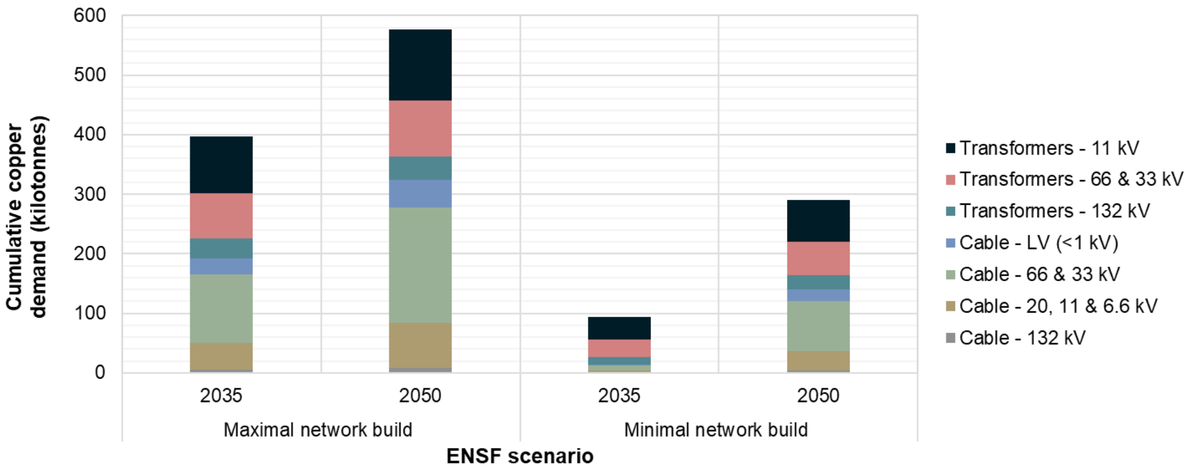


Figure 24 Calculated cumulative Cu demand of the GB distribution network (underground cables and transformers) between 2023 to 2050 by ENSF scenario. Source: DAS Analysis. BGS © UKRI.

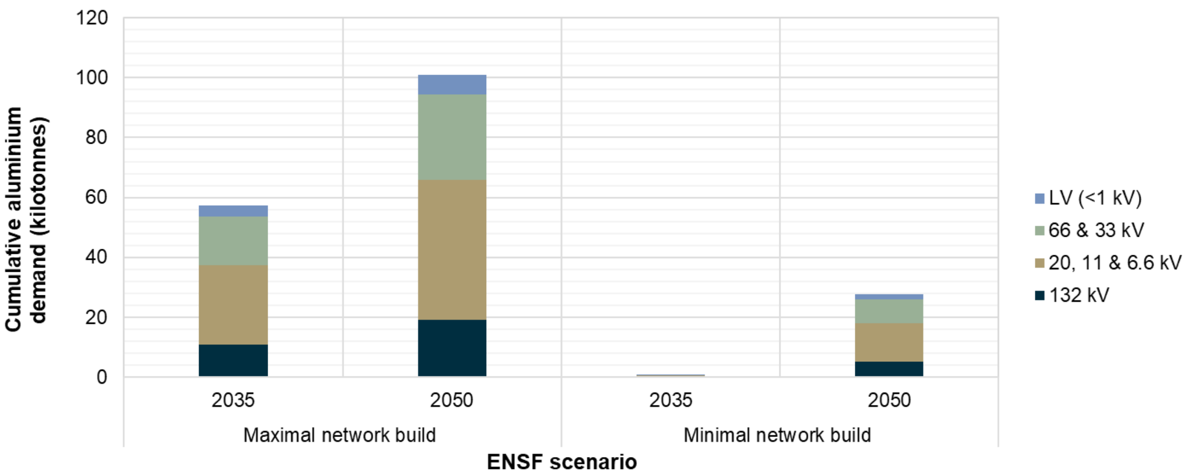


Figure 25 Calculated cumulative Al demand of the GB distribution network (overhead lines) between 2023 to 2050 by ENSF scenario. Source: DAS Analysis. BGS © UKRI.

DISTRIBUTION TECHNOLOGIES DEMAND

Web links to the DFES 2023 data sources that were used to support the calculation of the forecast demand of the different distribution technologies are provided in Table 12.

Table 12 DFES data source locations for each of the DNOs.

DNO	DFES Data Source
SSE Power Distribution	https://data.ssen.co.uk/@ssen-distribution/low_carbon_technologies
Northern PowerGrid	https://odileeds.github.io/northern-powergrid/2023-DFES/index.html
National Grid DNO	https://www.nationalgrid.co.uk/distribution-future-energy-scenarios-map
SP Energy Networks	https://spenergynetworks.opendatasoft.com/explore/?sort=modified&refine.theme=DFES
Electricity North West	https://www.enwl.co.uk/get-connected/network-information/dfes/
UK Power Networks	https://dso.ukpowernetworks.co.uk/distribution-future-energy-scenarios

Table 13 EV charging device statistics [8].

Type	Level	kW range	Average kW	Count	%
Slow	1	3–6	4.5	8913	24
Fast	2	7–22	14.5	21 255	57
Rapid	3	25–100	62.5	4592	12
Ultra	3	100+	225	2295	6
Total	-	-	-	37 055	

[8] https://www.gov.uk/government/statistics/electric-vehicle-charging-device-statistics-april-2023/electric-vehicle-charging-device-statistics-april-2023#location-of-charging-devices

Table 14 Distribution technology material intensity values [9].

Technology	Subtechnology	Material	Material intensity (t/MW)
Solar	Domestic roof-top (<10 kW)	Cu	3.7
Solar	Commercial roof-top (<1 MW)	Cu	2.3
Solar	Large ground-mounted (>1 MW)	Cu	2.3
Storage	Grid-scale battery storage	Cu	1.7
EV charger	Level 1 (3–6 kW)	Cu	0.16
EV charger	Level 2 (7–22 kW)	Cu	0.07
EV charger	Level 3 (>25 kW)	Cu	0.03

[9] https://www.copper.org/publications/pub_list/pdf/a6197-na-solar-pv-analysis.pdf; https://cdn.ihsmarkit.com/www/pdf/0722/The-Future-of-Copper_Full-Report_14July2022.pdf

Acronyms and abbreviations

AC	Alternating current
BEIS	Department for Business, Energy & Industrial Strategy
BESS	Battery energy storage system
CBAM	(UK) Carbon Border Adjustment Mechanism
CCUS	Carbon capture, utilisation and storage
CO_2e	Carbon dioxide equivalent: a measure used to compare emissions from various greenhouse gases including nitrous oxide, methane and sulfuric hexafluoride
CSNP	Centralised strategic network plan
DBT	Department for Business and Trade
DC	Direct current
DESNZ	Department for Energy Security & Net Zero
DNO	Distribution network operator
DRC	The Democratic Republic of the Congo
EMSF	Electricity Network Strategic Framework
ESG	Environmental, social and governance
ESO	Energy system operator
EV	Electric vehicle
FES	Future energy scenarios
GB	Great Britain: the island comprising England, Wales and Scotland
HS	Harmonized System
HTS	High-temperature superconductors
HVAC	High-voltage alternating current
HVDC	High-voltage direct current
IAI	International Aluminium Institute
ICA	International Copper Association
IEA	International Energy Agency
NICER	National Interdisciplinary Circular Economy Research
Ofgem	Office of Gas and Electricity Markets
OFTO	Offshore transmission owner
RIIO	Revenue = incentives + innovation + outputs
RIR	Recycling input rate
SSEP	Strategic spatial energy plan
TAAP	Transmission Acceleration Action Plan
TO	Transmission owner

References

4C Offshore. (2022, 3). *Ofgem Pushes Back Regime Start Date for NeuConnect*. Retrieved September 5, 2024, from https://www.4coffshore.com/news/ofgem-pushes-back-regime-start-date-for-neuconnect-nid25226.html

ABB. (2024). *Technical Support and Repairs*. Retrieved July 30, 2024, from ABB: https://new.abb.com/service/electrification/technical-support-repairs

Alvance British Aluminium. (2024). *The Future*. Retrieved July 30, 2024, from Alvance: https://alvancebritishaluminium.com/the-future/

Baringa. (2024, April 1). *UK Renewables Deployment Supply Chain Readiness.* Retrieved September 5, 2024, from UK Government: https://www.gov.uk/government/publications/uk-renewables-deployment-supply-chain-readiness

BBC. (2023, 11 29). *Cobre Panamá: Panama Orders Controversial Copper Mine's Closure*. Retrieved July 10, 2024, from BBC: https://www.bbc.co.uk/news/world-latin-america-67565315

BCAST. (2024). *Sustainability Strategy Day - Opportunities for UK Aluminium.* Daventry: UK Aluminium Federation.

Blinová, L., & Godovcin, P. (2021). Importance of Recycling the Waste-Cables Containing Copper and PVC. *Research Papers Faculty of Materials Science and Technology Slovak University of Technolog, 29*(48), 1-21. doi:10.2478/rput-2021-0001

British Geological Survey. (2023). *World Mineral Production 2017-2021.* Nottingham: British Geological Survey.

Calvo, G., Mudd, G., Valero, A., & Valero, A. (2016). Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality? *Resources, 5*(4), 36.

CRU International. (2024). *The UK Aluminium Market Update.* London: CRU International.

Department for Energy Security and Net Zero. (2023a, December 18). *Factsheet: UK Carbon Border Adjustment Mechanism*. Retrieved June 18, 2024, from GOV.UK: https://www.gov.uk/government/consultations/addressing-carbon-leakage-risk-to-support-decarbonisation/outcome/factsheet-uk-carbon-border-adjustment-mechanism

Department for Energy Security and Net Zero. (2023b). *Transmission Acceleration Action Plan.* London: DESNZ.

Department for Energy Security and Net Zero. (2024, May 15). *Renewable Energy Planning Database: quarterly extract.* Retrieved July 5, 2024, from Gov.UK: https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract

Eland Cables. (2024a). *How Are Copper Conductors Made?* Retrieved September 5, 2024, from Eland Cables: https://www.elandcables.com/the-cable-lab/faqs/faq-how-are-copper-conductors-made-processed-mine-extraction-to-stranding

Eland Cables. (2024b). *How Are Aluminium Conductors Made?* Retrieved September 5, 2024, from Eland Cables: https://www.elandcables.com/the-cable-lab/faqs/faq-how-is-the-aluminium-for-cables-made

Eland Cables. (2024c). *Eland Cables*. Retrieved June 24, 2024, from https://www.elandcables.com/

Ellen MacArthur Foundation. (2025, January 1). *Circular Economy Glossary*. Retrieved from Circular Economy Introduction: https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/glossary

Energy Networks Association. (2015, April 28). *Climate Change Adaptation Reporting Power.* Retrieved September 5, 2024, from Energy Networks Association: https://assets.publishing.service.gov.uk/media/5a807eb6e5274a2e8ab5078c/clim-adrep-ena-2015.pdf

European Commission. (2024). *Critical Raw Materials Act*. Retrieved July 30, 2024, from European Commission: https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en#:~:text=Overview%20of%20the%20Critical%20Raw%20Materials%20Act,-Critical%20raw%20materials&text=The%20European%20

European Network of Transmission System Operators for Electricity. (2024, January 1). *High Temperature Superconductor (HTS) Cables*. Retrieved September 5, 2024, from High Temperature Superconductor (HTS) Cables: https://www.entsoe.eu/Technopedia/techsheets/high-temperature-superconductor-hts-cables

Evolve Metals. (2024). *Evolve Metals*. Retrieved July 10, 2024, from https://www.evolvemetals.uk/

Financial Times. (2017). *Escondida Strike Raises Broader Supply Fears for Copper*. Retrieved September 5, 2024, from Financial Times: https://www.ft.com/content/034b7142-f1e7-11e6-8758-6876151821a6

Financial Times. (2023, 7). *Will There be Enough Cables for the Clean Energy Transition?* Retrieved September 5, 2024, from Financial Times: https://www.ft.com/content/c88c0c6d-c4b2-4c16-9b51-7b8beed88d75

Financial Times. (2024, July 21). *Copper Miners Predict Industry Overhaul as End Users Rush to Secure Supply*. Retrieved September 5, 2024, from Financial Times: https://www.ft.com/content/220ef9d2-df1e-4b93-b044-fb1957591428

Graphene-info. (2022, March 21). *Korea's KEPCO Launches R&D Project to Develop Graphene-Based Power Lines*. Retrieved September 5, 2024, from Korea's KEPCO launches R&D project to develop graphene-based power lines: https://www.graphene-info.com/koreas-kepco-launches-rd-project-develop-graphene-based-power-lines

Graphene-info. (2023, December 21). *Copper-Graphene Composites Could Lead to Better Electrical Wires and Motors*. Retrieved September 5, 2024, from Graphene-info: https://www.graphene-info.com/copper-graphene-composites-could-lead-better-electrical-wires-and-motors

Gwalani, B., Li, X., Nittala, A., Choi, W., Reza-E-Rabby, M., Atehortua, J. E., . . . Kappagantula, K. (2024). Unprecedented Electrical Performance of Friction-Extruded Copper-Graphene Composites. *Materials & Design, 237*, 112555.

Hitachi Energy. (2020). *ABB Power Grids and Stena Recycling in Circular Cooperation Around Transformers*. Retrieved June 25, 2024, from https://www.hitachienergy.com/news/features/2020/06/abb-power-grids-and-stena-recycling-in-circular-cooperation-around-transformers

Idoine, N., Raycraft, E., Price, F., Hobbs, S., Deady, E., Everett, P., . . . Idoine, N. E. (2023). *World Mineral Production 2017-21.* Nottingham: British Geological Survey.

IndustriALL. (2017, 5). *Freeport Fires Striking Workers at Grasberg Mine in Indonesia*. Retrieved September 5, 2024, from IndustriALL: https://www.industriall-union.org/freeport-fires-striking-workers-at-grasberg-mine-in-indonesia

Innovate UK. (2023, July 1). *Innovation Action Plan for Aluminium in a Circular Economy.* Retrieved September 5, 2024, from Innovation action plan for aluminium in a circular economy: https://iuk.ktn-uk.org/wp-content/uploads/2023/07/Aluminium_Report_v5.pdf

International Aluminium Institute. (2021, September 1). *Aluminium Sector Greenhouse Gas Pathways to 2050.* Retrieved September 5, 2024, from International Aluminium Institute: https://international-aluminium.org/resource/aluminium-sector-greenhouse-gas-pathways-to-2050-2021/

International Aluminium Institute. (2022). *Opportunities For Aluminium In A Post-Covid Economy.* London: International Aluminium. Retrieved 07 30, 2024, from https://international-aluminium.org/resource/opportunities-for-aluminium-in-a-post-covid-economy/

International Aluminium Institute. (2023a). *Mining and Refining*. Retrieved September 5, 2024, from The Aluminium Story: https://thealuminiumstory.com/mining-refining/

International Aluminium Institute. (2023b). *Production Process: Reduction*. Retrieved September 5, 2024, from The Aluminium Story: https://thealuminiumstory.com/primary-production/reduction/

International Aluminium Institute. (2023c, January 25). *Greenhouse Gas Emissions – Aluminium Sector*. Retrieved September 5, 2024, from Greenhouse Gas Emissions – Aluminium Sector: https://international-aluminium.org/statistics/greenhouse-gas-emissions-aluminium-sector/

International Aluminium Institute. (2023d, January 1). *GHG Emissions Reductions in the Global Aluminium Industry.* Retrieved September 5, 2024, from GHG Emissions Reductions in the Global Aluminium Industry: https://international-aluminium.org/wp-content/uploads/2023/02/Emissions-Technology-Factsheet-_UPDATE-2023.pdf

International Aluminium Institute. (2023e, November 29). *Greenhouse Gas Emissions Intensity- Primary Aluminium*. Retrieved September 5, 2024, from Greenhouse Gas Emissions Intensity- Primary Aluminium: https://international-aluminium.org/statistics/greenhouse-gas-emissions-primary-aluminium/

International Aluminium Institute. (2023f). *Global Aluminium Cycle 2021*. Retrieved September 5, 2024, from International Aluminium: https://alucycle.international-aluminium.org/public-access/public-global-cycle/

International Aluminium Institute. (2023g, June 1). *Material Flow Analysis.* Retrieved September 5, 2024, from IAI: https://international-aluminium.org/wp-content/uploads/2024/04/Material-Flow-Analysis_Mar2023.pdf

International Copper Association. (2023, March 1). *Copper - Pathway to Net Zero.* Retrieved June 13, 2024, from https://internationalcopper.org/wp-content/uploads/2023/03/ICA-GlobalDecar-202301-English-Final-singlepgs.pdf

International Copper Association. (2024a). *Copper Life Cycle*. Retrieved September 5, 2024, from International Copper Association: https://internationalcopper.org/sustainable-copper/about-copper/copper-life-cycle/

International Copper Association. (2024b). *Stocks and Flows*. Retrieved June 13, 2024, from International copper association: https://internationalcopper.org/sustainable-copper/about-copper/cu-demand-long-term-availability/stocks-flows/

International Copper Study Group. (2023). *The World Copper Factbook 2023.* Lisbon: International Copper Study Group.

International Energy Agency. (2021). *The Role of Critical Minerals in Clean Energy Transitions.* Paris: International Energy Agency.

International Energy Agency. (2023a, March 1). *CO2 Emissions in 2022.* Retrieved September 5, 2024, from CO2 Emissions in 2022: https://www.iea.org/reports/co2-emissions-in-2022

International Energy Agency. (2023b, July 11). *Aluminium*. Retrieved September 5, 2024, from Aluminium: https://www.iea.org/energy-system/industry/aluminium

International Energy Agency. (2023c, November 1). *Electricity Grids and Secure Energy Transitions.* Retrieved September 5, 2024, from IEA: https://iea.blob.core.windows.net/assets/ea2ff609-8180-4312-8de9-494bcf21696d/ElectricityGridsandSecureEnergyTransitions.pdf

International Energy Agency. (2024). *Global Critical Minerals Outlook 2024.* Paris: International Energy Agency.

ISS Insights. (2022, November 24). *Copper or Robber: Supply Risks and ESG Issues.* Retrieved September 5, 2024, from ISS Insights: https://insights.issgovernance.com/posts/copper-or-robber-supply-risks-and-esg-issues/

JDR Cables. (2022, 11). *JDR Cables Starts Construction on £130m Subsea Cable Facility*. Retrieved September 5, 2024, from JDR Cables: https://www.jdrcables.com/jdr-cables-starts-construction-on-130m-subsea-cable-facility/

JDR Cables. (2024). *The Project*. Retrieved June 26, 2024, from JDR Cables: https://offshore.jdrcables.com/the-project/

Jorge, R., Hawkins, T., & Hertwich, E. (2012a). Life Cycle Assessment of Electricity Transmission and Distribution—Part 1: Power Lines and Cables. *International Journal of Life Cycle Assessment, 17*, 9-15. doi:https://doi.org/10.1007/s11367-011-0335-1

Jorge, R., Hawkins, T., & Hertwich, E. (2012b). Life Cycle Assessment of Electricity Transmission and Distribution—Part 2: Transformers and Substation Equipment. *International Journal of Life Cycle Assessment, 17*, 184-191. doi:https://doi.org/10.1007/s11367-011-0336-0

Josso, P., Lusty, P., Gunn, A., Shaw, R., Singh, N., Horn, S., & Petavratzi, E. (2023). *Review and Development of the Methodology and Data Used to Produce the UK Criticality Assessment of Technology-critical Minerals.* Nottingham: British Geological Survey.

Khawaja, A. H., Huang, Q., & Khan, Z. H. (2017). Monitoring of Overhead Transmission Lines: A Review from the Perspective of Contactless Technologies. *Sensing and Imaging, 18*, 1-18. doi:10.1007/s11220-017-0172-9

Kramer, D. (2024). Advanced Conductors Could Double Power Flows on the Grid. *Physics Today, 77*(6), 21-23.

Krook, J., Carlsson, A., Eklund, M., Frändegård, P., & Svensson, N. (2011). Urban Mining: Hibernating Copper Stocks in Local Power Grids. *Journal of Cleaner Production, 19*(9-10), 1052-1056. doi:https://doi.org/10.1016/j.jclepro.2011.01.015

Krook, J., Wallsten, B., Svensson, N., & Anderberg, S. (2020). Chapter 35: Urban Mining: On the Potential and Multifaceted Challenges of Facilitating Recycling of Wire-Based City Infrastructure. In J. Krook, B. Wallsten, N. Svensson, S. Anderberg, & M. Brandão (Ed.), *Handbook of the Circular Economy* (pp. 465-477). Cheltenham: Edward Elgar Publishing. doi:https://doi.org/10.4337/9781788972727.00045

Liu, R., & Roberts, L. (2024, 7). *Indonesian Government Looking to Ease Bauxite Export Ban*. Retrieved September 5, 2024, from Fastmarkets: https://www.fastmarkets.com/insights/indonesian-government-looking-to-ease-bauxite-export-ban/

London Metal Exchange. (2024, July 30). *Copper 3-month Closing Price*. Retrieved September 5, 2024, from London Metal Exchange: https://www.lme.com/en/Metals/Non-ferrous/LME-Copper#Price+graphs

Lysaght, O., Hopkinson, P., Zils, M., Nolan, R., Charnley, F., & Cunningham, N. (2024). *Public Policy Taxonomy For a UK Circular Economy.* London: CE-Hub. Retrieved 07 31, 2024, from https://ce-hub.org/knowledge-hub/public-policy-taxonomy-for-a-uk-circular-economy/

Maddox Transformer. (2022, November 1). *Aluminum Versus Copper in Distribution Transformers*. Retrieved September 5, 2024, from Maddox Transformer: https://www.maddoxtransformer.com/resources/articles/aluminum-vs-copper-in-distribution-transformers

MatWeb. (2024a, January 1). *Copper Annealed*. Retrieved September 5, 2024, from MatWeb Material Property Data: https://www.matweb.com/search/DataSheet.aspx?MatGUID=9aebe83845c04c1db5126fada6f76f7e

MatWeb. (2024b, January 1). *Aluminium*. Retrieved September 5, 2024, from MatWeb Material Property Data: https://www.matweb.com/search/datasheet.aspx?bassnum=AMEAL00

Mining Technology. (2024, July 18). *Peruvian Copper Production to Grow by Just 0.6% in 2024, Linked to Disruptions.* Retrieved September 5, 2024, from Mining Technology: https://www.mining-technology.com/analyst-comment/peru-copper-production-2024-disruptions/

Mining.com. (2024, July 16). *Copper Market's Biggest Whale Fuels Speculation of a Major Shift*. Retrieved September 5, 2024, from Mining.com: https://www.mining.com/web/copper-markets-biggest-whale-fuels-speculation-of-a-major-shift/

Mudd, G., & Jowitt, S. (2018). Growing Global Copper Resources, Reserves and Production: Discovery Is Not the Only Control on Supply. *Economic Geology, 113*(6), 1235-1267.

National Graphene Institute. (2024, January 1). *Graphene*. Retrieved September 5, 2024, from Graphene: https://www.graphene.manchester.ac.uk/about/faqs/#:~:text=How%20expensive%20is%20graphene%3F,type%20and%20volume%20of%20material.

National Grid. (2015, January 1). *Undergrounding High Voltage Electricity Transmission Lines.* Retrieved September 5, 2024, from National Grid: https://www.nationalgrid.com/sites/default/files/documents/39111-Undergrounding_high_voltage_electricity_transmission_lines_The_technical_issues_INT.pdf

National Grid. (2023, August 14). *The Innovative and Futuristic Technologies Improving Our Electricity Networks*. Retrieved September 5, 2024, from The innovative and futuristic technologies improving our electricity networks: https://www.nationalgrid.com/stories/engineering-innovation-stories/innovative-and-futuristic-technologies-improving-our-electricity-networks

National Grid Energy Transmission. (2024, April 1). *Our 2021–2026 Environmental Action Plan.* Retrieved September 5, 2024, from https://www.nationalgrid.com/electricity-transmission/document/136551/download

National Grid ESO. (2022a, March 1). *Energy Storage for Constraint Management*. Retrieved September 5, 2024, from Energy Storage for Constraint Management: https://www.nationalgrideso.com/document/247646/download

National Grid ESO. (2022b). *Pathway to 2030 - A Holistic Network Design to Support Offshore Wind Deployment for Net Zero.* Warwick: National Grid ESO. Retrieved from https://www.nationalgrideso.com/document/262676/download

National Grid ESO. (2023a). *Future Energy Scenarios (2023).* Warwick: National Grid ESO. Retrieved from https://www.nationalgrideso.com/document/283101/download

National Grid ESO. (2023b, November 30). *ETYS 2023 Appendix B - System Technical Data.* Retrieved July 05, 2024, from National Grid ESO:

https://www.nationalgrideso.com/research-and-publications/electricity-ten-year-statement-etys/etys-documents-and-appendices

National Grid ESO. (2024a). *Beyond 2030 - A National Blueprint for a Decarbonised Electricity System in Great Britain.* Warwick: National Grid ESO. Retrieved from https://www.nationalgrideso.com/document/304756/download

National Grid ESO. (2024b, March 1). *Interconnector Analysis Report.* Retrieved September 5, 2024, from Beyond 2030: https://www.nationalgrideso.com/document/304771/download

National Grid ESO. (2024c, July 05). *Interconnector Register.* Retrieved July 5, 2024, from National Grid ESO: https://www.nationalgrideso.com/data-portal/interconnector-register

Nexans. (2022, January 1). *Superconductors for Electricity Grids.* Retrieved September 5, 2024, from Superconductors for Electricity Grids: https://www.nexans.com/app/uploads/2024/01/superconductors-for-electricity-grids-nexans-white-paper-2022.pdf

Nexans. (2024, July 30). *Circular Economy*. Retrieved September 5, 2024, from Nexans: https://www.nexans.com/impact/environment/circular-economy/

Offshore Wind Scotland. (2024, January 1). *Factsheet 4 - Cables and Accessories.* Retrieved September 5, 2024, from Manufacturing Supply Chain Factsheets: https://www.offshorewindscotland.org.uk/media/ns2flsmx/04-cables-accessories.pdf

Ofgem. (2018, February 23). *ESO Roles and Principles.* Retrieved September 5, 2024, from ESO Roles and Principles: https://www.ofgem.gov.uk/sites/default/files/docs/2018/02/eso_roles_and_principles.pdf

Ofgem. (2021, January 1). *Network Price Controls 2021-2028 (RIIO-2)*. Retrieved September 5, 2024, from Network price controls 2021-2028 (RIIO-2): https://www.ofgem.gov.uk/energy-policy-and-regulation/policy-and-regulatory-programmes/network-price-controls-2021-2028-riio-2

Ofgem. (2023, 4). *National Grid Viking Link Limited*. Retrieved September 5, 2024, from OFGEM.gov.uk: https://www.ofgem.gov.uk/sites/default/files/2023-04/National%20Grid%20Viking%20Link%20Limited%20%E2%80%93%20Decision%20on%20a%20request%20for%20a%20later%20regime%20start%20date%20for%20the%20Viking%20Link%20interconnector%20project%20.pdf

Ofgem. (2024a). *Interconnectors.* Retrieved September 5, 2024, from Ofgem: https://www.ofgem.gov.uk/energy-policy-and-regulation/policy-and-regulatory-programmes/interconnectors

Ofgem. (2024b, July 18). *RIIO-3 Sector Specific Methodology Decision – Overview.* Retrieved September 5, 2024, from https://www.ofgem.gov.uk/sites/default/files/2024-07/RIIO_3_SSMD_Overview.pdf

Organisation for Economic Co-operation and Development. (2022). Inventory of Restrictions on Exports of Industrial Raw Materials. Paris: OECD.

Prysmian. (2023, December 31). *Integrated Annual Report 2023.* Retrieved September 5, 2024, from https://www.prysmian.com/sites/www.prysmian.com/files/media/documents/Integrated-Annual-Report-2023.pdf

Reuters. (2023, 6). *Bauxite Miners Urge Indonesia to Rethink Export Ban as Deadline Looms*. Retrieved September 5, 2024, from Reuters: https://www.reuters.com/article/technology/bauxite-miners-urge-indonesia-to-rethink-export-ban-as-deadline-looms-idUSL1N37Y0QC/

Scottish & Southern Electricity Networks. (2019, July 1). *A Network for Net Zero: SHE Transmission RIIO-T2 Transmission Losses Strategy.* Retrieved July 29, 2024, from https://www.ssen-transmission.co.uk/globalassets/documents/a-network-for-net-zero/leadership-in-sustainability/ssen---losses-document.pdf

SP Energy Networks. (2024). *Supply Chain*. Retrieved July 10, 2024, from SP Energy Networks: https://www.spenergynetworks.co.uk/pages/supply_chain.aspx

Stellantis. (2023, February 27). *Stellantis Announces Strategic Copper Investment in Argentina, Reinforcing Commitment to Reaching Carbon Net Zero by 2038*. Retrieved September 5, 2024, from Stellantis: https://www.stellantis.com/en/news/press-releases/2023/february/stellantis-announces-strategic-copper-investment-in-argentina-reinforcing-commitment-to-reaching-carbon-net-zero-by-2038

Sumitomo Electric. (2024, May 14). *Sumitomo Electric Commences Construction Work for its New Subsea Cable Factory*. Retrieved September 5, 2024, from Sumitomo Electric commences construction work for its new Subsea Cable factory: https://sumitomoelectric.com/press/2024/05/prs018

TenneT. (2023, May 5). *TenneT Accelerates Grid Expansion and Energy Transition*. Retrieved September 5, 2024, from TenneT accelerates grid expansion and energy transition: https://www.tennet.eu/news/tennet-accelerates-grid-expansion-and-energy-transition

The Copper Mark. (2024, April 18). *Decarbonizing the Copper Sector.* Retrieved September 5, 2024, from https://coppermark.org/wp-content/uploads/2024/05/CopperMark_DecarbonizingTheCopperSector_2024.04.18.pdf

Thorne and Derrick International. (2021, August 4). *Can Aluminium Really Beat Copper In Underground Power Cables?* Retrieved September 5, 2024, from Thorne and Derrick International: https://www.powerandcables.com/electrify-the-future-can-aluminium-really-beat-copper-in-underground-power-cables/

UK Government. (2022a, August 1). *Appendix I: Electricity Networks Modelling.* Retrieved September 5, 2024, from gov.uk: https://assets.publishing.service.gov.uk/media/6690f4320808eaf43b50ce42/electricity-networks-strategic-framework-appendix-1.pdf

UK Government. (2022b). *Resilience for the Future: The UK's Critical Minerals Strategy.* London: UK Government. Retrieved from https://www.gov.uk/government/publications/uk-critical-mineral-strategy/resilience-for-the-future-the-uks-critical-minerals-strategy

UK Government and Ofgem. (2022, August 01). *Electricity Networks Strategic Framework: Enabling a Secure, Net Zero Energy System.* Retrieved June 26, 2024, from https://assets.publishing.service.gov.uk/media/62eb9bd78fa8f503349631c5/electricity-networks-strategic-framework.pdf

United Nations. (2024). UN Comtrade Database. New York: UN.

University of Arizona Superfund Research Center. (2024). *Copper Mining and Processing: Processing Copper Ores*. Retrieved September 5, 2024, from University of Arizona Superfund Research Center: https://superfund.arizona.edu/resources/learning-modules-english/copper-mining-and-processing/processing-copper-ores

Wood Mackenzie. (2024, 4). *Supply Shortages and an Inflexible Market Give Rise to High Power Transformer Lead Times*. Retrieved September 5, 2024, from Wood Mackenzie: https://www.woodmac.com/news/opinion/supply-shortages-and-an-inflexible-market-give-rise-to-high-power-transformer-lead-times/

World Customs Organization. (2022). *HS Nomenclature 2022 Edition*. Retrieved March 11, 2024, from https://www.wcoomd.org/en/topics/nomenclature/instrument-and-tools/hs-nomenclature-2022-edition.aspx

World Economic Forum. (2023, November 28). *Aluminium Demand Will Rise 40% by 2030. Here's How to Make it Sustainable*. Retrieved September 5, 2024, from World Economic

Forum: https://www.weforum.org/agenda/2023/11/aluminium-demand-how-to-make-it-sustainable/

XLCC. (2023, 11). *XLCC Awarded £9 million Scottish Enterprise Grant to Help Build Net Zero Industry Hub*. Retrieved September 5, 2024, from XLCC: https://xlcc.co.uk/2023/11/scottish-enterprise-grant/

XLCC. (2024). *Our Services*. Retrieved September 5, 2024, from XLCC: https://xlcc.co.uk/our-services/