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A UK foresight study of materials in decarbonisation technologies: the case of nuclear

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BRITISH GEOLOGICAL SURVEY
DECARBONISATION AND RESOURCE MANAGEMENT PROGRAMME
OPEN REPORT

A UK foresight study of materials in decarbonisation technologies: the case of nuclear

R Jackson, D Kemp, A Rahman, M Wilcox, S Cave, R Wildblood
(Decision Analysis Services Ltd)

Editors

A G Gunn, J M Hannaford

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British Geological Survey offices

Nicker Hill, Keyworth,
Nottingham NG12 5GG

Tel 0115 936 3100

BGS Central Enquiries Desk

Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales

Tel 0115 936 3241
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South,
Edinburgh EH14 4AP

Tel 0131 667 1000
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road,
London SW7 5BD

Tel 020 7589 4090
Tel 020 7942 5344/45
email bgslondonstaff@bgs.ac.uk

Cardiff University, Main Building, Park Place,
Cardiff CF10 3AT

Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford,
Wallingford OX10 8BB

Tel 01491 838800

Geological Survey of Northern Ireland, Department for the Economy, Dundonald House, Upper Newtownards Road, Ballymiscaw, Belfast, BT4 3SB

Tel 0289 038 8462

www2.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500   Fax 01793 411501
www.nerc.ac.uk

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1 Introduction to nuclear technology

Nuclear fission is a key energy source for many countries and will play a growing role in global decarbonisation. It is an attractive low-carbon technology due to its on-demand reliability and energy security. As of 2022, the installed global nuclear capacity is approximately 370 GW (International Atomic Energy Agency, 2023). It provides 10 per cent of global energy demand and 20 per cent of demand in advanced economies (International Energy Agency, 2022).

The UK's civil nuclear capacity as of 2024 is approximately 6 GW (National Grid, 2023). The UK Government recently published the Civil Nuclear Roadmap, outlining an ambition to grow the UK's civil nuclear capacity to 24 GW by 2050 (UK Government, 2024a). To achieve this growth, the UK needs a supply of specialist nuclear components, which require an array of materials including some critical raw materials (materials with high economic vulnerability and high global supply risk). The purpose of this report is to deliver an assessment of the UK material supply dependencies and demand to 2050 relating to nuclear sub-technologies.

1.1 PRINCIPLES OF OPERATION

Nuclear fission is a fundamental mechanism of current nuclear technology for power generation. This mechanism is defined as the splitting of atoms and results in the release of smaller, lighter atoms and large amounts of energy. In nuclear technology, nuclear fission is induced by the collisions of neutrons with fissile atoms. Certain fissile atoms yield multiple neutrons after fission, which can continue to initiate fission in other fissile atoms. The repetition of this process is a nuclear chain reaction. Nuclear power plants use this process under carefully controlled conditions to produce a desired amount of energy (EIA, 2024).

Figure 1 shows the key components within a reactor core. To enable self-sustaining nuclear fission and power from nuclear chain reactions, reactors require carefully controlled operating conditions. Certain fissile atoms such as uranium-235 (^{235}U), are used as nuclear fuel. A neutron moderator is used to slow down the initial release of fast neutrons from nuclear fission, creating heat energy and increasing the chance of subsequent fission by interaction with other ^{235}U atoms. Control rods containing neutron poisons are inserted into the nuclear reactor to absorb neutrons and reduce the rate of or stop the nuclear chain reaction (EIA, 2024).

Thermal energy generated by nuclear fission is transferred to a coolant that is pumped through the primary closed-loop circuit. For reactor designs with a secondary loop, a heat exchanger transfers heat from the primary loop to a secondary loop of water to produce steam. This steam then drives a turbine that generates electricity.

The scope of materials that make up the fuel, moderator, control rods and coolant vary depending on the type of nuclear sub-technology. Pressurised water reactors (PWRs) are a sub-technology that uses water as both the moderator and coolant, as shown in Figure 1. Advanced gas-cooled reactors (AGRs) use graphite as a moderator and carbon dioxide as a coolant. PWRs and AGRs typically have a power capacity greater than 700 MW.

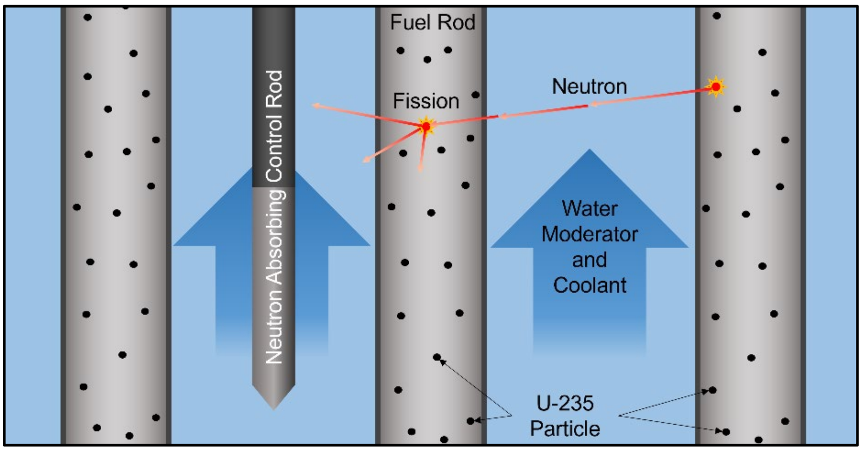


Figure 1 Summary of the principles of operation for a pressurised water reactor, showing the fuel rod, control rod, moderator and coolant. © DAS Ltd.

Small modular reactors (SMRs) are smaller versions of conventional water-cooled reactors (like PWRs) and have a capacity less than 500 MW. Advanced modular reactors (AMRs) are next-generation reactors that will use novel fuels and coolants to generate high-grade heat (UK Government, 2024a).

The UK's nuclear capacity is currently formed of PWRs and AGRs. The AGR fleet, which contributes 4.8 GW of capacity, is due to be shut down by 2028 (EDF, 2024a).

1.2 SUBTECHNOLOGIES

This section outlines three classes of sub-technology: PWRs, SMRs and AMRs (see Section 1.1). Section 1.2.3 details AMRs and includes high-temperature gas reactors (HTGRs), molten salt reactors (MSRs) and fast reactors (FRs). Table 1 presents a list of some of the vendors with interest in UK deployment, by sub-technology.

Table 1 Some of the vendors with interest in UK deployment, by subtechnology (Nuclear Advanced Manufacturing Research Centre, 2024).

Pressurised Water Reactors (PWRs)	Small Modular Reactors (SMRs)	Advanced Modular Reactors (AMRs)		
		High Temperature Gas Reactors (HTGRs)	Molten Salt Reactors (MSRs)	Fast Reactors (FRs)
EDF	Rolls Royce SMR	X-energy	UK Atomics	Newcleo
China General Nuclear Power	NuScale Power	National Nuclear Laboratory	MoltexFlex	

	EDF	Japan Atomic Energy Agency
	GE-Hitachi (BWR)	Ultra Safe Nuclear
	Westinghouse	
	Holtec Britain	

1.2.1 Pressurised water reactors

PWRs are traditional, large-scale reactors operating on the fundamental principles described in Section 1.1. While Sizewell B (1.2 GW) is currently the only operating PWR in the UK, Hinkley Point C (3.2 GW) is under construction, with an estimated commissioning date of 2029. Sizewell C (3.2 GW) is a further PWR currently under public consultation with an estimated commissioning year of 2035, should its construction be approved.

1.2.2 Small modular reactors

SMRs have a modular design with some inherent advantages, such as factory build prior to site installation, resulting in reduced construction time and cost. While no SMRs are currently in operation in the UK, Great British Nuclear is leading a SMR technology selection process, with a final investment decision (FID) on which technologies will be supported due by 2029. Table 1 provides a list of vendors competing in this process. All six vendors are proposing designs that use proven ‘light water’ reactor technology (water as both the coolant and moderator) and that will place a similar demand on materials, regardless of the chosen vendors. (Note that the boiling water reactor (BWR) being developed by GE-Hitachi is based on light water reactor technology similar to PWRs.) The UK Government anticipates that SMRs will start to deliver electricity to the grid by the mid-2030s (UK Government, 2024a).

1.2.3 Advanced modular reactors

AMRs will be able to generate a higher heat output (500°C to 900°C) compared to SMRs (around 300°C). Although they may have a role in providing energy to the grid, they also have attractive benefits for off-grid applications, which have high temperature requirements (for example, industrial heat and power; hydrogen production; district heating) (UK Government, 2023).

High-temperature gas reactors (HTGRs) use a helium coolant and a graphite core moderator. They are more technologically advanced than other AMRs, since they share similar technology to the existing AGR fleet. The UK Government has committed to investing in research and development to achieve an HTGR demonstrator by the early 2030s (UK Government, 2023), but it is unlikely that they will be deployed before 2040 according to independent estimates (Nuclear Innovation and Research Advisory Board, 2020). While PWRs and SMRs require low-enriched uranium (LEU, with ^{235}U enrichment to around 5 per cent), most AMR designs (including HTGRs) require high-assay low-enriched uranium (HALEU) fuel (with ^{235}U enrichment up to 20 per cent).

In molten salt reactors (MSRs), both the fuel and coolant typically contain fluoride or chloride salts, while the moderator is made of graphite.

Fast reactors (FRs) are those where the reaction is sustained by fast neutrons (as opposed to slow or thermal neutrons). There is no moderator in FRs and the coolant can be molten lead or sodium. Fuel options include mixed oxide fuel (MOX) that contains both uranium (U) and plutonium (Pu).

Table 2 summarises the differences in fuel, moderator and coolant materials in each of the nuclear subtechnologies discussed.

Table 2 Key differentiators of each nuclear subtechnology (Nuclear Innovation and Research Office, 2021)

	Pressurised Water Reactors (PWR	Small Modular Reactors (SMR	High Temperature Gas Reactors (HTGRs)	Molten Salt Reactors (MSRs)	Fast Reactors (FRs)
Fuel	LEU or MOX	LEU	HALEU	Fuel salt (for example, thorium or LEU)	A variety, including MOX
Moderator	Water	Water	Graphite	Graphite	None
Coolant	Water	Water	Helium	Fluoride or chloride salts	Lead or Sodium

1.3 SCOPE OF THIS STUDY

Evidence from the UK Government Civil Nuclear Roadmap and stakeholder engagement for this study has strongly suggested that large-scale PWRs and SMRs are the most likely sub-technologies to be contributing towards the civil on-grid nuclear capacity between now and 2050. Deployment scenarios for these sub-technologies are also more advanced. PWR and SMR technologies are therefore the subject of the quantitative material analysis and scenario demand projections within the scope and timescales of this study. Although deployment scenarios for AMRs are less mature, qualitative context and narrative are provided for these sub-technologies due to their strategic importance.

1.3.1 Nuclear fusion

Nuclear fusion is the process of combining two atomic nuclei into a heavier, single nucleus, releasing energy in the process. While nuclear fusion is an active area of research in the UK, evidence suggests it is unlikely that fusion reactors in the UK will contribute towards the national energy supply before 2050 (House of Commons, 2023). Therefore, fusion material requirements are not considered within the scope of this study.

1.4 ESSENTIAL COMPONENTS AND MATERIALS

This analysis concentrates on materials that contribute to the key functionality of nuclear PWR and SMR technologies (Table 3). The subsequent description of the detailed bill of materials (BOM) for PWRs and SMRs is drawn from publicly accessible design documents for the UK European pressure reactor (UK EPR, the type of PWR that Hinkley Point C is based on) and the Rolls-Royce SMR (EDF, 2012; Rolls Royce SMR, 2023). Evidence from the design documentation is used to estimate values of material intensity (the mass of each material required per gigawatt of plant power capacity (kg/GW)).

The scope of this study is limited to the selection of components from these design documents that satisfy the following criteria:

- either located within the reactor core or is unique, bespoke or particularly significant to nuclear technology (for example, steam turbine)
- not a structural component (structural steel and concrete components)
- not a steel component, noting the similarity to structural components

These criteria were applied to ensure the study was manageable within the available constraints while enabling focus on prioritised nuclear technology components.

Table 3 Materials used in PWR and SMR nuclear sub-technologies (Source: DAS Analysis).

Subtechnology	UK critical minerals[1]	Other
PWR	Gadolinium, Indium, Niobium, Silicon, Tin	Boron, Cadmium, Chromium, Molybdenum, Silver, Titanium, Uranium, Zirconium, Manganese, Nickel, Iron, Aluminium, Copper
SMR		

Elements in red are excluded from the analysis because they are used either in structural components or in ancillary components such as the surrounding subsystems, instrumentation, electronics and control systems.

1.4.1 Pressurised water reactors

Figure 2 presents the salient features of a PWR nuclear island. The core of the nuclear reactor (labelled ‘1’), is contained in a large steel reactor pressure vessel (RPV), which can weigh about 600 t for a 1.6 GW reactor (EDF, 2012).

[1] The full list of UK critical minerals is provided in the latest criticality assessment report (Lusty, et al., 2021)

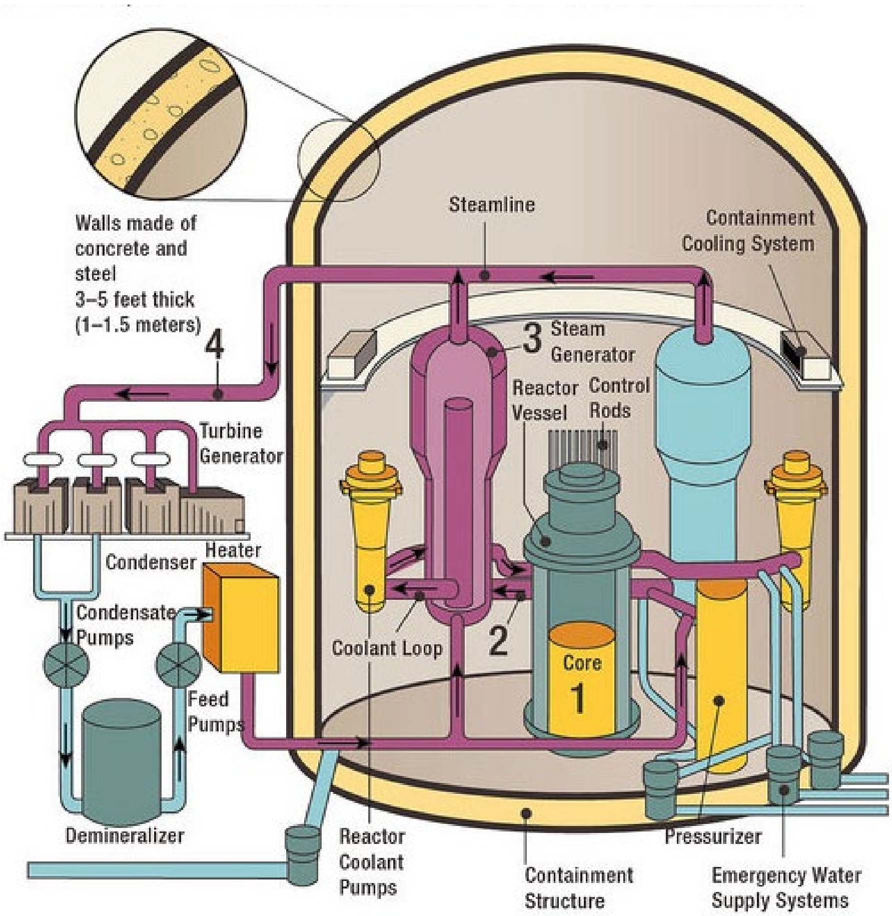


Figure 2 Salient components of a PWR (Nuclear Regulatory Commission, 2023). © NRC.

A circular grid of fuel assemblies (241 in UK EPRs) (EDF, 2012)) makes up the reactor core. Fuel assemblies are consumables that are rotated within the fuel assembly grid during their operating lifetime, to account for burn-up and to maintain power generation distribution across the reactor core. About one-third of fuel assemblies are replaced in each 18-month refuelling cycle.

Reactor coolant pumps circulate light water around the primary loop (labelled '2' in Figure 2 (EDF, 2012). This loop has several steam generators (labelled '3'), containing temperature-resistant nickel-chromium alloy ('Inconel') heat exchangers, which transfer heat from the primary loop to produce steam in the secondary loop (labelled '4'). Steam drives high-pressure and low-pressure turbines, which consist of Inconel alloys, that enable operation under the appropriate conditions. The turbines are connected to a generator that converts the thermal energy to electrical energy, so it can be transferred to the grid. Steam exiting the turbine assembly is cooled, condensed and recirculated back through the secondary loop.

Fuel assemblies contain arrays of fuel rods and guide tubes housed in corrosion-resistant zirconium alloy and Inconel spacer grids (EDF, 2012). Each fuel rod contains enriched uranium dioxide (UO_2) pellets. The UK EPR design uses gadolinium oxide (Gd_2O_3) as a burnable neutron poison within the fuel pellet to adjust power distribution. Silver-indium-cadmium (Ag-In-Cd) and boron carbide (B_4C) control-rod assemblies are lowered into fuel assemblies to control the fission reaction and power distribution within the reactor. The BOM considered in this analysis is shown in Table 4.

Table 4 Bill of materials of a PWR (EDF, 2012). Control-rod life estimates derived from stakeholder engagement.

System	Assembly	Component	Life (years)	Material
Reactor and core	Fuel assembly	Fuel pellet	4.5	UO_2
		Fuel pellet burnable poison		Gd_2O_3
		Fuel rod cladding		Zirconium alloy
		Guide thimbles		Zirconium alloy
		Spacer grids		Zirconium alloy
		Spacer spring		Inconel 718
		Top and bottom spacer grids		Inconel 718
	Control rods	Ag-In-Cd portion	10	Ag-In-Cd
		B_4C portion		B_4C
	Coolant	Boric acid (PWR only)	-	^{10}B
Primary loop	Steam generator	Tubes	-	Inconel 690
		Tube sheet cladding	-	Inconel 600
Secondary loop	Turbine	Turbine blade assembly	-	Inconel 625

1.4.2 Small modular reactors

All materials present in the UK EPR are also present in the Rolls-Royce SMR, given the similarity in technology. The Rolls-Royce SMR BOM used in this study is very similar to the UK EPR BOM, with the key difference being that the SMR does not use boric acid as a neutron absorber (Rolls-Royce SMR, 2019). Where design information is not sufficient, the Rolls-Royce SMR components have been scaled from the UK EPR design documents, using power capacity (gigawatts) as the scaling factor.

2 Supply chain mapping of nuclear technologies

The different stages of the nuclear supply chain for each of the fifteen materials within scope are displayed in Figure 3. The material transformations across the mining, refining, pre-processing and component stages are shown. All components are common across PWR and SMR sub-technologies except boric acid, which is only used in PWRs and is not used in the Rolls-Royce SMR design. Some intermediate steps in the supply chain could not be analysed due to the lack of available data. These include, for example, most of the gadolinium (Gd) value chain following the mining of rare earth ores, the refining stage of titanium (Ti) to create ferrotitanium and the refining stage of zirconium (Zr).

Figure 3 Supply chain mapping of key materials in PWR and SMR nuclear reactors. The green shading indicates materials for which data availability has permitted inclusion in the quantitative supply chain analysis. A star indicates a material produced as a by-product in the refining stage. BGS © UKRI.

U has a complex value chain, as illustrated in Figure 4. U is mined from ores containing a variety of U-bearing minerals, such as uraninite, brannerite and carnotite (World Nuclear Association, 2020). These are processed into a uranium oxide concentrate, typically a form known as yellowcake (U_3O_8). The next stage involves conversion of yellowcake into uranium hexafluoride (UF_6), a precursor for the enrichment stage.

Naturally occurring U deposits comprise dominantly the ^{238}U isotope (greater than 99 per cent of total natural U), accompanied by minor amounts of ^{235}U (0.7 per cent) and ^{234}U (trace amounts). ^{235}U is the fissile isotope that is required in nuclear reactors. Enrichment increases the concentration of ^{235}U to a level that enables nuclear criticality, resulting in an enriched UF_6 product and a depleted UF_6 by-product. Enriched UF_6 undergoes a deconversion process to UO_2 before being pressed into small ceramic pellets of about 1 cm diameter and encased in Zr alloy cladding to form a fuel pin (Nuclear Regulatory Commission, 2020). Fuel pins are placed into fuel assemblies for use in a reactor. The used fuel is carefully stored, before either being disposed of or reprocessed.

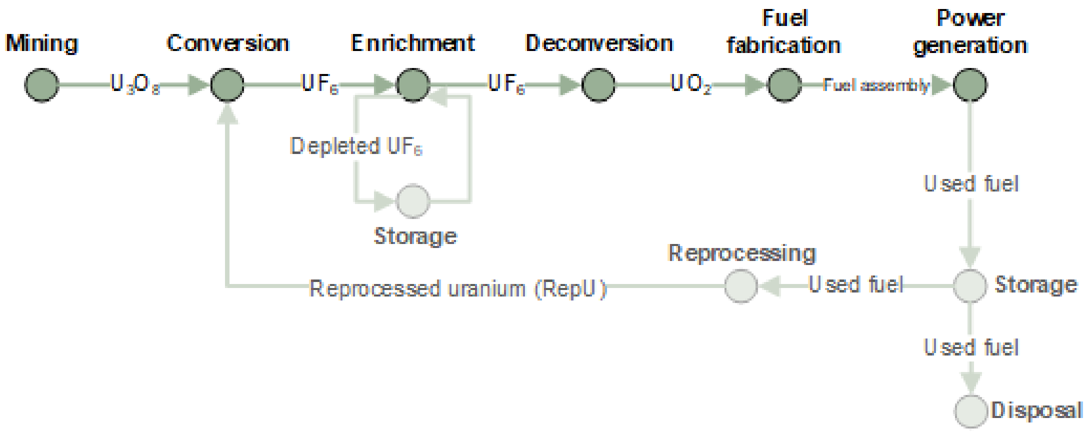


Figure 4 High-level overview of U in the nuclear supply chain. Adapted from World Nuclear Association (2021a).

Gd is extracted from a range of rare earth element (REE) minerals, including monazite and bastnaesite (Wall, 2014), denoted in Figure 5 as ’rare earth element ores & concentrates’. The ore is processed to remove impurities and then refined by solvent extraction to separate Gd from the other REEs. The extracted Gd_2O_3 is incorporated into fuel pellets as a burnable neutron poison to limit reactivity and extend fuel life (World Nuclear Association, 2021b).

Refined nickel (Ni) and chromium (Cr) are alloyed together with smaller fractions of ferro-alloys (manganese (Mn), molybdenum (Mo), niobium (Nb), silicon (Si) and titanium (Ti)) to create various Ni-Cr alloys (Inconels), which are used in the fuel assembly, steam generator and turbine. Most of these elements are extracted from ores containing minerals of each metal.

Zr is derived chiefly from the mineral zircon, which is found in mineral sand deposits in several countries, notably Australia and southern Africa (Zircon Industry Association, 2022). Zircon is concentrated and then refined to zircon powder before conversion to a sponge. Alloying elements, including Cr, Nb and tin (Sn), are added. The derived alloy is extruded into billets for cladding the fuel assembly (Framatome, 2018).

Most indium (In) and cadmium (Cd) are by-products of the extraction of other elements. Both can be extracted from zinc (Zn), while In is, to a lesser extent, also extracted from Sn (Shanks, et al., 2017; US Geological Survey, 2018). These elements are alloyed with silver (Ag) and used in the manufacture of Ag-In-Cd control rods (Cohen, 1959).

B_4C is manufactured from borate minerals via an intermediate processing step to boron trioxide (B_2O_3) (Goller et al., 1996). Borates are also used in the production of enriched boric acid as a neutron absorber (US Geological Survey, 2019).

3 Supply chain bottlenecks

The assembly of nuclear technologies depends upon the supply of specialist components. The raw materials and manufacturing infrastructure required to create these components are restricted to certain countries. This concentration of material and manufacturing capability can increase the risk of supply disruption and act as a bottleneck. Materials highlighted in green in Figure 3 are materials that have been included in the analysis of the supply chain bottlenecks discussed in this section, made possible by the availability of relevant data.

Figure 5 presents the key countries involved in the mining, refining and precursor stages of the nuclear supply chain. For the mining and refining stages, the country flags of the top three producers are presented. At the precursor production stage, the flags highlight the location of key producers, but their order does not reflect their respective market share.

At the mining stage, supply is relatively diversified, with nineteen different countries appearing as top three producers for the twelve materials analysed. Eight of the twelve are associated with a different leading producer country. South Africa is the top producer of both Mn and Cr and appears as the second and third largest producer of Zr and Ti, respectively. China is the leading producer for four materials (Mo, Ti, Sn and Gd) and is the second and the third largest producer of Mn and Ag, respectively.

Producer diversity persists at the refined stage of the value chain, with twelve different countries appearing as top three producers for eight materials. Notably, China emerges as the top producer for four of the materials: refined Ni, Sn, In and Cd. Japan and South Korea appear in the top producer lists for refined products of Mn, In and Cd, with Japan also a key producer of refined Ni.

More western countries are involved in the production of precursors, including the UK, the USA, Germany and France. However, it is important to note that Russia and China feature prominently in the production of U fuel, Zr alloy cladding and Ag-In-Cd control rods.

3.1 MINING AND REFINING

3.1.1 Production concentration

Figure 6 illustrates the global production share of materials used in nuclear technologies for the top three producing countries in the mining and refining stages. The materials are ordered from the highest to the lowest concentrated among the top three producers. Gd is a REE and is represented under the aggregate grouping of rare earth oxides (REOs), since data for Gd alone are unavailable.

The mine production of eight of the twelve materials evaluated is highly concentrated, with the top three producing nations responsible for more than 60 per cent of the global total. A similar level of concentration is present for five of the eight refinery products assessed. Nb is the most concentrated at both the mining and refining stages. Brazil, Canada and Nigeria account for 98 per cent of global mining production, with Brazil and Canada producing 100 per cent of the world's ferroniobium, the main traded form of Nb.

The mine production of REOs and B are also highly concentrated, in China and Türkiye, respectively. In and Cd are not included in the mining stage because they are recovered in the refinery as a by-product from the extraction of Zn.

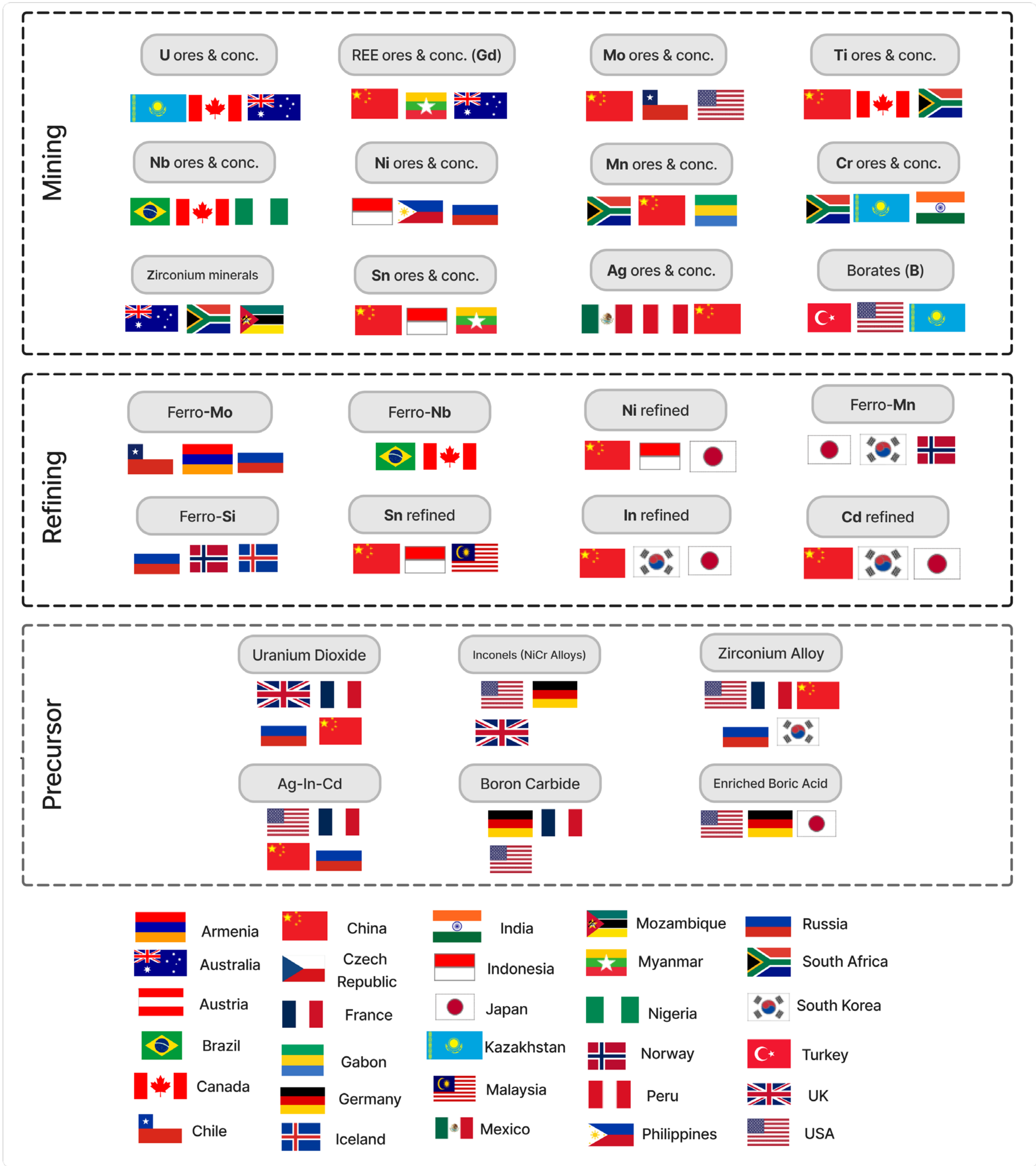


Figure 5 Geographical production concentration in the nuclear supply chain. At the mining and refining stages, the national flags show the top three producers, from left to right, based on a five-year production average between 2017 and 2021 from the BGS World Mineral Statistics Database (Idoine, et al., 2023). BGS © UKRI.

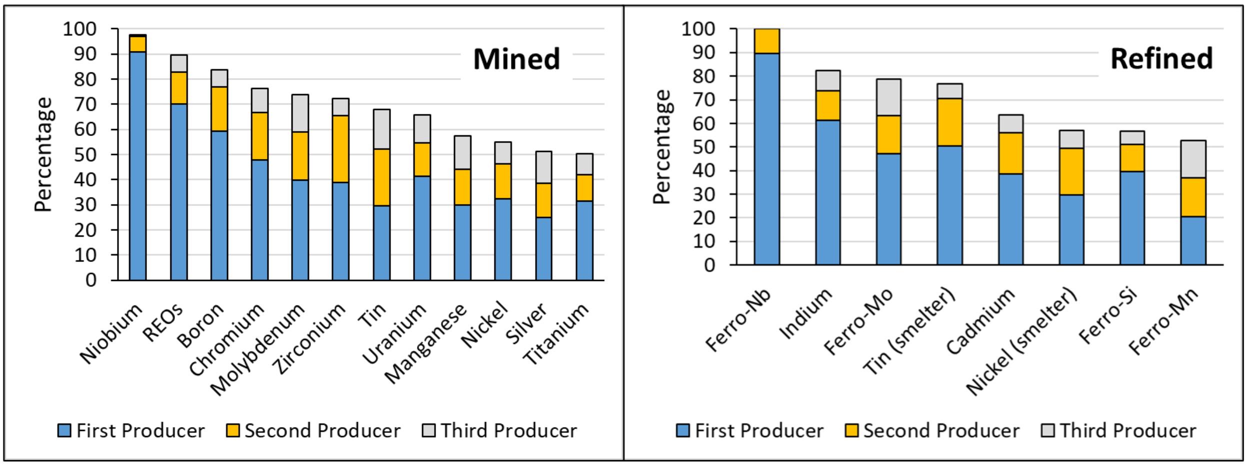


Figure 6 Global mine and refined production of key materials in nuclear technologies, showing the production shares of the top three producing countries. Data from the British Geological Survey World Mineral Statistics Database (Idoine et al., 2023). BGS © UKRI.

Figure 7 shows the ranked production concentration of each material at the mined and refined stages. This is based on the indicator recommended in the revised methodology for UK criticality assessment (Josso, et al., 2023). It is derived from the production shares of the leading producers modified by a factor that reflects the environmental, social and governance (ESG) performance of those countries.

Of the five minerals analysed for both stages, four have a similar or lower score at the refining stage than the mining stage, showing that the production concentration generally reduces along the value chain. Nevertheless, there are some materials with a very high ranked production concentration score. Nb in particular scores 7.9 and 7.8, for the mining and refining stages respectively. This is due to Brazil's market dominance coupled with its intermediate ESG score, leading to greater supply risk.

The three elements at greatest supply risk based on production concentration share (Figure 6) and concentration scores (Figure 7) are Nb, In and Gd, which, in turn, places downstream risk on Zr and N-Cr alloys, Ag-In-Cd control rods and the burnable neutron poison.

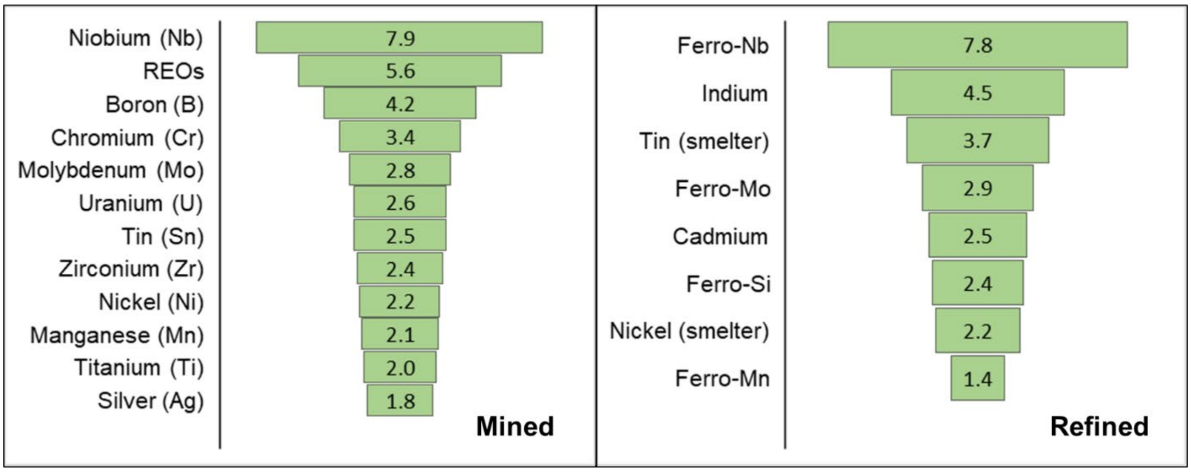


Figure 7 Ranked production concentration scores for key materials (mined and refined) used in nuclear technologies based on an ESG-weighted Herfindahl-Hirschman Index for each of the top three producing countries. BGS © UKRI.

3.1.2 Global trade concentration and trade restrictions

As with the production of mined and refined materials used in nuclear technologies, 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 some of the materials assessed (ores and refined metals) are not available or are reported at too low a resolution to be useful. For example, trade data for Gd are aggregated with several other REEs and are reported together under a single trade code. Consequently, it was not possible to evaluate trade for all the materials selected for this study.

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 5 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 years 2017 and 2021, inclusive, were analysed. This assessment includes information on trade restrictions, which are sourced from the OECD (OECD, 2022).

Figure 8 illustrates trade at the mining stage for five materials: Cr, Ni, Ag, Zr and borates. The assessment of alloying elements (Mn, Mo, Sn and Ti) is presented in Appendix A. The trade concentration of other minerals is not presented here, either because they are aggregated with other minerals under the same HS code (Gd is aggregated with REEs and Nb is aggregated with tantalum (Ta) and vanadium (V)), or because the data are not reliable (as is the case for U).

China emerges as the top global importer for all materials shown in Figure 8. For four of these materials, China’s global import share exceeds 60 per cent. Additionally, South Africa plays a significant role as the primary exporter of Cr and Zr. Exports of the mine production of Ni, Ag and borates are also highly concentrated with single nations predominant: the Philippines, Peru and Türkiye, respectively.

There are trade restrictions that affect exports at the mining stage for Ni, Ag, Zr and borates. Currently, there are no known active restrictions on Cr. The two leading Ni-producing nations, Indonesia and the Philippines, both impose significant restrictions on the export of Ni-bearing materials. Indonesia has prohibited the export of unprocessed Ni (ores and concentrates) since 2020. The Philippines currently requires a licensing agreement and applies a fiscal tax on the export of Ni ores and concentrates.

Senegal imposes a 3 per cent fiscal tax on the sale price of mined Zr, while Bolivia applies a fiscal tax of 0.05 per cent of the gross value of mined Ag. For the export of mined borates, Argentina applies an export tax of 4.5 per cent and Bolivia requires an export licence and applies a fiscal tax of 0.05 per cent of the gross value.

Figure 9 shows the distribution of trade in refined materials. Appendix A presents the trade flows of other ferro-alloys. China and USA are the top importers for six of the seven materials shown in Figure 9. However, unlike at the mining stage, the share of imports is more evenly distributed. Global exports of ferro-niobium, refined Cr, refined Zr and boric acid are highly concentrated, with the top three trading nations accounting for 43 to 77 per cent of global exports.

There are no restrictions on the trade in refined products of the seven materials assessed in Figure 9.

Table 5 Materials included in the analysis of global trade concentration and trade restrictions, with their corresponding HS codes.

Element	Supply chain stage	HS code	Description
B	Mined	252800	Natural borates
	Refined	281000	Boric acids
Cd	Mined	N/A	N/A
	Refined	810720	Unwrought cadmium and powders
Cr	Mined	261000	Chromium ores and concentrates
	Refined	811221	Chromium metal: unwrought, powder
Mn	Mined	260200	Manganese ores and concentrates
	Refined	720211	Ferro-manganese containing by weight more than 2 per cent of carbon
Mo	Mined	2613	Molybdenum ores and concentrates
	Refined	720270	Ferro-molybdenum
Ni	Mined	260400	Nickel ores and concentrates
	Refined	750210	Nickel, not alloyed
Nb	Mined	N/A	N/A
	Refined	720293	Ferro-niobium
Si	Mined	N/A	N/A
	Refined	720221	Ferro-silicon, containing by weight more than 55 per cent of silicon
Ag	Mined	261610	Silver ores and concentrates
	Refined	710691	Silver unwrought (but not powder)
Sn	Mined	260900	Tin ores and concentrates
	Refined	800110	Tin unwrought, not alloyed
Ti	Mined	261400	Titanium ores and concentrates
	Refined	720291	Ferro-titanium and ferro-silico-titanium
Zr	Mined	261510	Zirconium ores and concentrates
	Refined	810920	Unwrought zirconium; powders

Figure 8 The top three importing and exporting countries for mined ores and concentrates 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 OECD (2022). BGS © UKRI.

Figure 9 The top three importing and exporting countries of refined minerals with the share of global trade flows shown for each country. Countries highlighted in red are dominant exporters or importers with a global share exceeding 40 per cent), whilst countries with a cross have active trade restrictions. Compiled from data derived from United Nations (2024) and OECD (2022). BGS © UKRI.

3.2 COMPONENT AND PRODUCT MANUFACTURE

Quantitative data on component and product manufacturing is generally not available. Instead, contextual narrative is provided on the key suppliers and their countries of operation.

3.2.1 Nuclear fuel

At the conversion stage, there are only five companies that produce UF_6:

- Orano (France)
- CNNC (China)
- Cameco (Canada)
- Rosatom (Russia)
- CoverDyn (USA)

These have a combined annual production capacity of 62 000 tonnes of UF_6. Plants in Russia and China control 45 per cent of global conversion capacity, with China's capacity expected to grow considerably through to 2025 to keep up with domestic requirements (World Nuclear Association, 2022a).

At the enrichment phase, the number of key companies reduces to four suppliers:

- Urenco (USA, UK, Germany and Netherlands consortium)
- Orano (France)
- Rosatom (Russia)
- CNNC (China)

These suppliers account for over 99 per cent of global enrichment capacity. CNNC's capacity is planned to nearly triple between 2020 and 2030, placing greater demand on the need for U ores (World Nuclear Association, 2022b).

Despite the few suppliers of enriched U, there are several global suppliers of fuel assemblies, with multiple production facilities. These include:

- Westinghouse (USA, UK and Sweden)
- Framatome (France, Germany and USA)
- CNNC (China)
- Mitsubishi Heavy Industries (Japan)
- KEPCO (South Korea)
- Rosatom (Russia)
- Global Nuclear Fuel (USA)

Key precursors within fuel assemblies include the enriched U fuel rods, Gd burnable poison and structural components made of Zr alloys and Ni-Cr alloys.

3.2.2 Other key component suppliers

The two biggest component suppliers to global nuclear reactor plants are Westinghouse (USA) and Framatome (France), who supply components to 66 and 64 plants, respectively. Other key suppliers are (International Atomic Energy Agency, 2022):

- GE (USA): 38 plants
- Atomenergomash (Russia; subdivision of Rosatom): 37 plants
- Ontario Hydro (Canada): 18 plants
- NPCIL (India): 17 plants
- Mitsubishi Heavy Industries (Japan): 15 plants
- Atommash (Russia): 15 plants
- Dongfang Electric Corportation (China): 12 plants

- Doosan Heavy Industries (Korea): 12 plants
- Škoda (Czech Republic): 10 plants
- Toshiba (Japan): 10 plants
- CNNC (China): 9 plants

Table 6 maps some of these suppliers to the key components that contain the materials investigated in this study.

Rod cluster control assemblies (RCCAs), which house the control rods, are made by several of the key players, including Framatome, Westinghouse, CNNC and Rosatom. A number of other companies manufacture control-rod drive mechanisms (CRDMs), which form part of the RCCAs. These include Mitsubishi, GE-Hitachi and Škoda. Engagement with stakeholders as part of this report revealed a growing concern around the lead time for CRDMs.

RPVs are another long lead item, which stakeholders indicated can take up to eight years from placing the order to delivery. This is due to the scale of these single-forged items, with a weight of about 600 t for a 1.6 GW reactor. These require very large forging presses available from only a handful of companies worldwide.

Manufacturers of steam generators include:

- Westinghouse
- Framatome
- Mistubishi Heavy Industries
- GE-Hitachi
- Doosan Heavy Industries
- Babcock & Wilcox
- KEPCO
- Atomenergomash

In addition, a few turbine manufacturers supply to nuclear operators. These include:

- Rosatom
- Doosan Heavy Industries
- GE
- Mitsubishi Heavy Industries
- Siemens

Table 6 Selected suppliers of key components.

Fuel assemblies	RCCAs	CRDMs	Steam generators	Turbines
Westinghouse	Westinghouse	Mitsubishi Heavy Industries	Westinghouse	Rosatom
Framatome	Framatome	GE-Hitachi	Framatome	Doosan Heavy Industries
CNNC	CNCC	Škoda	Mitsubishi Heavy Industries	GE-Hitachi
Mitsubishi Heavy Industries	Rosatom	Curtiss-Wright	GE-Hitachi	Mitsubishi Heavy Industries
KEPCO			Doosan Heavy Industries	Siemens
Rostaom			Babcock & Wilcox	
Global Nuclear Fuel			KEPCO	
			Rosatom	
			Japan Steel Works	
			BWX Technologies	

Globally, there are about 70 SMRs that are either in conception, development or construction, or are currently operating. Key players include (International Atomic Energy Agency, 2020):

- CNNC (China)
- GE-Hitachi (USA-Japan)
- NIKIET (Russia)
- EDF (France)
- Rolls-Royce (UK)
- several American companies such as:
    - NuScale
    - Holtec
    - Westinghouse

It is expected that some of the current suppliers will also provide components to these companies, should their designs be constructed.

4 UK supply chain in nuclear technology

As of 2023, an estimated 77 000 people are employed across the UK in the civil nuclear supply chain. In addition to manufacturing, the skills base of this workforce also covers the nuclear fuel cycle, operators, vendors and those offering related services such as decommissioning and waste management (Nuclear Industry Association, 2023).

4.1.1 Vendors and operators

UK nuclear vendors are at the forefront of global nuclear technology development. EDF Energy is responsible for the construction and commissioning of Hinkley Point C and Sizewell C. EDF is also developing the Nuward SMR design.

Other UK vendors designing SMRs include:

- Rolls-Royce SMR
- Westinghouse Electric Company UK (developing the AP300)
- Holtec Britain (developing the SMR-300)

There are also several UK AMR developers, including:

- Newcleo (lead-cooled fast reactor)
- UK Atomics (Th molten salt reactor)
- GMET

4.1.2 Nuclear fuel

The UK plays a critical role in the production of nuclear fuel. It has a strategically significant U-enrichment capability, operated by Urenco UK, which is the only U-enrichment facility in the country (Nuclear Decommissioning Authority, 2021). Located in Capenhurst, Cheshire, Urenco's enrichment capacity is approximately 8 per cent of the current global capacity (World Nuclear Association, 2022b; Urenco UK, 2024).

The UK Government is investing £300 million to develop a HALEU fuel supply chain in the UK, including an enrichment facility (UK Government, 2024b). This is in addition to £10 million for Urenco to develop HALEU-enrichment capability at Capenhurst. These investments aim to mitigate supply risk to the UK as Rosatom (Russia) is currently the sole global supplier of commercially viable HALEU fuel.

Westinghouse Springfields is a fuel production facility based near Preston, Lancashire. The site manufactures both AGR and PWR fuel assemblies. In November 2023, Framatome committed to setting up a fuel fabrication facility in the UK. It is currently evaluating potential sites through engagement with Department for Energy Security and Net Zero and EDF (Framatome, 2023).

The UK Government considers nuclear exports a significant opportunity for UK industry (UK Government, 2024a). Existing infrastructure has been reinforced by investment commitments into SMRs, HALEU and fuel fabrication made in 2023, cementing the UK's position in these supply chains. These exports would need significant volumes of raw materials and high-grade refined materials would be required by the UK value chain beyond the UK's domestic energy demands. For example, the UK nuclear roadmap states an ambition for the Springfields site to deliver an additional 7500 tonnes of reprocessed U and non-irradiated U conversion capacity to the global market (UK Government, 2024a).

4.1.3 Nuclear components

There is a global supply risk for larger items with long lead times (for example, RPVs and steam generators). For RPVs, the UK is seeking to mitigate the supply risk in two ways: by enabling capacity for Sheffield Forgemasters to be able to make RPVs in the UK and by investing in electron-beam welding through the Nuclear Advanced Manufacturing Research Centre (NAMRC). Electron-beam welding is a novel manufacturing technique that can reduce the lead time of SMR RPVs from two and a half years to less than one year (UK Government, 2024a). Sheffield Forgemasters has a Memorandum of Understanding in place with Rolls-Royce SMR for the manufacture and supply of RPVs (Sheffield Forgemasters, 2021).

NAMRC provides support on UK supply chain development, through the Fit for Nuclear initiative (F4N). This is a service used by companies to ensure that they are ready to win work in the nuclear supply chain. Approximately 100 companies have been granted F4N to date, offering components that include, but are not limited to, pressure vessels, valves, pumps and pipework.

5 UK future demand

5.1 SCENARIOS AND MODELLING CONDITIONS

Future UK energy demand is modelled using a range of scenarios, which are presented in Figure 10. The five scenarios analysed in this report include the four National Grid Future Energy Scenarios (FES) (National Grid, 2023) and a scenario inferred from the UK Civil Nuclear Roadmap to 2050, which has been validated with stakeholders (UK Government, 2024a). The FES scenarios reflect the UK energy system as a whole and the names are not representative of nuclear ambition. All modelled scenarios exclude the AGR fleet, which has an expected final decommission year of 2028 (EDF, 2024b). The 2050 nuclear capacity presented by the FES scenarios ranges between 10 and 16 GW, which is significantly lower than the UK Government's ambition of 24 GW. For all scenarios, Hinkley Point C is commissioned by 2030 and Sizewell C is operating by the late 2030s or early 2040s. A 2.2 GW PWR in the mid-2040s has been assumed for the Government Roadmap scenario, as the UK Government 'commits to exploring further large [gigawatt] reactor development' (UK Government, 2024a).

Figures 10b to 10f show possible deployment schedules for the five scenarios. Stakeholders with expertise in nuclear technology development were consulted on these deployment rates to ensure that they are realistic.

The FES scenarios consider a small number of SMRs from the mid-2030s. The low deployment rates of SMRs in the FES scenarios are not consistent with either the UK Government ambition or with findings from stakeholder engagement in this study. The UK Government aims to secure investment decisions that will deliver between 3 and 7 GW of nuclear capacity from a combination of subtechnologies every five years between 2030 and 2044. The Government Roadmap scenario, Figure 10b, assumes that the earliest SMR deployment will occur in 2033 and that there is a consistent level of deployment of SMRs (more than 3.5 GW every five years) to meet the gap between the capacity of PWRs and the ambition of 24 GW by 2050.

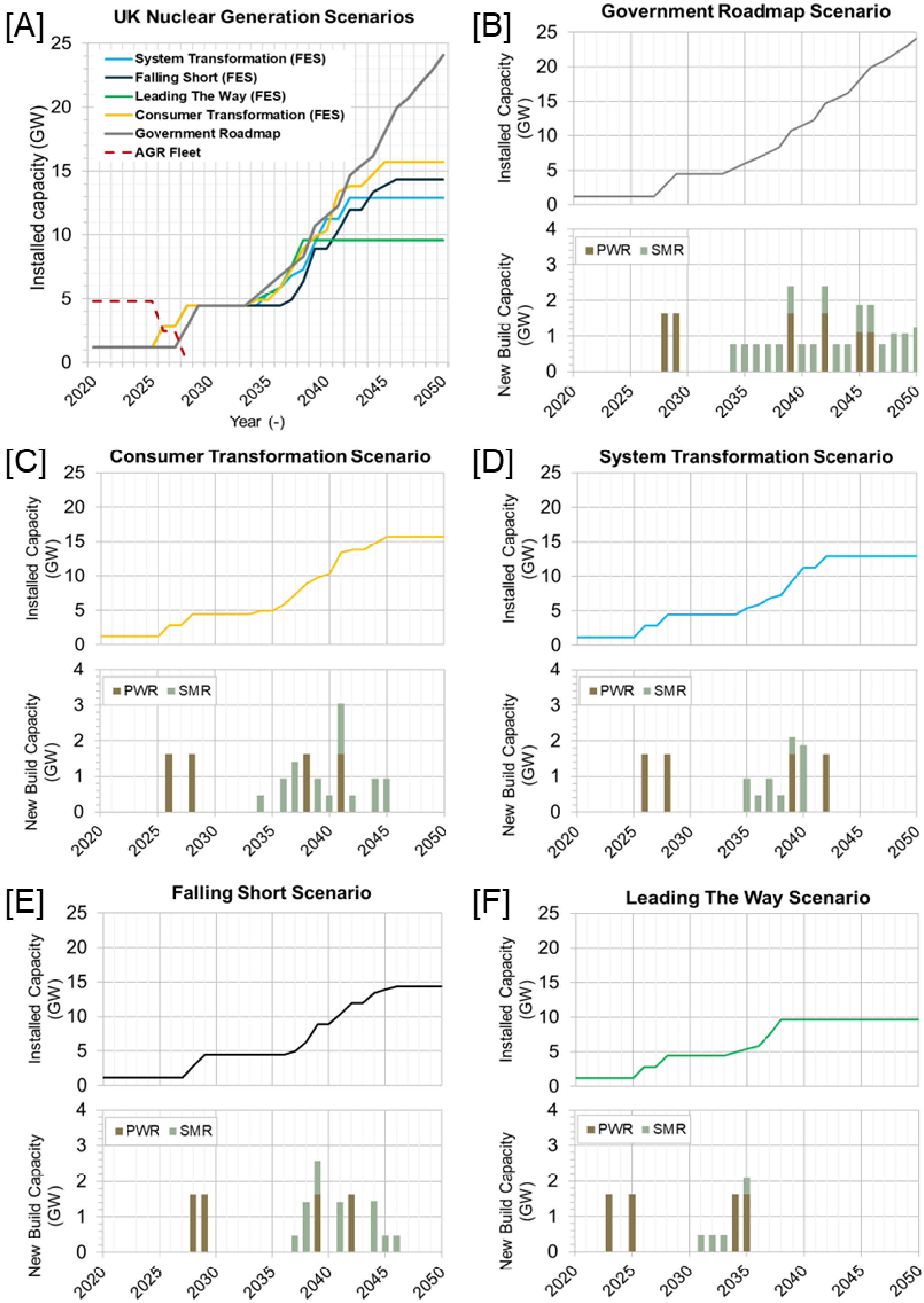


Figure 10 UK nuclear deployment scenarios, showing A: the full set of five scenarios; B: Government Roadmap; C: 'Consumer transformation'; D: 'System transformation'; E: 'Falling short'; F: 'Leading the way' (FES). (UK Government, 2024a; National Grid, 2023). BGS © UKRI.

5.2 FUTURE UK RAW MATERIAL NEEDS FOR NUCLEAR TECHNOLOGIES

The calculation of future UK material requirements for nuclear technologies includes those needed for both the initial build (kg/GW) and the operational maintenance (or annual consumable demand, kg/GW/year). The material demand for the initial build components appears in the year the reactor goes operational. The demand for consumable components is calculated as a yearly average based on the total capacity of each subtechnology operational in that year. These values feed into the cumulative UK material demand to 2050 (Figure 11). The cumulative demand captures the total mass of materials required by UK nuclear reactors between 2023 and each year shown.

Nuclear technologies place a particularly high demand on U fuel and, by extension, mined U ore. Under the UK Government Roadmap scenario, the cumulative demand for U to 2050 is estimated to be equivalent to 60 000 t of mined U. Ni, Cr and Zr also have relatively high demands of 5500, 2500 and 2000 t, respectively. The remaining eleven materials evaluated each require a supply of less than 1000 t up to 2050.

Cumulative UK demand to 2050 should be considered relative to global production levels. Table 7 shows the annual global production output of the material evaluated in this study. Gd is not included because global production data are not in the public domain. Literature estimates annual Chinese production to be between 1300 and 2000 t between 2011 and 2020 (Zhao, et al., 2023). Comparison of UK demand projections with current global production indicates where further bottlenecks are likely to exist.

Table 7 Global mine production (five-year average, 2017 to 2021) for the materials assessed in this study (Idoine, et al., 2023).

Element	Global production (5-year average) (t)
Borates	7 370 822
Cd	25 750
Cr	34 967 765
In	813
Mn	54 566 982
Mo	294 154
Ni	2 492 760
Nb	114 096
Si	3 035 036
Ag	27 252
Sn	305 400
Ti	6 558 489
U	52 731
Zr minerals	1 227 153

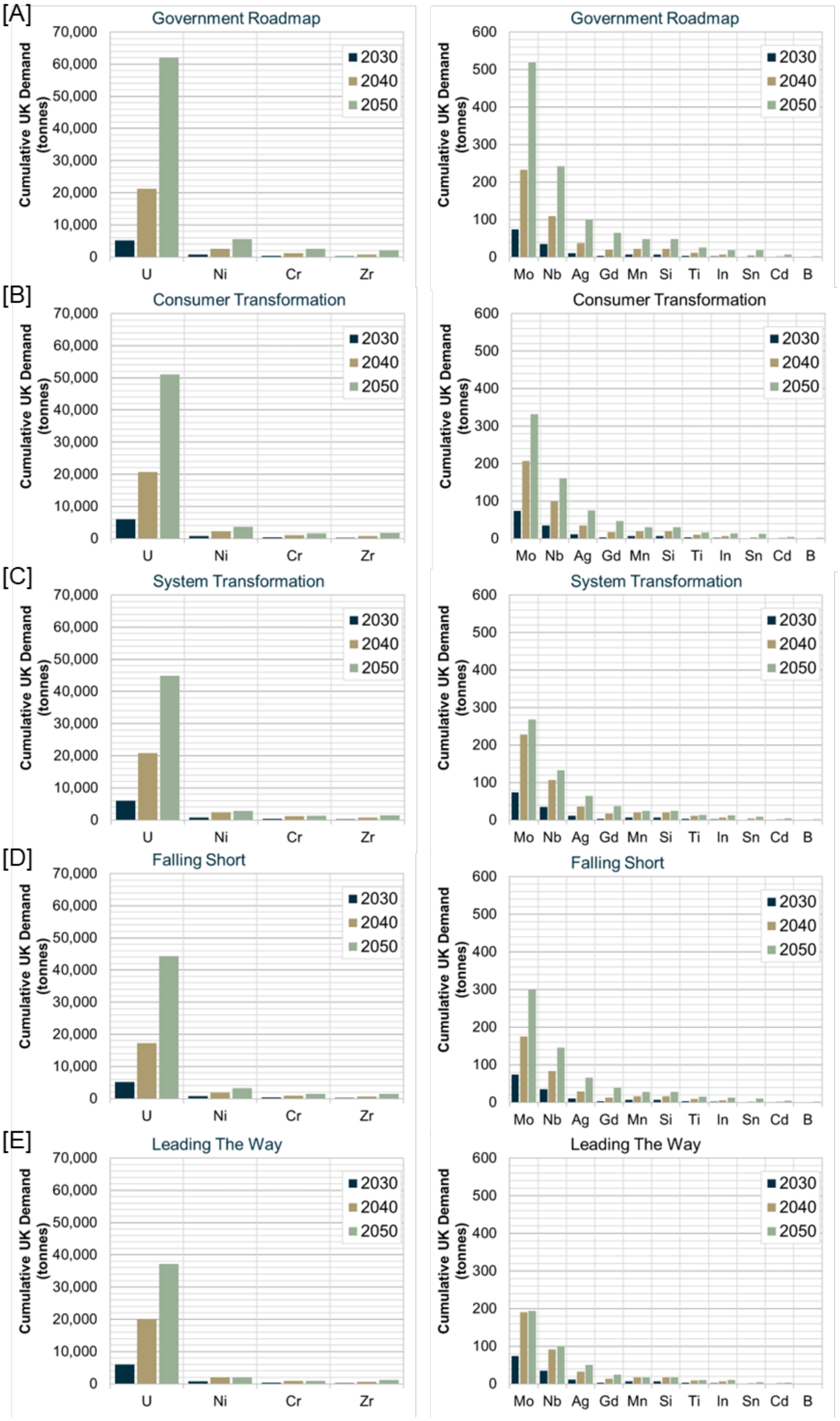


Figure 11 Cumulative forecast UK demand (tonnes) for the elements considered in nuclear technologies between 2023 and 2050 under five scenarios, A: Government Roadmap; B: 'Falling short'; C: 'System transformation'; D: 'Consumer transformation'; E: 'Leading the way'. (UK Government, 2024a; National Grid, 2023). BGS © UKRI.

Figure 12 shows the average annual UK demand for selected materials within successive ten-year periods as a fraction of the corresponding annual global mineral production (Table 7). The UK's U requirements under the Government Roadmap scenario between 2040 and 2050 are estimated to be 7.5 per cent of the current annual production of mined U. In has the second-highest demand relative to current supply, but the maximum annual UK demand amounts to approximately 0.14 per cent of global production. The forecast average annual UK demand for the other materials is typically less than 0.02 per cent of current global output. Appendix B presents the average annual forecast demand for all the materials considered in this study.

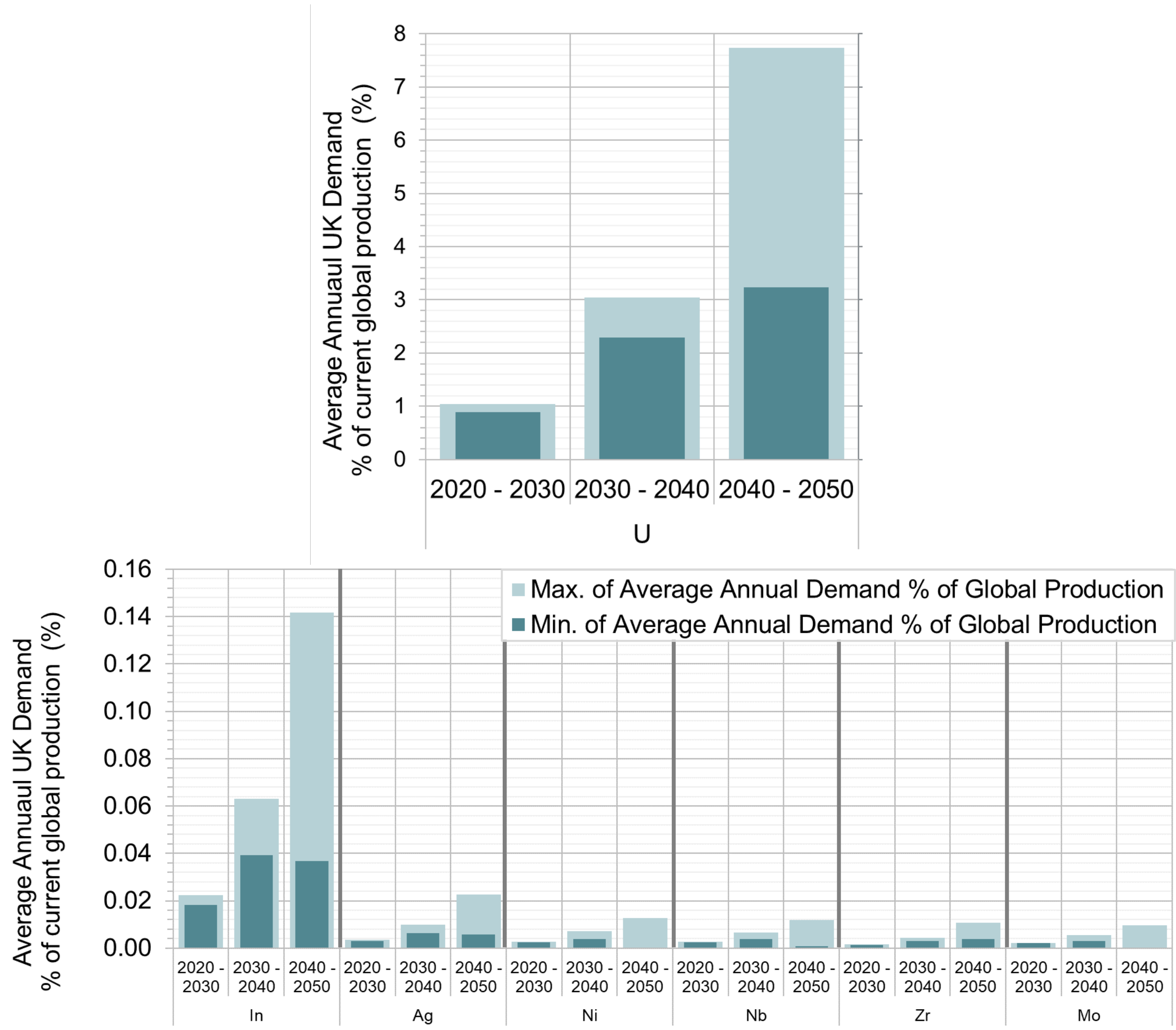


Figure 12 Average annual UK demand to 2030, 2040, 2050 as a percentage of current global metal production (five-year average, 2017 to 2021). The minimum and maximum values represent outputs of the different scenarios. BGS © UKRI.

5.3 GLOBAL DEMAND VS UK DEMAND PROJECTIONS

The current global landscape of nuclear technologies shows that approximately 80 per cent of installed capacity is from PWRs, 10 per cent from BWRs and 10 per cent from other large reactor technologies (International Atomic Energy Agency, 2024). The Nuclear Energy Agency (NEA) forecasts that, by 2050, SMRs and AMRs could provide at least 25 per cent of global installed nuclear capacity (Nuclear Energy Agency, 2022). These market shares lead to the global nuclear technology forecast shown in Figure 13. The relative market share of AMRs and SMRs is scaled based on the ratio of AMR to SMR designs in active development (International Atomic Energy Agency, 2020).

The global demand model for nuclear technologies is based on the market share forecast in Figure 13 together with IEA nuclear capacity forecasts from their 'Stated policies' (STEP) and 'Net zero' (NZE) scenarios (International Energy Agency, 2022). Current global capacity is 370 GW.

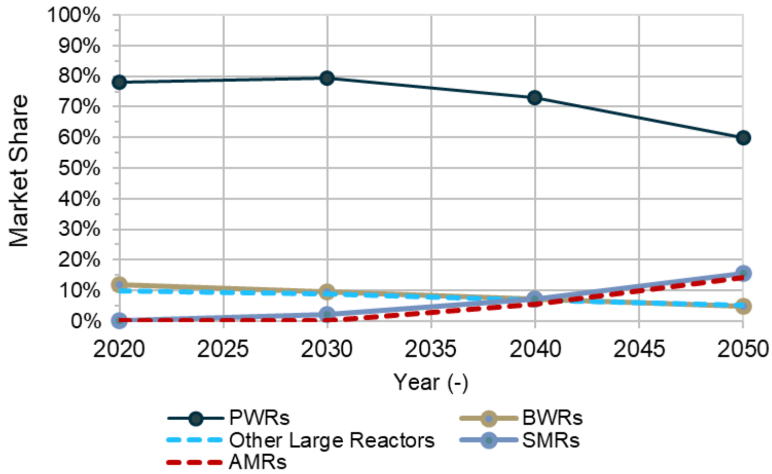


Figure 13 Global nuclear subtechnology market share to 2050. BGS © UKRI.

The STEP scenario forecasts an increase in capacity to 600 GW by 2050, while the NZE scenario forecasts an increase to 850 GW in the same year. To put this into perspective, the UK Government Roadmap ambition of 24 GW is 4 per cent of the global STEP scenario and 3 per cent of the NZE scenario. The IEA scenarios also provide decommissioning and addition rates to the global nuclear fleet (not including possible life extensions). The model captures all PWRs, BWRs and SMRs, which account for 75 to 90 per cent of installed capacity to 2050 and 75 per cent of new additions to 2050. Since BWRs share many components with PWRs, the material intensities for BWRs are assumed to be the same as those of PWRs.

The global material demand forecasts for nuclear will be higher when AMRs are considered. AMRs are not within scope for this study.

Figure 14 shows the average annual global demand for selected materials used in nuclear technology as a fraction of current global production. The estimated average annual global U demand between 2020 and 2030 is equivalent to approximately 150 per cent of current mined U production, potentially rising to 225 per cent by 2050. This follows a trend of demand outstripping U mine production by an increasing margin: in 2019, U demand was equivalent to 115 per cent of mined U, rising to 125 per cent in 2021 (Nuclear Energy Agency, International Atomic Energy Agency, 2022). The discrepancy has historically been accounted for from sources of secondary supply, such as reprocessed U and civil stockpiles.

Annual demand for In reaches between 2.5 per cent and 3.2 per cent of current global production during the 2040s (Figure 14). However, there is likely to be serious competition for In supply from other decarbonisation technologies, such as indium tin oxide films for liquid crystal displays and photovoltaics.

Future demand for the other materials evaluated is generally less than 0.5 per cent of current global production (Figure 14).

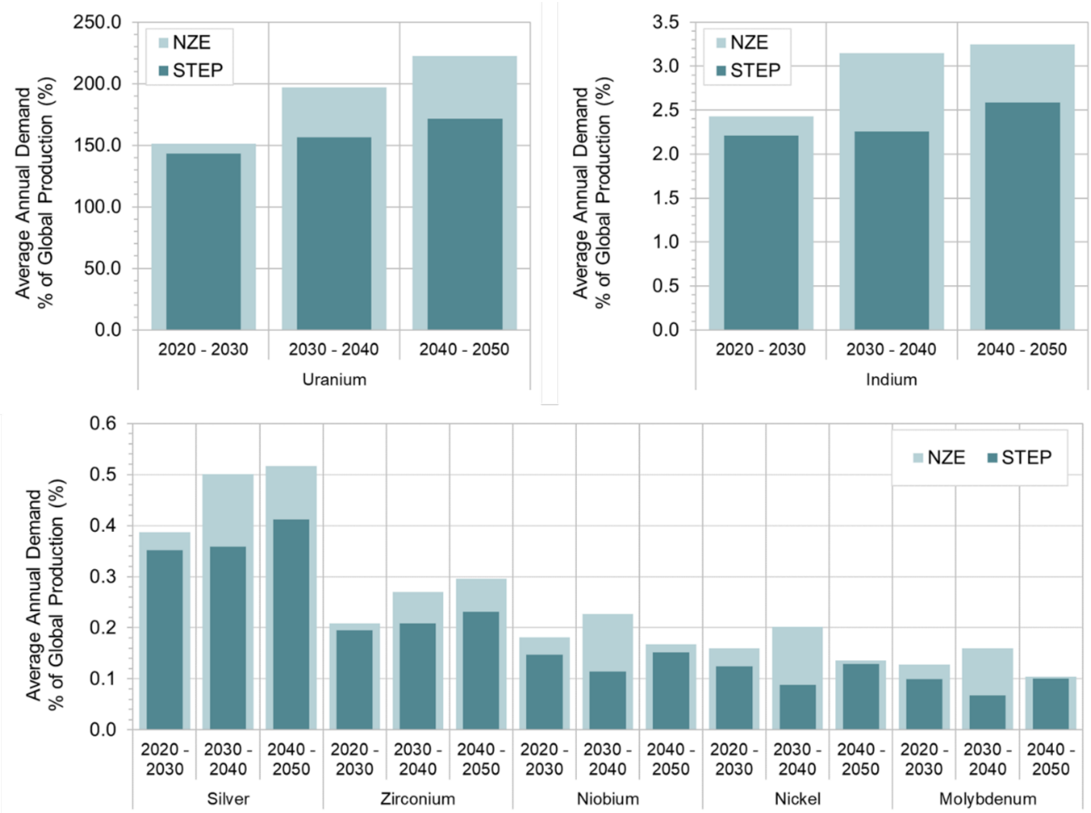


Figure 14 Average annual global demand as a percentage of current global metal production for materials with highest relative demand in nuclear technologies. Outputs based on two scenarios: NZE and STEP from IEA analysis (International Energy Agency, 2022) BGS © UKRI.

It is also instructive to examine the regional global breakdown of nuclear material demand, as shown in Figure 15 for the NZE scenario based on data from the IEA (International Energy Agency, 2022). The four regions presented are:

- China
- the G7
- other advanced economies (OAE)
- other emerging and developed economies (OEDE)

The UK Government Scenario represents the UK demand. The G7 demand excludes the UK's value. The demand from China and OEDEs is significant because of anticipated growth in new nuclear capacity. Consumable material needed for fuel assemblies have G7 as their highest demand region due to their high current nuclear capacity that continues to grow, although at a lower rate than that of China and OEDEs. The UK's demand is significant despite its relatively small size. It has requirements greater than OAEs for certain materials required for new reactor builds including Nb, Ni and Cr, as shown for the full list of materials in Appendix C.

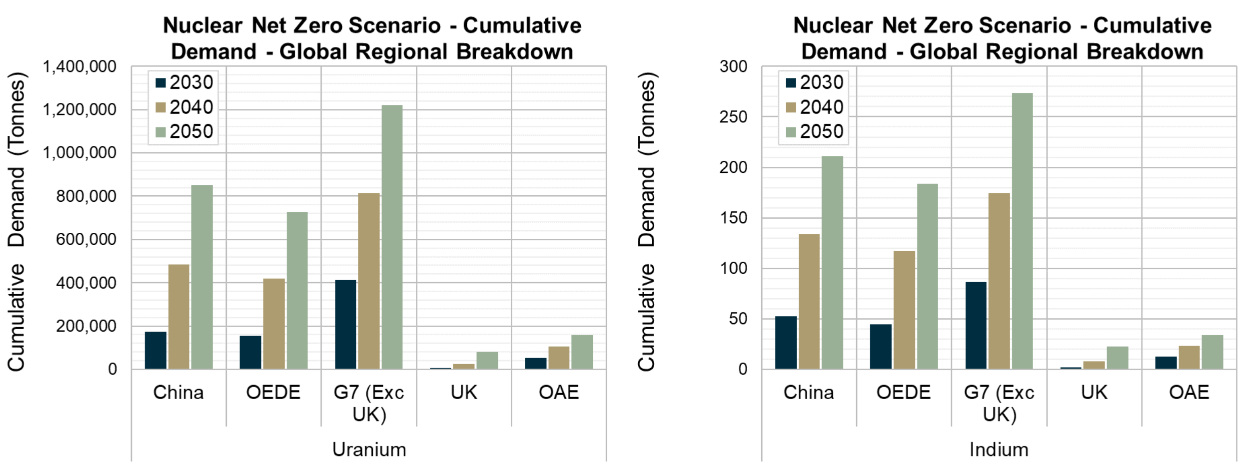


Figure 15 Cumulative material demand for selected elements (in tonnes) embedded in nuclear in the UK, China, G7 (excluding UK), OEDE and OAE in 2030, 2040 and 2050. The data for the non-UK demand projections are based on IEA data (International Energy Agency, 2022). Data for the other materials is presented in Appendix C. BGS © UKRI.

5.4 ADDITIONAL PWR AND SMR REQUIREMENTS

Stakeholder engagement undertaken during this study led to the identification of additional specialised materials likely to be required in relatively small quantities for PWR and SMR subtechnologies. The material intensity for these is not known so they have not been included in the quantitative analysis.

Californium-252 (^{252}Cf) is a synthetic material and a neutron emitter that is commonly used as a start-up neutron source. Stakeholders identified that only two companies in the world manufacture ^{252}Cf: Oak Ridge National Laboratory in the USA and the Research Institute of Atomic Reactors in Russia. The increase in global manufacture of nuclear reactors will place significant demand on these suppliers, with reactors built in the western world likely to be reliant solely on supply from the Oak Ridge Laboratory.

Lithium-7 (^{7}Li) is the most naturally abundant stable isotope of lithium (Li). As a hydroxide and enriched to more than 99 per cent, it is an important material used in PWR cooling systems to regulate the acidity of the coolant, countering the corrosive effects of boric acid. The current annual requirement for ^{7}Li in PWRs is estimated at about 1 t per year (World Nuclear Association, 2022c). This could double by 2050 under the NZE IEA scenario. The production of highly enriched ^{7}Li requires isotopic separation facilities. Currently, the only sources of enriched ^{7}Li are in Russia and China. The Novosibirsk Chemical Concentrates Plant (Rosatom, Russia) provides up to 80 per cent of the world's requirements.

5.5 AMR REQUIREMENTS

UK nuclear demand from off-grid applications could require a further capacity increase of 16 GW (Stakeholder Engagement, 2023; Peakman & Merk, 2019; National Nuclear Laboratory, 2023). Stakeholders suggested the USA alone could require an additional 100 GW of nuclear capacity by 2050 for meeting industrial heat applications (US Department of Energy, 2023). This rapid increase in off-grid nuclear capacity will place further pressures on the global supply chain.

While some lower-temperature industrial processes can be delivered with SMRs, AMRs are necessary to meet higher temperature requirements. AMRs would require similar high-grade alloy heat exchangers to SMRs but may not need turbine-generator assemblies. The implications of significant global demand for industrial heat from nuclear technology would lead to higher demand for those materials used in nuclear technology and, in many cases, there would also be increasing competition from other decarbonisation technologies.

AMRs will place additional requirements on HALEU fuel, graphite (for HTGRs) and Li and beryllium (Be) salts (for MSRs). As an example of graphite demand, DAS analysis indicates that 12 to 15 t will be required each year for the Xe-100, an 80 MW HTGR (X-Energy, 2021). Competing demand for graphite and Li for battery technologies may make it challenging to provide additional supply. ^{7}Li requirements for MSRs equate to 'tens of tonnes', with an aggregate global demand that could reach up to 250 t per year (World Nuclear Association, 2022c).

Since AMR HALEU fuel is enriched to between 5 and 20 per cent, this will place even greater demand on mined U and enrichment capacity. For example, the HALEU fuel that will power X-Energy's Xe-100 HTGR needs to be enriched to 15.5 per cent (X-Energy, 2021). This level of enrichment requires about 30 t of mined U to produce 1 t of HALEU (DAS analysis), compared to 8 to 10 t of mined U to produce 1 t of PWR or SMR fuel.

6 Discussion and conclusions

Nuclear technologies fulfil an essential role in the net zero transitions of the UK and global decarbonisation pathways to 2050 and beyond. The UK Government has set out an ambition to quadruple nuclear capacity by 2050 (6 GW to 24 GW), while global forecasts suggest nuclear capacity will need to more than double in the same period to achieve net zero (370 GW to 850 GW). Combined with the development of new and advanced nuclear technologies, these growth ambitions at national and international levels will place unique pressures on the global supply chains of the requisite materials.

The main analysis conducted in this study focused on those nuclear technologies that the UK Government Roadmap has indicated are most likely to contribute to the civil on-grid nuclear capacity between now and 2050: large-scale PWRs and SMRs. Fifteen materials, essential to these subtechnologies, were selected for analysis:

- B
- Cd
- Cr
- Gd
- In
- Mn
- Mo
- Ni
- Nb
- Si
- Ag
- Sn
- Ti
- U
- Zr

6.1 URANIUM

The major increase in global and UK demand for mined U to 2050 increases risk to the supply chain. Although the production concentration risk factor for mined U is relatively low, it is forecast that, by the 2040s, the UK's annual demand may equate to 7.5 per cent of current annual global production. However, the UK's requirements are estimated to be just 3 per cent of global needs, when considering the IEA's NZE scenario.

The additional global demands for off-grid capacity may be significant, amounting to hundreds of gigawatts by 2050 if significant portions of industrial heat requirements are met by nuclear. Since HALEU fuel, which powers some proposed AMR designs, requires a higher enrichment value than PWRs (5 to 20 per cent), either additional enrichment capacity or more U ore will be required. Russia is also the only country that currently manufactures HALEU fuel for AMR use.

However, this risk should be offset through the planned £300 million investment to develop a HALEU fuel supply chain in the UK. The global demand for defence nuclear applications may further increase pressure on the civil nuclear supply. The compound effect of these additional factors could further intensify stresses within an already volatile U market. This is reflected in a 16-year high price for U in early 2024 (Reuters, 2024).

Figure 16 compares the historic mined U production with historic and projected requirements. Historically, U supply has exceeded demand: between 1950 and 1990, supply exceeded demand by up to 40 000 t of U ore per year, resulting in the growth of stockpiles. However, U supply dropped below demand between 1990 and 2015, due to a lower growth in nuclear demand (Nuclear Energy Agency, International Atomic Energy Agency, 2022). After matching supply to U requirements in the mid-2010s, production dropped due to adverse market conditions and a lower perceived demand. In 2020, global U fuel requirements were equivalent to 125 per cent of global mine production, with 20 per cent of demand met by secondary sources. This trend is set to continue as it is estimated that U fuel demand will reach 175 per cent by 2050 — 225 per cent of current mined U, between 90 000 and 115 000 t per year.

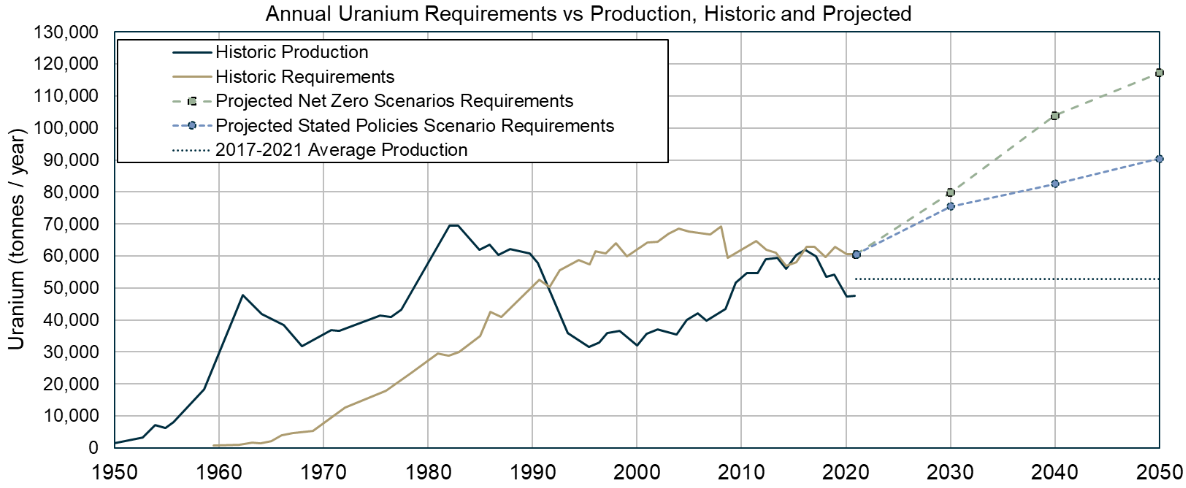


Figure 16 Historic and projected annual requirements and demand for uranium. Historic data from NEA and IEA (Nuclear Energy Agency, International Atomic Energy Agency, 2022). Projected requirements: DAS Ltd analysis. BGS © UKRI.

The increasing demand for U fuel will place greater pressure on increasing mining production or secondary sources of supply, such as from stockpiles. Countries and nuclear operators hold stockpiles of U, nuclear fuel and spent fuel, but information about them is uncertain and highly sensitive. The size of the stockpile was estimated to be 282 000 tonnes of mined U equivalent in 2020. Stockpiles of U can mitigate some global demand; however, mine production will continue to be necessary to meet most global U requirements.

These stockpiles are expected to be topped up, retaining their size, to provide energy security for utility companies and governments (World Nuclear Association, 2023). The upper limit of civil and defence stockpiles is estimated to be 525 000 t of mined U equivalent that could be available for conversion and enrichment for the global nuclear industry (Nuclear Energy Agency, International Atomic Energy Agency, 2022).

Enriched U banks, holding less than 100 t of reactor fuel, are available to mitigate extreme events with an expectation that they will not disrupt commercial markets (Nuclear Energy Agency, International Atomic Energy Agency, 2022).

The supply risk of nuclear fuel can potentially be mitigated in several ways:

- increasing mined production
- increasing enrichment capacity
- reprocessing nuclear fuel
- recycling nuclear fuel
- new HALEU facilities

6.1.1 Increasing mined production

Three new mines started production in the USA in late 2023 in response to the passing of a US government bill banning U imports from Russia (World Nuclear News, 2023). Very large resources of U are known in several western countries, notably Canada and Australia, but it has proved to be very challenging to permit working of these deposits over several decades. Numerous environmental, social and political obstacles have seriously restricted the development of new mines in these countries (World Nuclear Association, 2023).

6.1.2 Increasing enrichment capacity

The UK Civil Nuclear Roadmap (UK Government, 2024a) proposes supporting the conversion of stockpiles and new mine capacity through reopening closed plants or developing new ones.

6.1.3 Reprocessing of nuclear fuel

Reprocessed U uses spent U fuel from nuclear reactors as the feedstock for U enrichment. With ^{235}U enrichment already at 1 per cent, only 6 to 7 t of spent U fuel would be needed to produce 1 t of 5 per cent enriched U, compared to 8 to 10 t of mined U (World Nuclear Association, 2021a). As prices for mined U rise, reprocessing U may become an increasingly attractive option despite the presence of undesirable U isotopes (Kislov et al., 2013).

Funding towards re-establishing reprocessing capability in the UK was awarded in 2023 (UK Government, 2024a). Reprocessing could be paired with underfeeding, a more costly method of enrichment that depletes U to below the 0.25 per cent standard. This process results in more enriched U being extracted per unit of U feedstock.

6.1.4 Recycling of nuclear fuel

Recycling of nuclear fuel is achieved by blending depleted, reprocessed or natural U with Pu produced in the reactor to create MOX fuel. The UK Government has not outlined any plans to use MOX fuel in current or future reactors (UK Government, 2024a). A global increase in MOX use may reduce pressure on the fuel supply chain for UK reactors.

6.1.5 New HAELU facilities

Investment in new HALEU facilities to secure fuel requirements for AMRs has been announced by the UK and USA.

6.2 INDIUM

The UK's nuclear requirements for In up to 2050 are estimated to require about 0.14 per cent of current annual global production. This demand is coupled with a high production concentration factor, with over 80 per cent of refined In produced by three countries, of which China accounts for over 60 per cent. Cumulative global In demand for the nuclear industry to 2050 will require more than 3.2 per cent of current annual global production levels to achieve the NZE scenario. In supply will also face serious competition from higher demand sources, such as indium tin oxide films for LCDs and photovoltaics.

The by-product status of In, with most of it extracted during the processing of Zn ores, means that increasing global production of In will be inextricably linked to the Zn market and may be difficult to achieve.

6.3 GADOLINIUM

The UK is estimated to need a cumulative total of 60 t of Gd by 2050, with the cumulative global nuclear demand reaching 1500 tonnes in the same period under the NZE scenario. Although production data for Gd are not published, the global supply of REOs is dominated by China, with a 70 per cent share of the total. The supply chain for this element is not clear and further investigation may be required to better understand it.

6.4 NIOBIUM

The UK's average annual requirement for Nb in nuclear technology to 2050 is only 0.015 per cent of current global production. However, the high degree of production concentration in Brazil is inevitably a risk to supply security. Furthermore, the growing utilisation of Nb in other applications, such as special steels and batteries, may contribute to increased competition for access to ferroniobium, the main traded form of Nb.

6.5 OTHER MATERIALS

The other materials that have been assessed as part of this study are B, Cd, Cr, Mn, Mo, Ni, Si, Ag, Sn, Ti and Zr. For these materials, the maximum UK demand has been estimated to be less than 0.02 per cent of annual global production, with a corresponding maximum global demand of 0.5 per cent. This is coupled with lower supply risk as evidenced by the production concentration and global trade concentration data.

6.6 BROADER SUPPLY CHAIN

Overall, the global nuclear supply chain is complex, opaque and highly concentrated, especially in the downstream stages of the value chain. Some key components have fewer than ten suppliers.

The ability to build capacity in line with demand benefits from the inherent long lead times and early investment decisions, giving suppliers the confidence to build their capacity. While SMRs are designed with a shorter on-site lead time, owing to their modular construction, certainty of long-term demand for components is more likely if they are built as a fleet.

The supply chain is particularly susceptible to long lead time items such as Reactor Pressure Vessels RPVs and steam generators, which can take 5 to 10 years to deliver. The global forging market for RPVs is growing considerably, which raises questions about the adequacy of the installed capacity to cope with demand from the nuclear sector.

6.7 ADVANCED MODULAR REACTORS

The UK and global need for AMRs to power industrial applications will place further demand on key materials. In addition to HALEU fuels, there will be need for high-grade graphite (for HTGRs), and Li and Be salts (for MSRs), the supply of which will face competing pressures from other decarbonisation technologies.

7 Recommendations

This foresight study provides an overview of the materials required in key nuclear technology components to support the contribution of nuclear energy in the UK's transition to net zero. The study has provided a view at a particular time, which will require regular updates to ensure that the complexity and dynamics of the global market are captured. There are several areas where additional development could support security of material supply and delivery of the UK's civil nuclear ambition.

Continual oversight of the U market worldwide is required to identify risks and develop appropriate mitigation along the U supply chain in a timely and strategic manner. There is a key question of whether the UK has sufficient security of U fuel supply to meet its 2050 ambition. This knowledge gap could be addressed through developing a whole system model of the UK U fuel cycle, which considers the following questions:

- should the UK Government assist with new U mining projects?
- is the enrichment capacity at Urenco in Capenhurst sufficient to meet the UK's ambition?
- can some of the UK's nuclear fuel needs be met with reprocessed U?

The whole U lifecycle model should also consider defence requirements and off-grid applications (for example, AMRs).

While nuclear demand for Gd can be estimated, its supply chain is opaque and there is limited availability of public information. Industry experts should undertake an in-depth study of the Gd supply chain to quantify risks and identify appropriate mitigation.

Since only two companies in the world currently manufacture ^{252}Cf, a key neutron start-up source, alternative neutron emitter materials and suppliers should be explored to mitigate supply risk. In addition, alternative supply of enriched ^{7}Li should be sourced since Russia and China are the only known suppliers.

Although there are several UK organisations playing key roles in the supply chain, there is currently no detailed, coherent UK supply chain analysis for the civil nuclear sector. 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 UK nuclear supply chain that depend upon various raw and processed materials. This, in turn, will help to achieve energy resilience and secure jobs.

Reliable estimation of supply and demand risk depends upon good quality data. While there is good availability of demand data from design documentation and other literature sources, supply chain information is limited, particularly in the middle of the value chain at the refining and precursor stages. 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.

The supply/demand model in this report should be kept under continual review to reflect changes in the global market and the UK and global demand projections. As the UK's AMR deployment schedule becomes more refined, the material requirements for these subtechnologies should also be considered.

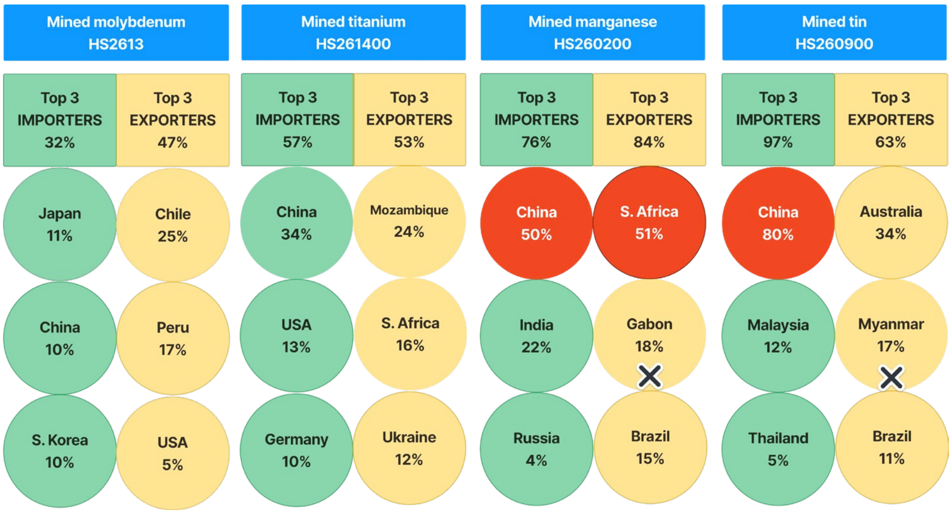
Additional overarching recommendations that have wider implications include:

- analysis of the risks from competing demand in other industrial applications; for example, In, Li, Ni, Zr and graphite are used in various decarbonisation technologies in addition to nuclear
- development of a taxonomy of market indicators and drivers of change should be monitored as part of a materials observatory — drivers could be political, economic, social, technological, legal and environmental, which can then be aggregated into a set of representative scenarios

- further work to build greater depth and breadth of foresight would be beneficial to provide a coherent and reliable assessment of supply risks; for example, analysis of economic factors, price volatility and ESG supply issues should be evaluated

Appendix A

The top three importing and exporting countries for mined and refined materials 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 OECD (2022). BGS © UKRI.



Ferro-molybdenum HS720270

Top 3 IMPORTERS 31%	Top 3 EXPORTERS 48%
Germany 13%	S. Korea 24%
USA 10%	UK 13%
Italy 9%	Chile 11%

Ferro-titanium HS720291

Top 3 IMPORTERS 20%	Top 3 EXPORTERS 54%
Netherlands 7%	Russia 30%
S. Korea 7%	UK 17%
Japan 6%	Ukraine 7%

Ferro-manganese HS720211

Top 3 IMPORTERS 30%	Top 3 EXPORTERS 56%
USA 15%	Malaysia 25%
Germany 9%	India 21%
Iran 7%	S. Africa 11%

Ferro-silicon HS720221

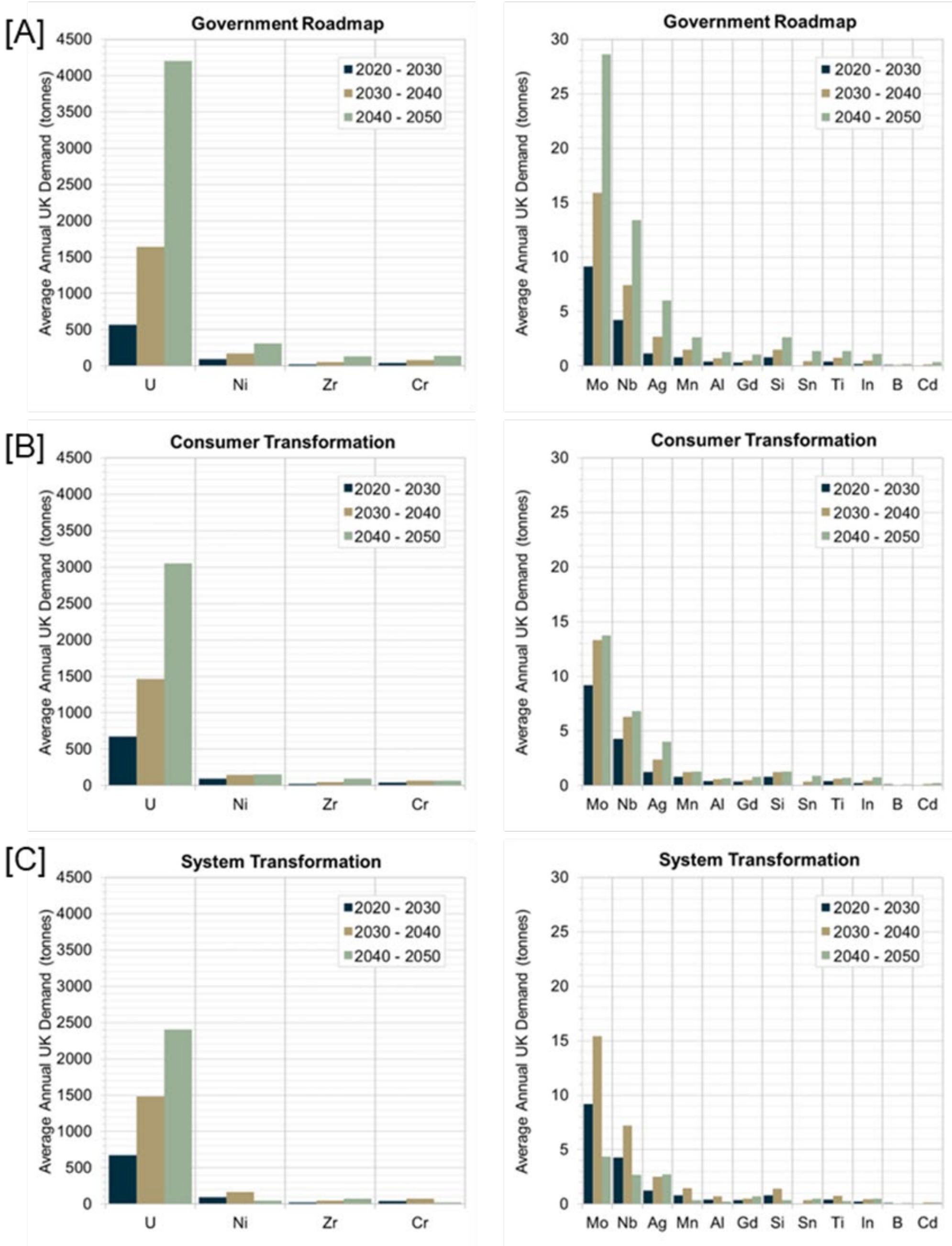
Top 3 IMPORTERS 32%	Top 3 EXPORTERS 43%
Japan 14%	China 18%
S. Korea 10%	Russia 16%
USA 7%	Malaysia 9%

Refined tin HS800110

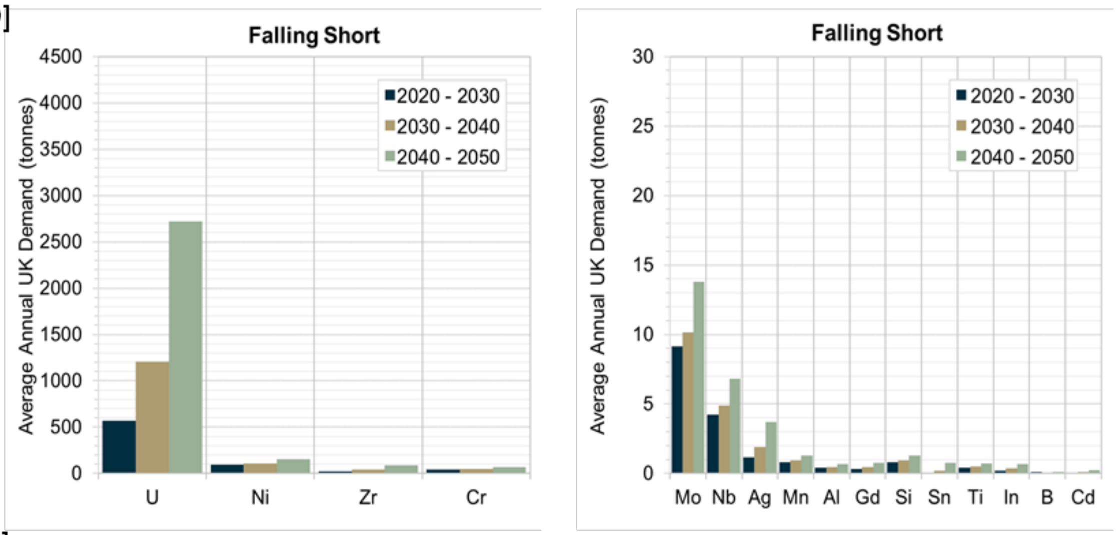
Top 3 IMPORTERS 36%	Top 3 EXPORTERS 52%
USA 16%	Indonesia 35%
Japan 12%	Malaysia 9%
Germany 9%	Peru 8%

Appendix B

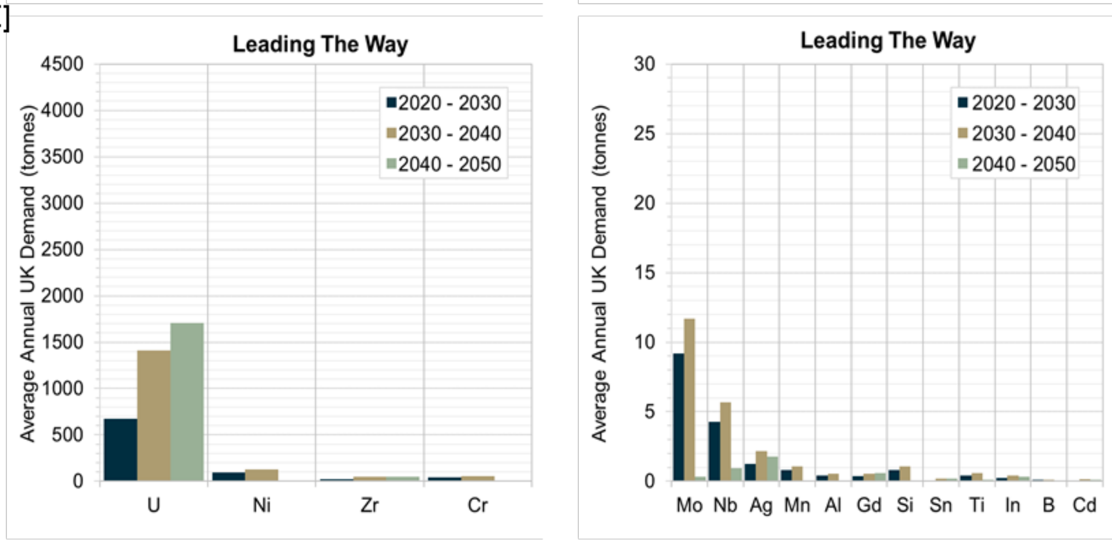
Average annual forecast demand (in tonnes) for the elements considered in this study for three time periods and under five different scenarios: A: Government Roadmap; B: ‘Consumer transformation’; C: ‘System transformation’; D: ‘Falling short’; E: ‘Leading the way’. BGS © UKRI. BGS © UKRI.



[D]

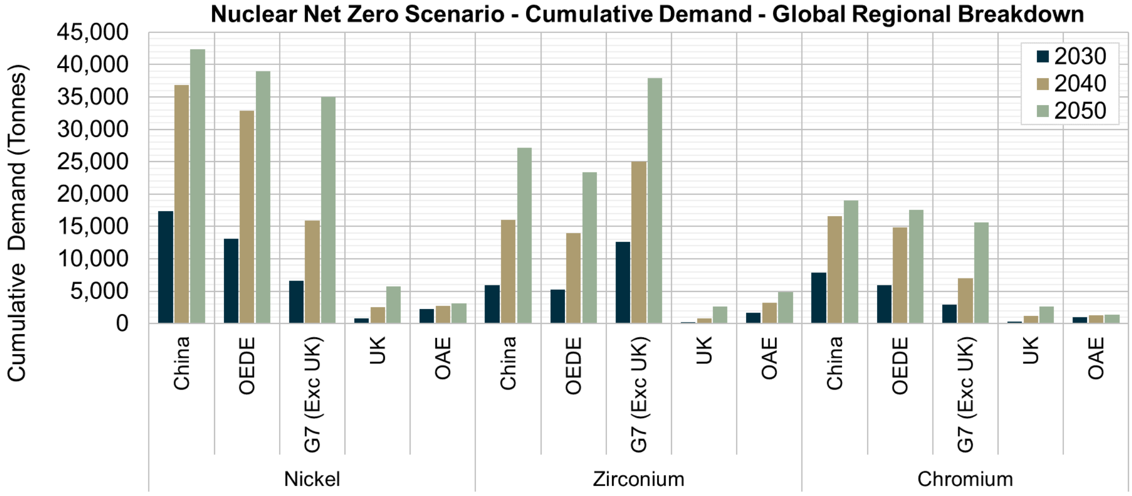

Falling Short
Average Annual UK Demand (tonnes)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
U
Ni
Zr
Cr
2020 - 2030
2030 - 2040
2040 - 2050
Falling Short
Average Annual UK Demand (tonnes)
30
25
20
15
10
5
0
Mo
Nb
Ag
Mn
Al
Gd
Si
Sn
Ti
In
B
Cd
2020 - 2030
2030 - 2040
2040 - 2050

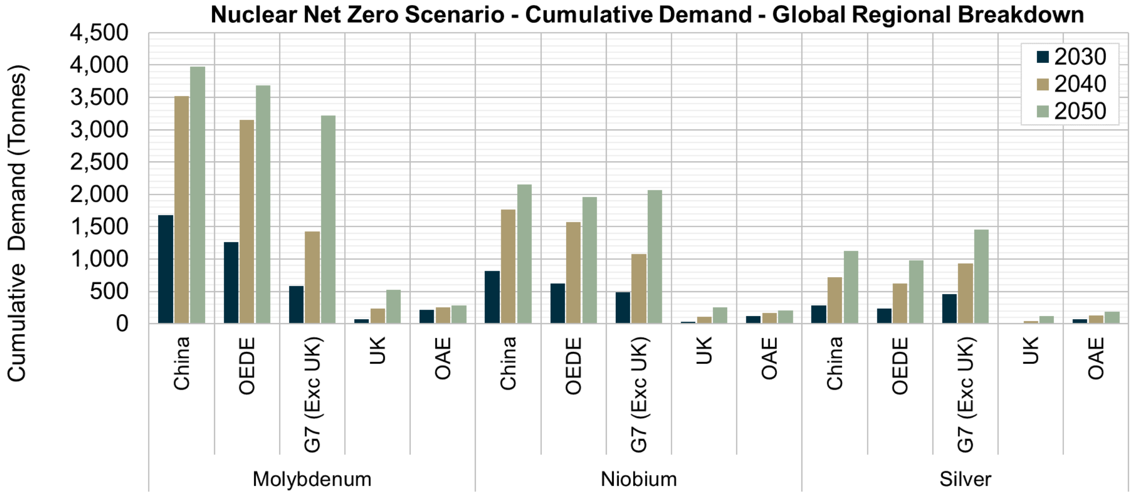
[E]

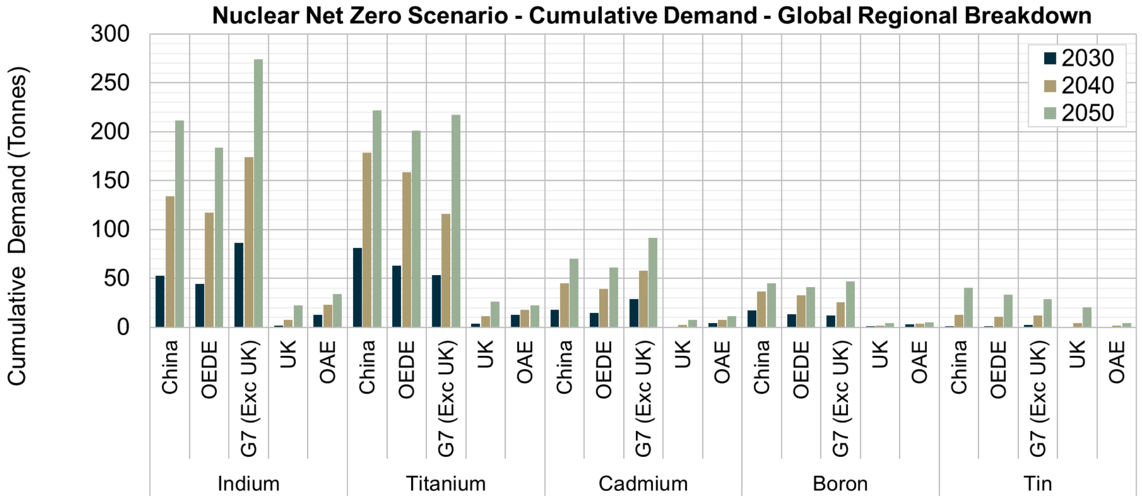

Leading The Way
Average Annual UK Demand (tonnes)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
U
Ni
Zr
Cr
2020 - 2030
2030 - 2040
2040 - 2050
Leading The Way
Average Annual UK Demand (tonnes)
30
25
20
15
10
5
0
Mo
Nb
Ag
Mn
Al
Gd
Si
Sn
Ti
In
B
Cd
2020 - 2030
2030 - 2040
2040 - 2050

Appendix C

The global material demand (in tonnes) for selected materials in nuclear technologies. Data from NZE (International Energy Agency, 2022). Regions are defined by the IEA: China; other emerging and developed economies (OEDE); G7 (amended to exclude the UK); UK (DAS analysis), and other advanced economies (OAE). BGS © UKRI.







Acronyms and abbreviations

AGR	Advanced gas-cooled reactor
AMR	Advanced modular reactor
BOM	Bill of materials
BWR	Boiling water reactor
DAS	Decision Analysis Services Ltd
ESG	Environmental, social and governance
F4N	Fit for Nuclear
FR	Fast reactor
G7	Group of Seven nations: Canada, France, Germany, Italy, Japan, UK, USA
HALEU	High-assay low enriched uranium
HTGR	High-temperature gas reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
LEU	Low enriched uranium
MOX	Mixed oxide fuels
MSR	Molten salt reactor
NAMRC	Nuclear Advanced Manufacturing Research Centre
NEA	Nuclear Energy Agency
NZE	Net zero (IEA scenario)
OAE	Other advanced economies (defined by the IEA)
OECD	Organisation for Economic Co-operation and Development
OEDE	Other emerging and developing economies (defined by the IEA)
PWR	Pressurised water reactor
REE	Rare earth element
REO	Rare earth oxide
RepU	Reprocessed uranium
RPV	Reactor pressure vessel
SMR	Small modular reactor
STEP	Stated policies (IEA scenario)
UK EPR	UK European pressurised reactor

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