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Mineral Requirements of Digital Technologies: data centres, artificial intelligence and quantum computing

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Mineral Requirements of Digital Technologies: data centres, artificial intelligence and quantum computing

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Foreword

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Summary

The digital revolution is accelerating the development of artificial intelligence (AI) and quantum computing, whilst also driving a growing demand for data centres. AI and quantum computing have moved rapidly from theoretical concepts to practical tools integrated into society and the economy. Quantum computers apply the principles of quantum physics to store much larger amounts of data, solve problems faster and undertake calculations beyond the capability of classical computers. They are not intended to replace classical computers but to address highly complex problems in a wide range of sectors, including health, manufacturing, and logistics. Artificial intelligence has advanced rapidly in recent years, with systems now able to learn and perform tasks that previously required near-human intelligence. AI is rapidly becoming integrated into everyday life, with applications ranging from content creation to medical diagnosis. As reliance on data and technology grows, demand for digital services is rising rapidly. Data centres, which store, process and manipulate data, are integral to both these data services and the functioning of artificial intelligence.

With demand for AI, quantum computing and data centres growing rapidly, so too does the need for raw materials to manufacture these technologies. The rising complexity of digital technology components is expanding both the range and quantities of materials required. In addition to many of the materials typically used in classical computers, quantum computing components also require such elements as niobium, caesium, hafnium and bismuth. Many materials, such as silicon, carbon, and helium, must meet very high purity or isotopic purity to prevent quantum decoherence. This is the process by which a quantum system loses its quantum properties and therefore its stored information. Demand for these specialised materials will depend on the pace of quantum computing adoption and the technology utilised. Data centres also require raw materials, including high purity silicon, copper, aluminium, rare earth elements, and battery materials, such as lithium and cobalt. Global demand for these materials is expected to rise rapidly as data centre development accelerates. In the UK, data centres are designated as critical national infrastructure, with over 90 new data centres planned by 2030.

This report provides an overview of AI, quantum computing and data centre technologies, as well as their applications and raw material requirements. A full outline of material requirements with specific compounds and quantities where known; reasons for material choice; and technology readiness levels are provided in the report appendices. These technologies are key to future growth and security, having been identified as frontier technologies by the UK Industrial Strategy's Digital and Technologies Sector Plan and critical technologies by the UK Science and Technology Framework. The future demand for these technologies and the underpinning raw materials requirements is discussed. The report also provides an overview of high purity and isotopically pure materials together with detailed case studies on the global supply chain for tellurium, bismuth, and hafnium, three key elements for digital technologies with concentrated supply chains. The UK supply chain for both raw materials and manufactured components is benchmarked against their global supply chains. A discussion surrounding UK and global supply chain challenges and opportunities is also provided. This report is a summary of existing literature, both scientific research papers and company technological reports, and insights from discussions with key UK stakeholders throughout the data centre and quantum computing supply chains.

Many of the materials required for digital technologies that have been identified in this report are produced as by-products of primary commodities and therefore less responsive to market demand. Alternatively, high-purity or isotopically pure materials may be required. Supply chains for all these materials are concentrated and dominated by a small number of countries, including China, USA, and Russia. Although there are some European facilities that are also producing these materials. As such, the supply chains for these materials, such as lithium, rare earth elements, niobium, high purity silicon, and helium-3, are uncertain and vulnerable with a

high risk of supply disruption. Many have therefore been identified as critical raw materials by the UK Government. The manufacture of technologies in many sectors, including aerospace, defence, and low carbon technologies, requires the same or similar suite of elements as quantum computers and data centres. Requirements for these sectors are also expected to grow in the future, which is likely to lead to sector competition.

Supply chains are currently limited in the UK for digital technologies, both in terms of the extraction and refining of raw materials and manufacture of components. Whilst the UK should endeavour to capitalise on opportunities to develop domestic supplies of raw materials and components, the UK cannot become a world leader in all parts of the digital technology value and supply chain. As such, international collaboration and strategic partnerships remain important to ensure future access to components and raw materials. The UK therefore needs to build a portfolio of skills, materials, components, and processes with which to trade in these international partnerships. This report highlights opportunities that are likely to develop as these digital technologies are more widely adopted and demand for materials increases. For example, potential exists for the UK to develop sections of the supply chain aside from the crucial quantum computing components of semiconductors and cryogenics, such as servers and photonics. Demand forecasts for many elements discussed in this report indicates future requirements are likely to outpace supply, therefore opportunities exist in diversification of critical mineral supply chains. The UK has the potential for domestic production of critical minerals, such as lithium, cobalt, and nickel, as well as recovering key by-products, such as caesium and rubidium. Recycling of digital components provides the opportunity to establish a secondary domestic supply where primary extraction is not possible in the UK. The UK therefore has the potential to become a global leader in the digital raw material and component supply chain, if opportunities are seized with sufficient speed and agility.

To ensure that the UK is able to capitalise upon these opportunities and become a global leader for data centre and quantum technologies, this report provides a series of recommendations. The UK should capitalise upon its strong knowledge base and expertise relating to isotopic purification and high-purity materials to develop domestic supply chains. Diversification of these highly concentrated global supply chains would help to meet growing UK demand and reduce global supply risks. Suggested focus areas include methane purification, silicon isotope purification, and recovery of helium-3 from nuclear reactors. The UK should expand upon well-established UK supply chains, such as cryogenics, photonics, and semiconductors, and enable the shift from design to manufacturing. This would reduce reliance on imports whilst developing high value downstream digital industry in the UK. Investment in electronic waste processing facilities and designing components for easier and more efficient recycling would ensure a future secondary domestic supply of a range of materials. The UK should also ensure that talent is retained domestically and strengthen the pipeline of skilled designers, manufacturers, and as mid-skilled roles, such as mechanical engineers and laboratory technicians, relevant to these technologies. This is likely to require measures that enable small and medium enterprises to offer apprenticeships and provide vocational certification.

1 Introduction

The rise of computers since the mid-20th century has seen the modern world undergo a comprehensive digital evolution, a trend which is accelerating in the 2020s with the combination of data centres and artificial intelligence (AI). This trend is amplified by the growing availability of and reliance on data, driving the adoption of AI as a general-purpose technology, available for public use through popular search engines and tools. The current development of quantum computing technologies promises to be the next major step change in computing power and capabilities. Quantum computers have quickly progressed from research curiosities to the development of prototypes built in the UK National Quantum Computing Centre (NQCC), with the aim of demonstrating capabilities and building a community to aid in technology progression (Department for Science Innovation and Technology and Griffith, 2024). AI, data centres and quantum computing have an important role in future economic growth and security, supporting the expansion of digital, technology and advanced manufacturing sectors, enabling efficient use of clean energy and underpinning national security. As such, these technologies have been identified as frontier technologies by the UK Industrial Strategy's Digital and Technologies Sector Plan (Department for Business and Trade and Department for Science, Innovation and Technology, 2025) and critical technologies by the UK Science and Technology Framework (Department for Science Innovation and Technology, 2025b). Estimates indicate that quantum computing alone will contribute approximately £11 billion to UK GDP and support more than 100 000 jobs by 2045, highlighting the strategic importance of strengthening capability (Westminster eForum, 2025).

The development of AI involves the use of models and algorithms, which in turn require vast amounts of data for processing. This has led to parallel expansion of data centres to store the large volumes of data needed by AI (Department for Digital Culture Media & Sport, 2020). In addition, AI-focussed data centres need significant numerical and graphical processing power along with large memory capacity. This results in high energy demand and significant heat generation necessitating advanced cooling systems. Data centres have been recognised as critical national infrastructure in the UK due to their fundamental role in economic activities and public services (Clark, 2025). The UK Government is investing in the construction and expansion of data centres and their supporting infrastructure, reaching an estimated £10 billion per year by 2029 (Reuters, 2025c). It is generally expected that as quantum computing grows and becomes commercially viable, it will be closely linked with AI and associated data centres. This can be considered a technology nexus: the combination of AI, data centres and quantum computing.

As the demand for data centres and quantum computers grows, so too does the requirement for the raw materials needed to manufacture their components and supporting infrastructure. A thorough investigation of the material requirements for these technologies is therefore required, mapping out their sources, main component manufacturers, and how demand may change in the future. Many of the materials required for digital technologies have been designated as critical minerals in the UK, due to their concentrated supply chains and associated supply risks and vulnerabilities, which could cause significant impact to the UK economy if a major disruption were to occur (Mudd et al., 2024a). There is a lack of transparency and reporting surrounding the types and quantities of materials required to manufacture data centres and quantum computers, with much of this information being classified as protected intellectual property. As a result, the materials required for the digital transition, especially quantum computing, remain poorly understood (Westminster eForum, 2025).

This report identifies the main raw material requirements of quantum computers, AI, and data centres. It also summarises the expected future demand for these materials. UK supply chains for both raw materials and technology components are mapped and benchmarked against global supply chains. This, in turn, supports the identification of potential challenges and opportunities for the UK in adopting these technologies and developing as a centre of excellence. This aim was achieved through a detailed review of available literature and stakeholder engagement. Abbreviations and a glossary of technical terms used in this report can be in Section 8 and Section 9, respectively.

2 Data centres and artificial intelligence: key technologies and requirements

UK society and the economy are becoming increasingly reliant on data and technology with demand for digital services increasing rapidly (Department for Digital Culture Media & Sport, 2020). Data centres, with or without AI-related hardware, are key strategic infrastructure for any jurisdiction (Department for Digital Culture, Media & Sport, 2020). They store, process and manipulate data for a wide variety of purposes. These include financial systems, patient and employee records and data used by AI. Due to their fundamental role in economic activities and public services, data centres were recognised as critical national infrastructure for the UK in 2024, similar to utility and emergency services (Clark, 2025). Data centres and associated AI have greater reach and impact than the footprint on which they are built, with significant raw material, energy, and water requirements for their hardware, associated infrastructure and network.

This section of the report provides a brief overview of data centre types, their applications and uses. It outlines the raw material, energy, and water requirements directly related to data centre construction. This report does not, however, capture the raw material requirements related to increased energy demand and energy source mix or construction materials required for the buildings in which data centres are located. Although these aspects should be considered to fully understand the implications related to an increase in requirements for data centres both globally and in the UK, they are beyond the scope of this report.

2.1 DATA CENTRE INFRASTRUCTURE AND TYPOLOGY

A data centre is a facility constructed to house computer systems, including servers, to store and manage data (US Geological Survey, 2024a). These facilities are the physical infrastructure through which virtually every digital interaction is routed (TechUK, 2025). Data centres act as infrastructural nodes for processing information transmitted wirelessly through the internet (Tang, 2023). They are considered the backbone of the modern digital economy (Kok et al., 2025).

The primary mission of a data centre is to remain operational 24 hours a day, seven days a week, 365 days a year (TechUK, 2025). To achieve this, all data centres require a guaranteed power supply with backup systems to ensure resilience against power outages and high-bandwidth internet connectivity. Robust physical and cyber security systems are required to ensure data and operations are protected. Advanced cooling systems are also required to dissipate the heat generated by the servers and supporting hardware.

Data centres are fundamental to the operation of modern businesses, being the main platform for storing and managing large volumes of data. Data centres deliver cloud services, enabling clients to access on demand computing resources for applications, websites, and enterprise systems (Kiziroglou et al., 2025). A wide range of digital workloads essential for business and consumer services are also processed by data centres. These include transactional data, such as financial transactions, e-commerce operations and real time analytics; enterprise applications, such as enterprise resource planning (ERP) systems, customer relationship management (CRM) platforms and productivity tools; and media and content delivery for streaming services, social media platforms and online gaming. Data centres also support scientific and industrial workloads alongside AI and machine learning datasets that demand high-speed storage and computer resources for training and tasks (Holmberg, 2025).

2.1.1 Key components

Each data centre will vary based on scale and capacity, but will typically comprise the same basic set of technological components:

- **Servers:** combination of hardware and software that allow computers to function, process and store data. They are often equipped with central processing units (CPUs) or specialised accelerators, such as graphics processing units (GPUs), for high-performance computing, especially in AI workloads (International Energy Agency, 2025c). Servers are typically housed in server racks and are connected to a network to allow data to be accessed, stored, and processed.
- **Networking:** networking equipment enables the storage and processing of applications and data through switching, routing, load balancing, and analytics (DCIM, 2025).
- **Storage:** consists of technologies, software, and devices that allow for the storing of data and applications within a data centre (DCIM, 2025).
- **Cabling infrastructure:** a network of cables allowing power supply and data transfer for critical operations, which require careful management to avoid downtime (DCIM, 2025).
- **Power infrastructure:** physical infrastructure, such as rack and floor power distribution units (PDUs), remote power panels, busways, and an uninterruptible power supply (UPS) are necessary to provide power to IT equipment. Backup power is usually supplied by a generator to minimise downtime (DCIM, 2025).
- **Cooling systems:** computer room air conditioning units regulate temperature and humidity and computer room air handler units prevent critical equipment from overheating (DCIM, 2025). For high-density AI server racks, advanced cooling technologies, such as liquid cooling, direct-to-chip, or immersion cooling are increasingly used.
- **Structure:** physical structures that support and contain the components of the data centre, such as server racks and cable trays, and does not comprise the construction materials associated with the building in which the data centre is housed.
- **Physical security:** equipment such as alarms, electronic door locks, biometric scanners, and closed circuit television (CCTV) are implemented to protect data and assets (DCIM, 2025).

2.1.2 Data centre types

Data centres with a range of functions, technology, scale, and capacity are the foundation to modern digital infrastructure. Data centre capacity is typically measured in megawatts (MW) or kilowatts (kW) of power consumed by critical computing equipment. Data centre types can therefore be categorised using a variety of methods, detailed below and summarised in Table 1:

1. Ownership, business model
2. Scale, architecture
3. Function/workload
4. Operational resilience

Table 1. Data centre types by ownership and business model, architecture and scale, and workload or function.

Type/Category	Definition/Description/Sample	Key Characteristics/Purpose
Ownership and business model		
Hyperscale data centres	Massive facilities supporting very large IT infrastructure. They are owned and operated by a single company, typically a major technology company, such as Apple Data Centre, Arizona and Google Data Centre, Oregon (International Energy Agency, 2025c).	Often exceed 1000 metres squared of floor space and contain over 5000 servers and 500 cabinets (Belden, 2024). They use scalable, highly efficient infrastructure to support cloud services, web hosting, and increasingly, AI services (International Energy Agency, 2025c).
Co-location and service provider data centres or multi-tenant data centres (MTDC)	Facilities that either lease space for customers to house their own computing equipment (co-location) or provide both the space and the computing equipment (International Energy Agency, 2025c). Facilities may be operated by major co-location investors, such as Equinix, Digital Realty, CyrusOne, or VIRTUS Data Centres (Kiziroglou, 2025).	Also referred to as multi-tenant data centres (MTDC). Operators provide space, power, and cooling, frequently refreshing hardware/technology to meet customer demand (Belden, 2024). Despite being designed for broad multi-tenant use, many co-location data centres include hyperscale tenants, influenced in part by regulatory pressures and the growing need for distributed capacity (Moody's, 2025).
Enterprise data centres	Private facilities run by businesses or institutions solely for their own use; they are owned and operated by the enterprise (Jupp et al., 2021; Ye, 2021). Data centres are operated internally by companies, such as Apple, Meta, and Salesforce.	These data centres are typically smaller and less efficient than other types but have a variety of scales from ten cabinets up to 40 MW in size (Ye, 2021).
Telecommunication data centres	Facilities owned and operated by telecommunications or service companies (Ye, 2021). Examples include facilities operated by China Mobile, China Telecom, and China Unicom.	Requires high connectivity to deliver content, mobile services, and cloud services; often utilise two-post or four-post racks for telecommunications equipment (Ye, 2021).
Managed data centres	Offer servers or cabinets for rent and provide management services, including maintenance and system upgrades.	A subset model often grouped with co-location or service provider offerings.
Architecture and scale		
Edge / micro data centres	Small facilities located near or on the same site as the people they serve or the data source (Belden, 2024).	Designed to allow real-time processing, analysis, and action, minimising communication delay (latency) for applications such as 5G, autonomous vehicles, wearable healthcare technology, and smart electrical grids (Belden, 2024).
Container / modular data centres	Systems delivered as a module or shipping container packaged with ready-made, plug-in-and-play components (Belden, 2024).	Pre-engineered and tested in a factory environment. Used for both temporary (e.g. construction sites, disaster areas) and permanent deployments for quick scale-up (Belden, 2024).
Traditional/ conventional data centres	Older generation of facilities.	Typically constructed using the time-consuming and high capital cost legacy building methods, such as brick and mortar, as opposed to steel frame construction.

Type/Category	Definition/Description/Sample	Key Characteristics/Purpose
Workload/function		
AI data centres / AI training cluster	IT infrastructure specifically used for AI model training, such as large language model (LLM) training. Examples include OpenAI's Stargate project with 5GW capacity requested (Reuters, 2025b) and xAI’s Memphis Supercluster containing up to 100,000 Nvidia H100 GPUs (Trueman, 2024a).	Requires extremely high capital expenditure, specialised facilities, and skilled workforce. A major shift in AI data centre design is the dramatic increase in power budgets, driven by the dense computational requirements of GPU and accelerator-based training clusters. Furthermore, AI training workloads typically have latency constraints within the computer fabric and memory architecture rather than in relation to the end user proximity, meaning these facilities do not necessarily need to be close to local user populations (Datacenters.com, 2025).
AI inference cluster	IT infrastructure used for AI model deployment and real-world use, such as running AI chatbots and generative AI applications. Generic cluster type with mixed hardware optimised for deployment.	Requires moderate to high capital expenditure depending on the scale.
Traditional supercomputer	Facilities distinct from general data centres, used for high-performance computing.	Primary purpose is scientific discovery and national security, such as climate modelling, nuclear simulations, and molecular modelling. Considering their role in handling highly sensitive scientific and national security computations, traditional supercomputers frequently require exceptionally strict access control. Some operate as air-gapped systems, entirely segregated from external networks to prevent data leakage or cyber intrusion (Fortinet, 2025).
Cloud computing and web content servers	Infrastructure for hosting and delivering web media, such as video streaming.	Focuses on minimising latency, maximising uptime, and ensuring scalability by utilising distributed data centres and scalable cloud infrastructure.

The operational resilience of a data centre indicates its ability to maintain operations and recover quickly following an unexpected event, such as a cyber-attack, power disruption, or natural disaster (Table 2). Despite their designation as critical national infrastructure in the UK, there are no minimum operational resilience requirements for data centres. This has the potential for severe implications should an unexpected event or compromise occur (Clark, 2025). Tier Standard Classifications were created to describe the infrastructure required to sustain data facility operations (Table 2). The Tier Standard Classifications allow for various levels of performance to be chosen based on the intended applications and business parameters associated with those applications. All subsystems and systems must be consistently deployed with the same facility uptime objective to satisfy the unique tier requirements. Therefore, the tier rating for an entire data facility is limited by the rating of the weakest subsystem that impacts facility operations (Data Facility, 2025).

Table 2. The four Uptime Institute Tier classifications, detailing their operational resilience and requirements (Ingenious Build, 2024; Tang, 2023).

Tier	Description	Uptime	Approximate downtime	Operational resilience	Typical use
I	Basic capacity	99.671 %	28.8 hours / year	Susceptible to disruptions during maintenance or faults	Small businesses or non-critical operations
II	Redundant capacity components	99.749 %	22.2 hours / year	Improved resilience, but still downtime during maintenance	Sor medium enterprises with moderate uptime needs
III	Concurrently maintainable	99.982 %	1.58 hours / year	Maintenance can occur without downtime	Enterprises requiring high availability
IV	Fault tolerant	99.995 %	26.3 minutes / year	Can withstand faults without impacting operations	Mission-critical systems (e.g., financial institutions, hospitals)

Hyperscale data centre facilities are single facilities designed for massive, efficient, and rapidly scalable computing capacity, typically operated by major cloud or AI providers, and currently lead the UK market with an approximate share of 37 per cent in 2025 (Mordor Intelligence, 2025b). Mega-campus developments are much larger sites containing multiple data centre buildings, often including several hyperscale facilities, and supported by shared infrastructure. These data centre types are projected to grow the fastest at approximately 31 per cent compound annual growth rate through 2031, driven by AI-related power and cooling requirements (Mordor Intelligence, 2025b).

Tier III facilities dominate both the UK and global landscape with an approximate share of 78 per cent, but Tier IV is expanding rapidly as AI and financial workloads demand higher resilience. Co-location remains the main deployment model in both the UK and worldwide, although hyperscale self-build strategies are accelerating. IT and telecommunications remain the largest end-user group, whilst banking, financial services, and insurance are the fastest growing end user sectors due to rising digital baking and real-time trading needs (Cushman & Wakefield, 2025; Mordor Intelligence, 2025b).

2.2 ARTIFICIAL INTELLIGENCE

Artificial Intelligence (AI) is defined as the science of creating machines with the capability to learn and undertake tasks that typically require near human intelligence and is one of the more transformative technologies of the 21st century (International Energy Agency, 2025c). AI systems integrate models and algorithms that provide the capacity to learn and perform cognitive tasks, leading to outcomes such as predictions and decision making (United Nations Environment Programme, 2024).

The development of AI is based on three primary learning and processing paradigms, moving from programmed rules to complex neural simulations (International Energy Agency, 2025c):

1. **Rules-based / symbolic AI:** systems are explicitly programmed to process information, make decisions and solve problems. This method is labour-intensive and struggles with open-ended or unexpected situations (Liang, 2025).
2. **Machine learning and reinforcement learning:** machine learning algorithms learn patterns and make decisions from data without explicit programming. Machine learning typically uses simple neural networks and requires human intervention for teaching, utilising supervised learning. Supervised learning necessitates structured, labelled input data to achieve accurate outputs. Reinforcement learning involves algorithms learning to achieve a specific objective through trial and error, improving performance over time through experience (Liang, 2025).
3. **Neural networks and deep learning:** inspired by the human brain, deep learning uses artificial neural networks to simulate how the brain works, allowing machines to undertake reinforcement learning. Deep learning models use deep neural networks, often hundreds or thousands of layers, to simulate human decision-making. Deep learning relies on unsupervised learning, where models extract necessary characteristics, features, and relationships from raw, unstructured data, improving accuracy over time. Deep learning requires high-performance computing resources, such as graphics processing units (GPUs; Liang, 2025), an electronic circuit or processor specially designed to process digital images and accelerate the rendering of graphics.

AI capability is characterised into three types (IBM Data and AI Team, 2025):

- **Artificial narrow AI (weak AI):** the only type of AI that currently exists. It is trained to perform a single task, often faster and better than humans, but cannot perform tasks outside its training.
- **General AI (strong AI):** a theoretical AI that would be able to use previous learning and skills to accomplish new tasks in different contexts without requiring human training. Ultimately, it could perform any task a human can.
- **Super AI (artificial super intelligence):** a theoretical AI that possesses cognitive abilities surpassing humans and develop its own emotions, needs, beliefs, and desires.

AI functionality is classified into four categories encompassing current and theorical systems as well as specific industrial applications (Khan, 2024):

- **Reactive machine AI**: this AI has no memory and is designed to perform a specific task. It analyses vast amounts of presently available data, often using statistical mathematics to provide intelligent output. Examples include chess computer counterparts and Netflix recommendation engines.
- **Limited memory AI:** can recall past events, outcomes and monitor situations for specific lengths of time. It uses both past and present data to determine a course of action. Examples include generative AI tools, such as ChatGPT, virtual assistants and self-driving cars.

- **Theory of mind AI:** a currently theoretical AI that would understand the thoughts and emotions of others which would influence its interactions allowing for the simulation of relationships, personalisation, and emotional responses.
- **Self-aware AI:** a theoretical AI of super capability that would understand its own internal conditions in addition to human emotions and thoughts.

AI is deployed across numerous specialised areas using machine learning and deep learning models and can be categorised based on specific functional types and applications (International Energy Agency, 2025c), including:

- **Predictive AI:** predicts future outcomes through scientific modelling, such as weather forecasts.
- **Generative AI:** generate new content, including text, audio, video, code, and mathematical models.
- **Computer vision:** interprets and understand visual data for tasks like object detection, facial recognition, self-driving cars, and augmented reality.
- **Physical AI:** systems that physically interact with the real world, such as autonomous cars and robots, learning from their environment and operating in uncertain situations.
- **Agentic AI:** autonomous agents for specific tasks, such as virtual voice assistants and dynamic building energy control.
- **Deep learning applications:** code creation and translation, image classification for defect detection, lane line detection, healthcare, marketing, retail, customer care, language processing, and speech recognition.

Despite this progress, the move towards larger and more computer-intensive AI models raises concerns about their long-term environmental and economic sustainability. This has led many researchers to propose more efficient architectures or smaller, task-specific AI systems as potential alternatives to today’s large-scale models (Leon, 2024).

2.2.1 Artificial intelligence hardware requirements

There are significant hardware and operational differences between traditional data centres designed for storage and data processing, and those focused on AI workloads. These distinctions arise because AI requires parallel processing, high memory capacity, and specific hardware configurations that substantially increase power consumption and heat generation compared to standard computational tasks (Chauhan, 2024). The main hardware and infrastructure requirements of AI include:

- **Computer hardware:** traditional data centres and general-purpose servers rely on central processing units (CPUs) to carry out instructions from programs (International Energy Agency, 2025c). In contrast, AI requires specialised accelerators, such as graphics processing units (GPUs), tensor processing units (TPUs), and application-specific integrated circuits (ASICs), which are required for parallel processing, needed for deep learning, AI model training, and high performance computing (International Energy Agency, 2025c). The capacity of accelerated servers grew four times faster than conventional server capacity between 2015 and 2024 (International Energy Agency, 2025c).
- **Power density and infrastructure:** AI specialised accelerators require more power to operate, with GPUs consuming 300-400 W under full load, compared to the estimated 85 W required for a traditional CPU (Chauhan, 2024). Latency is the time delay between issuing a request and receiving a response, from input, through computation to output. Many of the functions of a traditional data centre, such as hosting webpages and streaming videos and games, required low latency. This requirement forced data centres to be built close to where

demand was highest near population centres, which limited how large traditional data centres could grow. However, AI training is less sensitive to latency, allowing facilities to grow much larger (International Energy Agency, 2025c) and therefore requiring a more robust infrastructure to support the weight of specialised hardware (Arup, 2024).

- **Cooling systems:** the high heat output generated by high-density, accelerated servers makes traditional air cooling insufficient for AI data centres. Liquid cooling technologies are used for more efficient heat removal (McGlocklin, 2025). Such technologies reduce the energy required for cooling by nearly 90 per cent compared to traditional air systems, greatly increasing cost efficiency (United for Efficiency, 2025). Immersion cooling is an alternative mechanism involving the entire sever being submerged in dielectric fluid to allow uniform heat dissipation (East, 2024), providing energy savings of 30-50 per cent (He, 2025). The waste heat produced by high-density AI data centres can also be captured and integrated into district heating systems, improving overall system efficiency and reducing the environmental footprint of cooling operations (World Economic Forum, 2025).
- **Memory and storage:** storage demands are higher for AI than traditional systems due to the large datasets and faster access times, requiring faster solid-state drives (Jonker, 2025).
- **Networking:** high-bandwidth networks are required by AI for efficient transfer of large amounts of data between chips, memory, and servers (International Energy Agency, 2025c). AI networking therefore encompasses ultra-low latency and high-bandwidth connections (Kiziroglou et al., 2025).

2.3 MATERIAL REQUIREMENTS FOR DATA CENTRES AND ARTIFICIAL INTELLIGENCE

The material requirements for AI-focused data centres, particularly for semiconductors and high-performance computing infrastructure, rely on a complex system of critical minerals and specialised elements, many of which face concentrated supply chains and supply constraints (Mudd et al., 2024a). AI and data centres will be competing for critical minerals and for the specialised chemical elements refined from them, in the next stage of the digital revolution, alongside other sectors, such as green technologies, portable electronic devices, and aerospace. Assessing the material requirements of data centres and AI is crucial to understanding potential future demands for these elements, supply chain bottlenecks, and any mitigation measures that may be required. Much of the material requirements for data centres and AI is confidential intellectual property and detailed modelling of future demand is typically limited and basic. Nevertheless, academic research and government studies do provide significant detail on demand for the more niche raw materials required in the manufacture of these critical technologies.

The material demands for data centre components are diverse and summarised in Table 3 and Figure 1. A full outline of material requirements with specific compounds and quantities where available; reasons for material choice; and technology readiness levels are provided in Table 23 (Appendix 2). It should be noted that data centre construction also requires significant quantities of construction materials, such as steel and concrete. However, such materials are outside the scope of this study.

Table 3. Summary of material requirements for data centre components

Component	Material requirements	References
Servers	Aluminium (Al), antimony (Sb), arsenic (As), bismuth (Bi), cadmium (Cd), barium (Ba), beryllium (Be), bismuth (Bi), cobalt (Co), copper (Cu), gallium (as GaN, GaAs), germanium (Ge), gold (Au), hafnium (Hf), indium (In), iron (Fe), lead (Pb), lithium (Li), niobium (Nb), nickel (Ni), palladium (Pd), platinum (Pt), rare earth elements (REE), selenium (Se), silicon (Si), silver (Ag), tantalum (Ta), tellurium (Te), tin (Sn), titanium (Ti), tungsten (W), zinc (Zn)	(International Energy Agency, 2025c; Peñaherrera Vaca, 2024; SFA (Oxford), 2025)
Networking	Copper (Cu), germanium (as GeO_2), gold (Au), nickel (Ni)	(Peñaherrera Vaca, 2024)
Memory/storage	Antimony (Sb), barium (Ba), bismuth (Bi), boron (B), cobalt (Co), gallium (Ga), gold (Au), hafnium (Hf), indium (In), iron (Fe), niobium (Nb), palladium (Pd), platinum (Pt), rare earth elements (REE), ruthenium (Ru), silicon (Si), silver (Ag), tantalum (Ta), titanium (Ti), tungsten (W)	(Peñaherrera Vaca, 2024; SFA (Oxford), 2025)
Power	Boron (B), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), lithium (Li), manganese (Mn), platinum (Pt), rare earth elements (REE)	(Peñaherrera Vaca, 2024; SFA (Oxford), 2025)
Cooling	Aluminium (Al), beryllium (Be), copper (Cu), iron (Fe), rare earth elements (REE)	(Peñaherrera Vaca, 2024; SFA (Oxford), 2025)
Structure	Aluminium (Al), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn)	(SFA (Oxford), 2025)
Displays and optics	Aluminium (Al), arsenic (As), cerium (Ce), europium (Eu), gallium (Ga), germanium (Ge), indium (In), holmium (Ho), neodymium (Nd), nitrogen (N), oxygen (O), phosphorous (P), platinum (Pt), praseodymium (Pr), terbium (Tb), tin (Sn), yttrium (Y)	(SFA (Oxford), 2025)

Servers and memory require the greatest array of elements out of all the data centre components (Table 3) with silicon being one of the fundamental raw materials used in the manufacture of both components. Silicon (discussed in more detail in Section 5) is a semiconducting material, often used to enhance thermal stability and fire resistance in electronic components (Peñaherrera Vaca, 2024; SFA (Oxford), 2025). Copper and aluminium are elements that are utilised in the manufacture of nearly all components of a data centre (Table 3). Aluminium is a lightweight metal with good strength, high thermal conductivity, and resistance to corrosion (SFA (Oxford), 2025). It is widely used in structural components and as radiators, fans, and pumps within cooling systems (Peñaherrera Vaca, 2024). Copper is an excellent conductor and durable metal that is widely used within network and power systems, as well as servers, memory, and cooling components (Peñaherrera Vaca, 2024). Rare earth elements (REE) are a key component of permanent magnets and therefore widely used in servers, memory, power supply, and cooling systems. The use of permanent magnets in memory components facilitates rapid and accurate retrieval of data (Peñaherrera Vaca, 2024; SFA (Oxford), 2025). Dysprosium increases the heat resistance and magnetic stability of these permanent magnets, allowing their magnetic properties to be maintained under high temperature conditions (Peñaherrera Vaca, 2024; SFA (Oxford), 2025).

Data centres require an uninterruptible power supply and must demonstrate their operational resilience and capability to maintain operations if an unexpected event, such as a power cut, were to occur (Clark, 2025). Data centres require a reliable back up energy source for which most sites rely on diesel generators. Generators require several minutes to start and stabilise and therefore tend to be operated in a staged sequence. The uninterruptible power supply (UPS) is therefore essential to bridge the interval between the loss of mains power and the generators reaching full operational load. These UPS systems may be reliant on energy storage solutions, such as batteries (International Energy Agency, 2025c). Therefore, battery raw materials, such as lithium, cobalt, graphite, and manganese are all required for data centre construction, causing rising demand for these elements and competition with other sectors, such as electric vehicles and portable electronics.

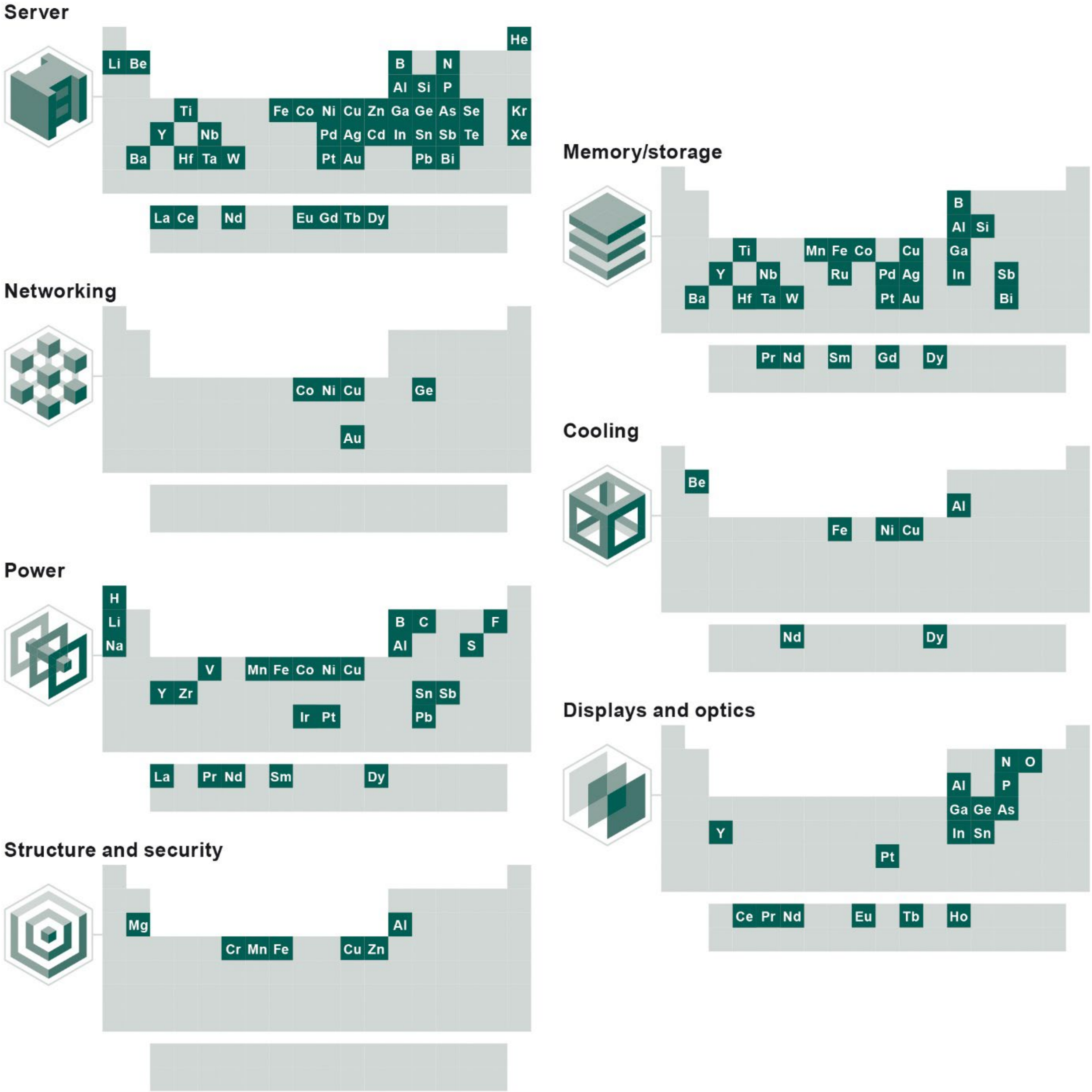


Figure 1. Summary of element requirements for data centre components, compiled from Table 3 and Table 6. BGS © UKRI 2026.

2.3.1 Estimates of future material requirements

The most comprehensive study of the constituents of data centre components can be found in Peñaherrera Vaca (2024). This study is based on enterprise data centres, which are private facilities used by a single organisation. In recent years, these centres have become less popular. Larger multi-tenant or hyperscale data centres are increasingly preferred because they support substantial IT infrastructure needs for organisations with high data and processing demands (Miller, 2022). Making precise assessments of future material requirements to meet data centre demand is therefore difficult. A summary of basic estimates of future mineral demand driven by data centre expansion is provided in Table 4.

Many of the elements required for the manufacture of data centre components are also utilised in a wide variety of other sectors, such as defence, construction, aviation, and clean energy technology. Current and future expansion of data centre facilities will therefore cause future sector competition for these critical minerals, many of which have highly concentrated supply chains or are produced as by-products and are therefore more vulnerable to geopolitical disruption or trade issues.

Table 4. Estimated change in element requirements for data centres by 2030 (International Energy Agency, 2025c).

Element	Future demand	Notes	Source
Gallium (Ga)	Increase of up to 11 % of today's total supply.	Driven by AI acceleration in computer chips and power electronics.	China accounts for approximately 99 % of global refined supply.
Copper (Cu)	Increase of up to 2 % of total demand in 2024.	Absolute volume of 512 kilotons (kt) by 2030 for project developers.	Nearly 60 % of refined supply from the top three producing countries (China, Chile, Democratic Republic of the Congo) in 2024.
Silicon (Si)	Increase of up to 2 % of total demand in 2024.	Absolute volume of 75 kt by 2030 for project developers.	Over 90 % of refined supply from the top three producing countries in (China, US, Norway) 2024.
Rare earth elements (REE)	Increase of over 3 % of total demand in 2024.	Used in high-performance magnets for cooling and drives.	Over 90 % of magnet REE refined supply from the top three producing countries (China, Malaysia, US) in 2024.

2.4 UK DATA CENTRE SUPPLY CHAIN

The UK AI and data centre supply chain is complex, globally connected, and geographically concentrated (Figure 2). Whilst the UK is rapidly expanding its data centre footprint (Reuters, 2025c), it remains a net importer of advanced semiconductor components and lithography equipment, with fabrication capacity concentrated in Asia (Department for Science, Innovation and Technology, 2024; Woods and Gajjar, 2024). The UK's strength lies in chip design and AI research, supported by companies such as Arm (Arm, 2025) and Graphcore (Graphcore, 2025), but large-scale manufacturing is limited compared to global leaders, such as Taiwan, South Korea, and the US. Despite the policy and investment efforts outlined in Section 2.4.1, the UK's position in the global hierarchy is primarily as a design and innovation hub rather than a manufacturing powerhouse, creating strategic vulnerabilities in hardware supply for hyperscale and AI-driven data centres.

2.4.1 Data centre location and investments

The UK is rapidly expanding and investing in the construction of next-generation AI-focused data centres. Total UK data-centre investment has dramatically increased, with an estimated £10 billion of spending per year by 2029, an increase of more than five times the investment in 2024 (£1.75 billion; Reuters, 2025c). Expenditure in 2025 is expected to reach approximately £2.3 billion (Reuters, 2025c). The designation of data centres as critical national infrastructure (Department for Science Innovation and Technology, 2025c) and creation of AI growth zones in former industrial areas aims to accelerate UK capability by removing barriers, such as reducing planning permission waiting times and supporting infrastructure construction and energy supply, whilst developing a skilled workforce and attracting investment (Department for Science Innovation and Technology, 2025c).

Recent government initiatives, including AI Growth Zones (Department for Science Innovation and Technology, 2025c) and the £31 billion Tech Prosperity Deal encompassing key global technology companies, such as Google, Microsoft, and Nvidia (Department for Science Innovation and Technology, 2025a), aim to attract investment and reduce reliance on overseas supply chains. Although the implementation of this investment has been put on pause by the US due to the UK maintaining its digital services tax on US technology companies, (Courea, 2025), negotiations between the two countries are expected to continue.

Data centre growth is being driven by AI development, creating an exponential increase in the demand for processing power (Dawson, 2025). Over 90 new data centres are planned in the UK by 2030, with an estimated value of £36 billion and providing a 20 per cent increase in facilities relative to 2025 (Dawson, 2025). More than half of the proposed new facilities will be in London and surrounding counties, while others are spread across the UK. Nine are planned for Wales, one in Scotland, five in Greater Manchester and several in other regions (Craske, 2025a). Multi-tenant data centres are provided by two leading companies in the UK: Ark Data Centres, who own 14 sites across the UK and Vantage, who own 15 sites. Additional data centres are owned by Equinix, Telehouse, and Virtus, predominantly located in London, Slough, and Manchester (Baxtel, 2025).

2.4.2 UK data centre component manufacturing supply chain

The UK has an already established supply chain for the manufacture of components and utilities required for AI and data centre construction. This foundation positions the UK to become a leading expert and provider within this sector. The location of leading companies established within the UK data centre supply chain are identified in Figure 2.

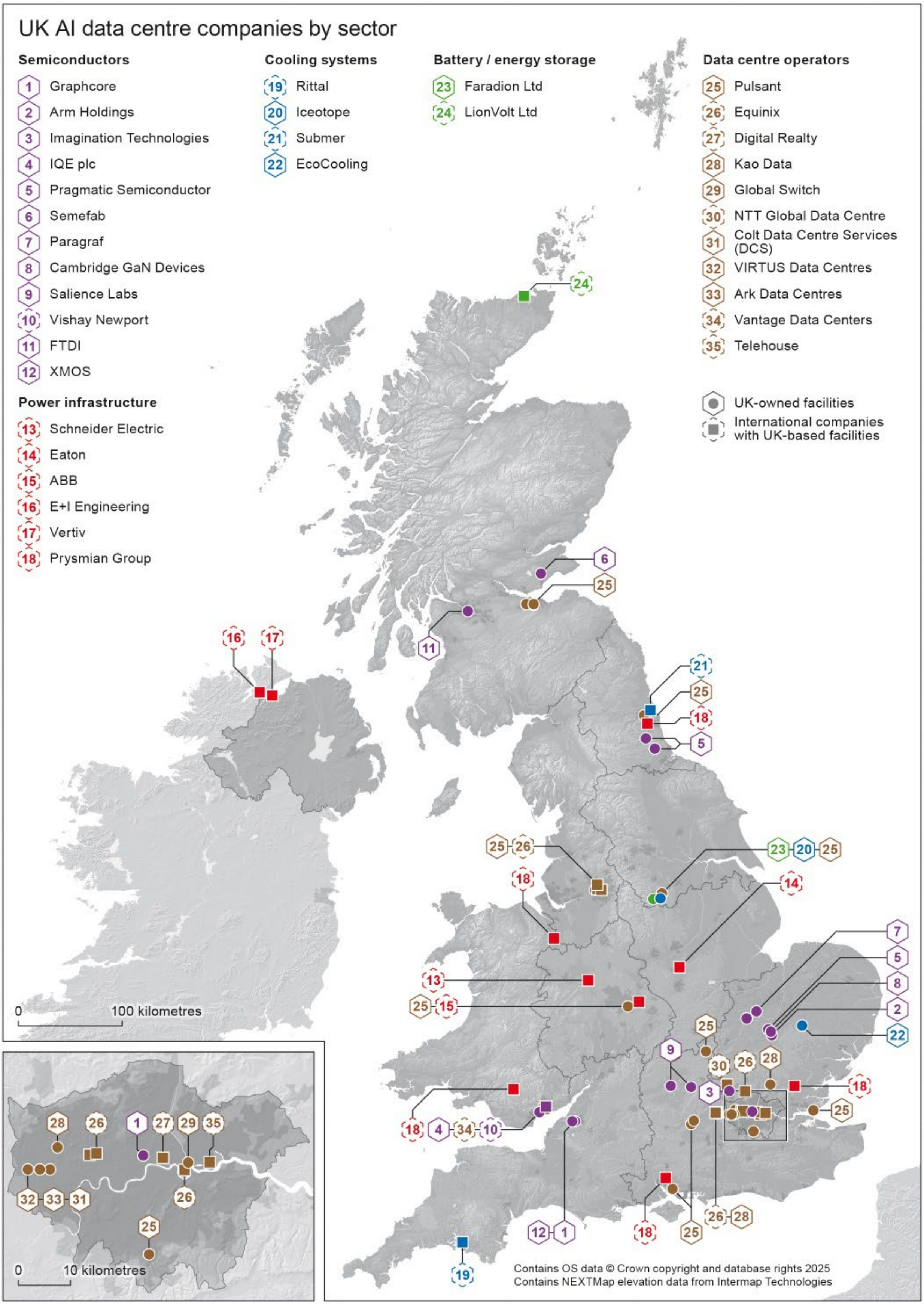
The UK has developed considerable expertise in semiconductor chip design but has limited fabrication capacity. The Cambridge-based company Arm, remains a global leader in the manufacture of central processing units (Hornstein, 2025) and other British startup companies, such as Graphcore, Bristol; Imagination Technologies, Hertfordshire; and Pragmatic Semiconductor, Cambridge, are designing cutting-edge AI accelerators. IQE are a UK-based company with fabrication facilities in Cardiff, Newport, US, and Taiwan. The use epitaxial growth, a technique to grow a thin film on a crystal substrate, to manufacture a global supply of semiconductors (IQE, 2026). The company imports GaAs, InP, and SiC host crystalline wafers and then grows thin epitaxial layers on top to make epiwafers that are then used for electronic and photonic devices (Davies oral communications, 03/02/2026). The UK Government is making the research and development of semiconductors a priority (Hornstein, 2025), awarding a £10 million Technology Missions Fund to boost domestic chip innovations. The UK Department for Science, Innovation and Technology have indicated that the UK semiconductor industry is expected to grow by 75 per cent by 2030 and that funding programs will provide access to specialised laboratories and expertise (Trueman, 2025b).

Most advanced semiconductor chips are manufactured in Asia. Therefore, the UK imports the majority of its processors and memory components, creating constraints on the domestic manufacturing of data centre hardware (Collins, 2025). The UK semiconductor sector is also regionally dispersed (Figure 2), with approximately half of dedicated firms located proximal to London, the South East and the East of England (Department for Science Innovation and Technology, 2024). Arm accounts for approximately 25 per cent of revenue (£2.4 billion) and 20 per cent of employment (3000 people) within UK dedicated semiconductor companies in 2022 (Department for Science Innovation and Technology, 2024). The presence of Arm’s headquarters in Cambridge makes the East of England a primary focal point for the UK semiconductor sector, aligning well with the Oxford-Cambridge Growth Corridor. This Growth Corridor is an innovation region linking Oxford, Cambridge, and Milton Keynes. It is regarded as a world-leading hub for science and technology and is described by policymakers as having the potential to become “Europe’s Silicon Valley” (HM Treasury, 2025). Scotland contributed 24 per cent of UK semiconductor revenues (£2.3 billion) in 2022 and Wales 30 per cent (£2.88 billion), despite Wales hosting only 8 per cent of dedicated UK-headquartered firms (Department for Science Innovation and Technology, 2024).

Recent employment growth among dedicated small and medium-sized enterprises (SMEs) has been driven by research and development, design, intellectual property, and manufacturing, particularly within companies specialising in compounds and emerging materials. Analysis of 1634 UK semiconductor sites assessed by the UK semiconductor sector study (Department for Science Innovation and Technology, 2024) reveals established geographical clusters in areas such as Bristol, Cambridge, the North East, Northern Ireland, Scotland, and South Wales. Additional clusters are also noted in the North West, Midlands, and along the south coast of England. The main manufacturing hubs are located in Scotland, Wales, and North East England, whilst design clusters are prominent in and around London, especially in Cambridge and extend along arterial routes connecting London with Bristol, Oxford, and Southampton.

UK companies are also developing cooling technologies for data centres. For example, the Leeds-based Airedale International Supplies company has developed a high efficiency data centre chiller (Airedale by Modine, 2025) and the Suffolk-based EcoCooling company manufactures evaporative air-cooling systems that can cut data centre cooling costs by approximately 90 per cent (EcoCooling, 2025).

The UK has strong photonics capabilities, especially within design and intellectual property that is important for data centres as well quantum computing technologies (see Section 3.4), but lacks significant manufacturing infrastructure (MoI oral communication, 30/01/2026). The epitaxial growth substrates produced by IQE comprise more than 50 per cent of all III-V epitaxial wafers (Roman numerals refer to periodic table groups) produced globally for products, including the lasers used for telecommunications and in data centres (Paul oral communication, 16/01/2026). Whilst Sivers Photonics manufacture over 5 per cent of the distributed feedback lasers for data communications applications and Kelvin Nanotechnology is involved in the manufacture of approximately 10 per cent of lasers incorporated into global data centres (Paul oral communication, 16/01/2026).



Contains OS data © Crown copyright and database rights 2025
Contains NEXTMap elevation data from Intermap Technologies

Figure 2. Overview Map of UK AI and data centre component manufacturing supply chain, categorised by component/sector. Data source: see Table 26, Appendix 3. BGS © UKRI 2025.

2.5 ARTIFICIAL INTELLIGENCE DATA CENTRES’ ENERGY AND WATER REQUIREMENTS

Although a detailed analysis of the energy and water requirements of AI data centres is outside the scope of this report, it is an important aspect to highlight. In addition to the raw materials requirement of the data centres themselves, energy and water demand can place significant stress on supporting infrastructure (International Energy Agency, 2025c; Laudisio et al., 2025).

2.5.1 Data centre energy requirements and demand

AI data centres consume large amounts of energy, comparable to the requirements of an aluminium smelter, but tend to be geographically concentrated into particular areas (International Energy Agency, 2025c). Data centres consumed 1.5 per cent of global energy demand in 2024, equating to approximately 415 TWh, an increase of approximately 12 per cent per year since 2017 (International Energy Agency, 2025c). Models of future scenarios expect consumption of electricity by data centres to more than double to approximately 945 TWh by 2030 and 1200 TWh by 2035. The US account for the largest proportion of this expected increase, followed by China (International Energy Agency, 2025c).

Data centres consumed approximately 2.5 per cent of annual UK national electricity use in 2024, with projections suggesting this could rise to around 6-10 per cent by 2030 (Clark, 2025; Department for Energy, Security and Net Zero, 2024b; Europe Economics, 2025). Concerns have been raised regarding the source of the energy required to meet growing data centre demand and ensuring operational resilience in regard to power supply (Clark, 2025). Outages have previously caused multi-million-pound losses and service disruption in healthcare and other sectors, highlighting the need for robust backup systems (Department for Science Innovation and Technology, 2025b). Given the significant expected rise in consumption, prioritising renewable energy sourcing and procurement strategies will be critical to meeting the UK’s decarbonisation objectives (Department for Energy, Security and Net Zero, 2024b; Europe Economics, 2025). As such, the UK Green Building Council have released a set of best practice guidelines to mitigate energy demand risk, including the use of on-site or traceable energy sources, improving the grid’s capacity through procurement strategies, and aligning energy purchases with renewable energy supply on an hourly or sub-hourly basis (UK Green Building Council, 2023).

Primary power for data centres is dominated by grid supply to ensure continuous operations. Hyperscale and AI-focused data centres can require over 100 MW per hour, causing grid strain and permitting delays (Clark, 2025). Onsite gas engines or turbines can be used for primary power production and long duration backup power, some of which have been designed to be versatile for fuel and capable of using gas, diesel, and hydrogen (Westwood, 2025).

To ensure operational resilience, data centres require an uninterruptible power supply with the ability to demonstrate backup power sources for at least three hours, should grid supply be disrupted. A range of solutions are being utilised to ensure this uninterruptible power supply, including:

- **Batteries:** these can provide instantaneous power, typically for a few minutes, should the grid supply fail, allowing time for backup generators to start. Battery energy storage systems may be used for longer-duration energy storage, load shifting, and supporting grid stability (Skidmore, 2025).
- **Onsite generators:** these traditional and most reliable forms of long-duration backup power can maintain power to a facility for hours to days during a grid outage. However, concerns over carbon emissions are causing these to be replaced by cleaner technologies (Clark, 2025).
- **Hydrogen fuel cells:** these are one of the potential cleaner technologies that could replace onsite diesel generators due to their zero carbon emissions (Reppas, 2024).

Proton exchange membranes (PEM) are able to start rapidly, have a low operating temperature (less than 100°C), and can be manufactured at a modular scale (Benstead, 2024). Solid oxide fuel cells (SOFCs) can be flexible regarding fuel source, running on hydrogen, natural, gas, or biogas, and are 50–65 per cent efficient, but operate at higher temperatures. Both technologies are currently being tested in hyperscale data centres as part of decarbonisation strategies, with PEM systems favoured for short-duration backup and SOFC systems for long-duration or primary power (Benstead, 2024).

- **Hydrogen dual-fuel engines:** are combustion engines capable of running on a blend of hydrogen and another fuel, such as natural gas or diesel, offering cleaner power but maintaining traditional engine reliability (Leigh, 2025).

2.5.1.1 ONSITE BACKUP POWER TECHNOLOGY MINERAL REQUIREMENTS

Future battery and energy storage technologies are expected to play a critical role in enhancing data centre resilience and supporting decarbonisation goals. As demand for data centres expands, demand for the raw materials required for backup power technologies to ensure an uninterruptable power supply will also grow. These raw materials, many of which have been designated as critical by the UK government (Mudd et al., 2024a), are summarised in Table 6. They are also in high demand from other sectors, such as electric vehicles and renewable energy (International Energy Agency, 2023).

Lithium-ion batteries currently dominate uninterruptible power supply (UPS) systems and battery energy storage systems (BESS) (Department for Business and Trade, 2023; United Nations Conference on Trade and Development, 2025). Other emerging chemistries, such as sodium-ion and antimony-based batteries, are gaining attention for stationary applications where weight and energy density are less critical (United Nations Conference on Trade and Development, 2025). Sodium-ion batteries offer cost advantages and improved thermal stability compared to lithium-ion, reducing reliance on lithium and cobalt; two minerals with highly concentrated supply chains (United Nations Conference on Trade and Development, 2025). Antimony-based batteries are still at the research stage but promise high volumetric energy density and long cycle life, positioning them as candidates for grid-scale storage (United Nations Conference on Trade and Development, 2025). Sodium-ion systems require abundant sodium but also depend on graphite for anodes (Department for Business and Trade, 2023; United Nations Conference on Trade and Development, 2025). Both technologies could alleviate pressure on lithium and cobalt markets but may create fresh vulnerabilities in antimony and graphite supply chains (Lazenby, 2025; Mudd et al., 2024b). As data centres scale to meet AI-driven demand, securing sustainable sources of these critical minerals and developing recycling pathways will be essential to ensure resilience and compliance with UK net-zero strategies ((Department for Energy, Security and Net Zero, 2024a).

Table 5. Summary of elements required for onsite backup power technologies, including batteries, proton exchange membranes (PEM), hydrogen fuel cells, and solid oxide fuel cells (SOFC) (Eikeng et al., 2024; United Nations Conference on Trade and Development, 2025).

Sodium-ion batteries	Antimony-based batteries	Lithium-ion batteries	PEM fuel cells	SOFC fuel cells
Sodium (Na) Graphite Iron (Fe) Manganese (Mn)	Antimony (Sb) Copper (Cu) Electrolyte salts (fluorides, sulphates)	Lithium (Li) Cobalt (Co) Nickel (Ni) Graphite Electrolyte salts ($LiPF_6$)	Platinum (Pt) Iridium (Ir) Fluropolymers	Nickel (Ni) Yttria-stabilised zirconia Cobalt (Co) Lanthanum (La) Other rare earth elements (REE)

2.5.2 Data centre water requirements and demand

Traditionally, large data centres have relied on chilled water systems for cooling, which can place significant pressure on local water resources. The International Energy Agency (IEA) estimate that global water consumption for data centres is currently at 560 billion litres per year, potentially rising to 1200 billion litres per year by 2030, creating a strategic challenge for national water planning (International Energy Agency, 2025c). The UK is projected to face water deficits of 5 billion litres per day by 2050 (Environment Agency, 2024).

The UK's National Framework for Water Resources and Regional Water Resource Management Plans do not currently fully account for future demand for water from digital infrastructure (Environment Agency, 2025). Data centres constructed in London and South West regions of England could significantly increase water demand in areas that are already water stressed (Environment Agency, 2021). Both the UK Government and industry agree that as AI growth accelerates, proactive measures are required to manage the risks surrounding water demand, such as mandatory water reporting, digital monitoring, and investment in resilient water infrastructure (Kenny, 2025; TechUK, 2025; Thames Water, 2024).

Future water demand risks are considered to be manageable. However, water companies are not required to provide water for non-domestic purposes if it is uneconomical or creates a risk to domestic supply. They retain the right to refuse supply to inefficient non-household users. Thames Water plans infrastructure to a mid-range data centre demand scenario and Anglian Water are calling for non-potable water to be used for industrial purposes (Thames Water, 2024; Anglian Water, 2025). Additionally, advanced cooling technologies are being increasingly adopted by data centres. These technologies include direct-to-chip liquid cooling, immersion cooling, and hybrid systems that combine air and liquid cooling. These technologies allow higher operating temperatures, reduce water use, and enable heat reuse. Operators are also exploring alternative water sources, such as rainwater harvesting and treated effluent, alongside non-potable supply options where feasible (Data Centre Alliance, 2025).

Collaboration between TechUK and the Environment Agency surveyed 73 data centre facilities and found that UK data centres already have a relatively low water footprint (TechUK, 2025). This report indicates that 51 per cent of facilities use waterless cooling systems, either air or refrigerant-based, and 64 per cent of facilities consume less than 10 million litres of water annually. Water use was either measured or closed-loop systems were used by 89 per cent of facilities, minimising consumption of water (TechUK, 2025). Despite indicating that the water demand risk is manageable, TechUK also recommends that the construction of new reservoirs be fast tracked, that an exploitation index be published for all major river basins, and that data centre operators should commit to measuring and reporting water usage (TechUK, 2025).

2.6 ARTIFICIAL INTELLIGENCE AND DATA CENTRE SUMMARY

The UK's rapid emergence as a global hub for AI-driven data centres presents both major opportunities and critical challenges. Government initiatives such as AI Growth Zones and the designation of data centres as critical national infrastructure have attracted significant investment (Department for Science Innovation and Technology, 2025c). This has positioned the UK as a leader in semiconductor design for a growing network of data centre operators and supporting industries.

However, data centre expansion will drive electricity demand, placing unprecedented pressure on grid capacity, backup power systems, and water resources (Kenny, 2025; National Energy System Operator, 2025). Whilst many UK facilities use waterless or closed-loop cooling, hyperscale sites that rely on chilled water systems could exacerbate stress in water-scarce regions (TechUK, 2025). Current planning frameworks, such as the National Framework for Water Resources and Regional Water Resource Management Plans, do not fully account for this risk, making proactive measures essential (Environment Agency, 2025).

Traditional backup energy solutions, such as diesel generators and lithium-ion batteries are being supplemented by hydrogen fuel cells, dual-fuel engines, and emerging battery chemistries (United Nations Conference on Trade and Development, 2025). Each technology requires a distinct set of raw materials, many of which have been designated as critical by the UK Government and are challenged by concentrated global supply chains and high geopolitical risk (Mudd et al., 2024a).

The manufacture of data centre components requires a wide variety of raw materials, the greatest array of which can be found within servers and memory drives. Demand for some elements, such as copper, silicon, and rare earth elements, is only expected to increase by 2 per cent of current demand by 2030, whilst demand for other elements, such as gallium, is expected to increase by up to 11 per cent of today's total supply (International Energy Agency, 2025c). Many of the elements required to manufacture data centre components are produced as by-products, have relatively juvenile supply chains, or have highly concentrated supply chains, making their supply vulnerable to geopolitical disruptions and trade issues (Mudd et al., 2024a). The future data centre raw material demand will also have to compete with the critical mineral needs of other sectors, such as defence and clean energy manufacturing.

3 Quantum computing: key technologies and material requirements

Quantum computers take advantage of four key principles of quantum mechanics (superposition, entanglement, decoherence, and interference) to operate mathematical techniques that cannot be undertaken by classical computers (IBM, 2023). Classical computers store information as bits, which are programmed to be either 0 or 1, whereas quantum computers use quantum bits (qubits) as their basic unit of information (de Leon et al., 2021). These qubits have the ability to be in an infinite number of states at the same time (IBM, 2023), leading to an information storage capacity exponentially greater than that of classical computers (de Leon et al., 2021). This capacity allows quantum computers to solve problems faster and undertake calculations not possible for classic computers (Wintersperger et al., 2023). The removal of binary limitations provides a much more accurate reflection of reality and natural systems, leading quantum computing to be particularly adept at addressing simulation, optimisation, and algebraic problems (IBM, 2023). Unlike classic computers, which typically provide a single answer to a problem, quantum computers are capable of providing a series of potential solutions (IBM, 2023).

3.1 KEY QUANTUM COMPUTING TECHNOLOGIES

There are many different quantum computer technology designs and approaches, building on varying mechanical principles, and relying on different materials to form and control qubits. This report does not aim to indicate which of these technologies may have greater chances of success or potential to be adopted in the future. Its aim is to provide an overview of the technologies and their material requirements.

There are seven main quantum computing principles and technologies, called quantum computing modalities:

1. **Superconducting qubits:** this technology uses superconducting resonant circuits, which leverage semiconductor nanofabrication techniques common to classic high-speed integrated circuits to build qubits within the energy states of a Josephson junction (de Leon et al., 2021; Ladd et al., 2010; Wintersperger et al., 2023). These junctions consist of a thin subcomponent barrier of layered aluminium and aluminium oxide, with insulating electrical properties, and another subcomponent what capitalises on the superconducting properties of aluminium, niobium, or tantalum compounds, such as niobium nitride (Ladd et al., 2010; Wintersperger et al., 2023). Superconducting qubits must operate at extremely low temperatures, requiring a dilution fridge to reach temperatures of 10 millikelvins (approximately -273°C), to maintain qubit stability and reduce errors (Ladd et al., 2010; Wintersperger et al., 2023). However, they still face challenges such as short lifetimes (Wintersperger et al., 2023) and interference from magnetic fluctuations (de Leon et al., 2021). An alternative approach uses the spin of electrons or nuclei in materials like silicon, but it is unclear whether this method can be scaled up effectively.

2. **Quantum dots:** create and store qubits in solid-state layered semiconductors, called heterostructures, which are manufactured by nanofabrication methods in Tier 1 (industry leading) fabrication centres, by controlling the spin states of electrons at a particular energy level (de Leon et al., 2021; Ladd et al., 2010). Electrostatic quantum dots are controlled electronically and created by applying voltages to metallic gates which operate at low temperatures of less than 1 kelvin (less than -272 °C), therefore requiring a dilution fridge. Self-assembled quantum dots are impurities created during random semiconductor growth processes and operate at higher temperatures of approximately 4 kelvin (-269 °C) and are

controlled optically (Ladd et al., 2010). The quantum state of electrons in superconducting qubits can be controlled through the generation of microwave, magnetic, and electric fields (Ladd et al., 2010).

3. **Trapped ion qubits:** information can be recorded in qubits created by the energy levels and spin states of ions, such as calcium, strontium, and ytterbium, trapped in a vacuum chamber using electric fields generated by electrodes (Ladd et al., 2010; Wintersperger et al., 2023). The quantum state of these ions can be manipulated using lasers, electromagnetic pulses of optical, microwave or radio frequency, or magnetic and electric fields (Ladd et al., 2010; Wintersperger et al., 2023). Qubits generated using this method are reliable and stable, having long coherence times (Ladd et al., 2010). However, levels of noise increase at higher temperatures, therefore the vacuum system is operated at room temperature or as low as 4 kelvin (de Leon et al., 2021).

4. **Neutral atoms:** this technology creates qubits using a similar method to trapped ions but uses a series of crossing laser beams in a vacuum chamber to create an optical lattice trap that acts like optical tweezers and can hold up to 10^3 to 10^6 atoms (Evered et al., 2023; Ladd et al., 2010). The quantum states of these atoms are then manipulated by optical light, microwave pulses, or magnetic and electric fields (Wintersperger et al., 2023) to elevate atoms to very high energy levels, called a Rydberg state, to create qubits with long coherence times (Evered et al., 2023; Wintersperger et al., 2023).

5. **Colour/vacancy centres:** qubits of energy are encoded into the electron orbitals and spin states of atom impurities within a solid host crystal (de Leon et al., 2021). These qubits can be controlled by lasers and through the generation of optical light, microwave pulses, or magnetic and electric fields at room temperature (de Leon et al., 2021; Wintersperger et al., 2023). The most commonly used system is the nitrogen vacancy centre within diamonds, within which qubits are able to maintain coherence for several milliseconds at room temperature. This increases considerably when using a synthesised ultra-high isotopically pure diamond (de Leon et al., 2021; Ladd et al., 2010). Other systems are under exploration, including the nitrogen and vanadium vacancy in silicon carbide (SiC), the T centre in silica, and rare earth element ions in solid-state crystals (de Leon et al., 2021).

6. **Photons:** quantum information is carried by photons of light, which can travel through space or optical fibres. As such, they are not susceptible to the stability issues surrounding decoherence seen within solid-state quantum technologies, such as interaction with other atoms, vibration, and electromagnetic noise. The main challenge associated with this technology is getting photons to interact with each other for quantum operations (Ladd et al., 2010; Wintersperger et al., 2023). Researchers have developed methods using mirrors, lenses, and beam splitters to process quantum information. One such approach is the Knill-Laflamme-Milburn scheme which has demonstrated that simple quantum algorithms are possible using only single photon sources and detectors. Silicon detectors, which use silicon nitride, are able to operate at room temperature with 70 per cent efficiency, whereas niobium nitride superconducting nanowire detectors are much faster, have achieved higher efficiency, and better resolution, but require cryogenic cooling (Ladd et al., 2010). Another electro-optical material that shows potential is barium titanate (Freedberg Jr, 2025; In Kim et al., 2025). Photon technology shows good potential at larger scales and could be used as a form of communication between qubits within solid-state technologies, although photon loss is still a challenge (Ladd et al., 2010).

7. **Topological qubits:** this technology is currently theoretical and is seen as a possible future method for creating a quantum computer that has the ability to tolerate faults. The concept involves storing information in special quantum states whose properties depend on how certain particles are arranged and move around each other, rather than on any single particle. Whether this could be achieved is still heavily debated but could involve the braiding of topological insulators and quantum processors in a way that prevents qubit

decoherence. Most research to date has focused on using superconducting interfaces, devices, or nanowires as those quantum processors and as such has many commonalities with the superconducting method described above (de Leon et al., 2021).

Recent uptake and adaptation of AI to a range of applications is driving the research and development of quantum computers (IBM, 2023). Quantum computing is still within the early stages of development, however, the basis and components for this digital sector is emerging, with commercial products now available (IBM, 2023; Wintersperger et al., 2023).

The UK National Quantum Technologies Programme (NQTP) is a £1 billion investment aiming to bring together industry, academic, and government stakeholders in collaboration to evolve the UK into a ‘quantum-enabled economy’. The programme aims to facilitate ideas, innovation, and investment relating to quantum technologies to ensure that the UK capitalises upon opportunities to become a centre of excellence, attracts and trains skilled professionals, and becomes a preferred location for the quantum sector (UK Research and Innovation, 2026). The UK’s National Quantum Computing Centre (NQCC) is a research institution funded by UKRI under this programme and has invested £30 million into the building of seven prototype quantum computers or testbeds at their Harwell Campus in Oxfordshire. The aim of these testbeds is to exhibit and demonstrate the capabilities of various quantum technologies to enable evaluation, validation, and benchmarking which will provide guidance for the suitability of these technologies for different applications (Department for Science Innovation and Technology and Griffith, 2024). Building a community and partnerships focused around the centre will enable the identification of and potential solutions for a range of challenges that may prevent the progression of quantum technologies, safety protocols, and security requirements (Infleqtion, 2024; National Quantum Computing Centre, 2024). Hosting these testbeds at the Harwell Campus will support the UK’s capabilities and infrastructure for quantum computers, whilst aiding in the development of domestic supply chains that will be required for manufacture of these technologies within the UK (NQCC, 2024). Quantum computer testbed projects to be hosted by the NQCC at the Harwell Campus are summarised in Table 7.

Table 6. Details of the seven quantum computer testbeds that are being / have been built during 2025 at the National Quantum Computing Centre (NQCC) in Oxfordshire (Department for Science Innovation and Technology and Griffith, 2024).

Testbed	Company	Technology	Details	Citation
ARTEMIS	Aegiq	Photonic	Integration of compound-semiconductor single photon sources with silicon-photonics processing	Harold (2025)
SQALE	Infleqtion	Neutral atom	Largest neutral atom array in the UK with 256 qubits	Infleqtion (2024)
Asteroidea	Orca Computing	Photonic	Designed for machine learning using hybrid quantum / classic neural networks and photonic quantum processors	ORCA Computing (2024)
QUARTET	Oxford Ionics	Trapped ion	Partnered with Infineon Technologies to manufacture semiconductor chips with full connectivity between qubits	Oxford Ionics (2024)
Error-corrected neutral atom quantum computer	QuEra	Neutral atom	Contains qubit shuttling and error correction capabilities	QuEra (2024)
Silicon Cloverleaf	Quantum Motion	Spin qubit	Built using standard silicon CMOS chip fabrication processes	Quantum Motion (2025a)
Ankaa	Rigetti Computing	Superconducting	24-qubit quantum computer with associated software and algorithms	Rigetti Computing (2024)

3.2 APPLICATIONS

Quantum computers are not being designed to replace the classical computer, rather, they are a different type of computer aiming to solve particular types of problems within a variety of fields that are not possible for a classic computer, referred to as ‘quantum advantage’ (Bhat et al., 2022; Ladd et al., 2010; Wintersperger et al., 2023). Quantum computers have been identified as one of five critical technologies within the UK Science and Technology Framework that has the potential to improve the lives of UK citizens, grow the UK economy, and ensure security and future leadership in the technology for the UK (Department for Science Innovation and Technology, 2025d). In addition, quantum computers have been identified as one of six frontier technologies that is key to future growth and security, by the UK Industrial Strategy’s Digital and Technologies Sector Plan (Department for Business and Trade and Department for Science, 2025).The largest global technology companies, such as Google, IBM, Amazon, and Microsoft, are already investing significant amounts of money into the research and development of quantum computers, with some countries already providing partial access for public and industry bodies (Rietsche et al., 2022).

Each quantum computing technology is likely to be best suited to tackling a specific complex application or problem type/domain (see Figure 3) and determining this suitability is one of the principal aims of the NQCC testbeds. The main problems to which quantum computers can potentially be applied include search and optimisation; algebraic, algorithm, or mathematical; simulation; machine learning; and cryptography (Bayerstadler et al., 2021; Rietsche et al., 2022).

Search and optimisation functions aim to find one or more optimised solutions from a large set of possible solutions to a complex problem which typically involves a large number of parameters, variables (Alexeev et al., 2021; Rietsche et al., 2022), optimised arrangements, or combinations of variables (Bhat et al., 2022). Optimisation problems occur in many areas and industries, including engineering, social sciences, natural sciences, production, and logistics (Alexeev et al., 2021; Bayerstadler et al., 2021). A classic example of this problem is that of the ‘travelling salesman’, which aims to identify the optimum and most efficient route between multiple points, such as routing of a delivery vehicle or network wire. The ‘knapsack problem’ identifies the optimum packing of items to minimise volume and weight, such as truck or airplane loading (Alexeev et al., 2021; Bayerstadler et al., 2021). Quantum software developed by Infleqtion is already being applied to the optimisation of traffic management by the Oxfordshire County Council (Infleqtion, 2024). Optimisation is also a key aspect of production efficiency, quality assurance, management of supply chains, and reduction of emissions (Bayerstadler et al., 2021). Tackling optimisation challenges is also highly pertinent to the finance industry, where quantum computing may be applied to such tasks as pricing, risk analysis, credit scoring and portfolio optimisation, and is already being addressed by such companies as Cogniframe and Multiverse Computing (Bova et al., 2021; Flöther, 2023).

Mathematical or algorithmic applications are most useful for machine learning and AI, allowing complex data to be processed (Flöther, 2023). Mathematical problems may involve complex algebraic calculations and transformations that are required for AI and machine learning applications (Rietsche et al., 2022), such as identification of objects in images or finding patterns in text. Models are simplified versions of a complex reality and require mathematical formulations to determine interactions between variables and predictions of future behaviour (Bayerstadler et al., 2021). An algorithm consists of a sequence of instructions that allow a computer to provide a solution to a mathematical problem (Bayerstadler et al., 2021; Rietsche et al., 2022), often undertaking large-scale combining of a large number of variables (Bova et al., 2021). Quantum algorithms are more efficient, designed to form a solution to a problem in fewer steps, and are much quicker than an algorithm on a classic computer (Bova et al., 2021; Rietsche et al., 2022). The three dominant quantum algorithms include:

- **Gower’s algorithm:** used to search a database or list that has not been ordered.
- **Shor’s algorithm:** able to factorise integer numbers at an exponentially faster rate than classic computers.
- **Harrow Hassidim Lloyd algorithm:** able to predict the solution to a linear system of equations (Rietsche et al., 2022).

Algorithms are also a key tool in quantum machine learning, one of the most researched fields relating to quantum computers (Wintersperger et al., 2023). Machine learning involves a computer being trained with diverse and real-world datasets to undertake a wide variety of tasks across many industrial sectors, such as engineering and design, and production and logistics (Bayerstadler et al., 2021). Within the medical industry, machine learning has been applied to the generation of new drug molecules, diagnosis based on image classification, and forecasting the effectiveness of treatment (Flöther, 2023). Machine learning has been applied to language processing (Bayerstadler et al., 2021) and the modelling of new molecules and molecular structures, including the creation of new proteins, a technique highly applicable to chemical and pharmaceutical industries (Alexeev et al., 2021; Bova et al., 2021). The company AIRBUS is already utilising quantum-based machine learning to solve partial differential equations within the engineering and design industry. Whereas Siemens is using quantum-assisted reinforcement learning within their production and logistics (Bayerstadler et al., 2021).

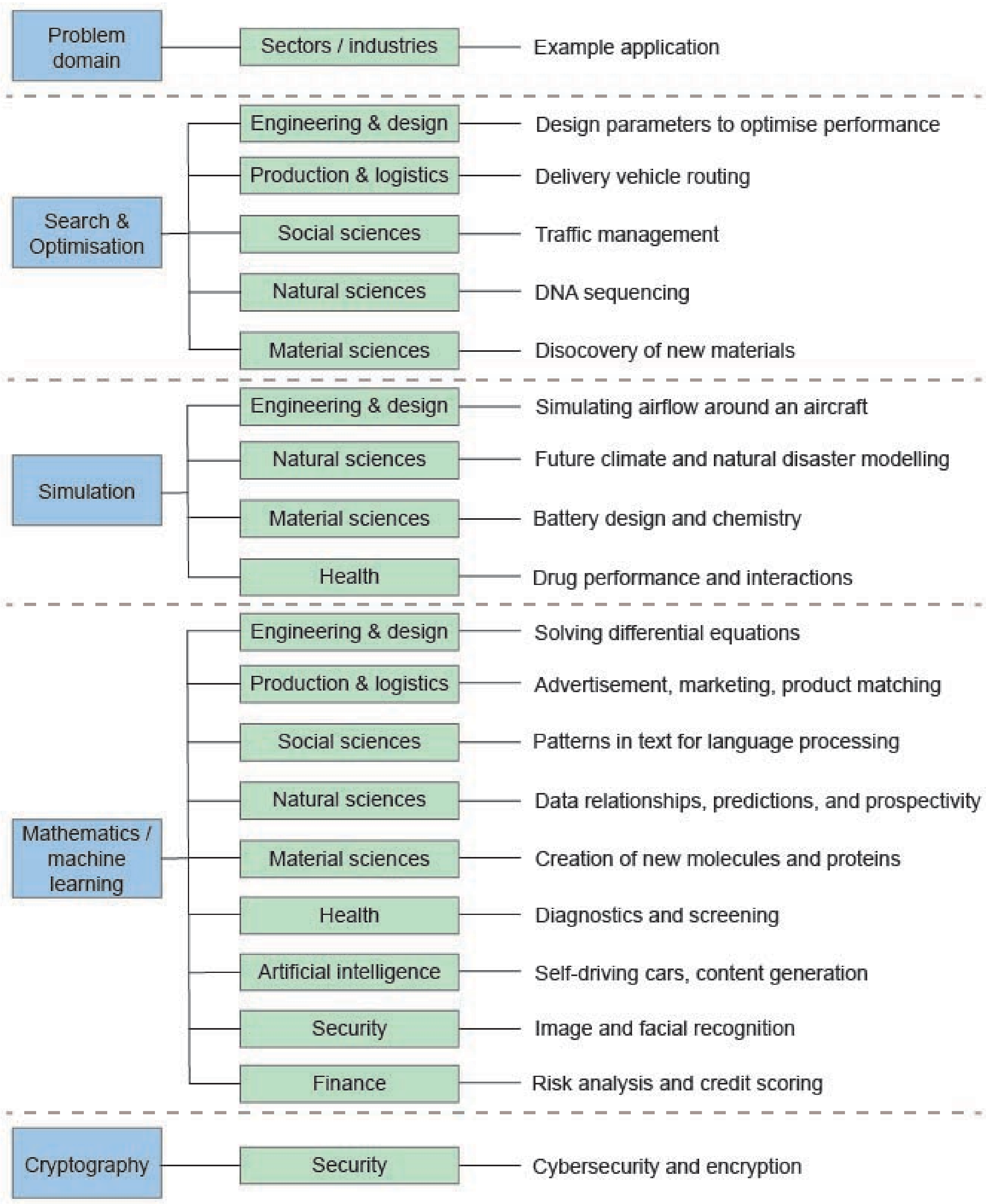


Figure 3. Summary of potential example applications and industries for quantum computers within each problem domain. Key for categories is provided at the top of the figure. BGS © UKRI 2026.

One of the fastest growing sectors for quantum algorithm use is cybersecurity or ‘cryptography’, a practice primarily focused on secure communication and long-term data protection (Bayerstadler et al., 2021). Modern cryptography relies on coding and combinatorics (Bova et al., 2021), a technique reliant on the arrangement and counting of discrete objects. Quantum computer algorithms, such as Shor’s and Grover’s algorithms, would cause many modern encryption methods to be compromised and obsolete, leading to the potential for communications to become vulnerable and creating a large-scale threat (Bova et al., 2021; Flöther, 2023). This is of particular concern for medical data and records, which have a long sensitivity time (Flöther, 2023). As such, quantum-resistant algorithms, quantum safe solutions, and standards are already being developed, with hardware and software solutions already being offered by companies such as KETS Quantum Security and Evolution (Bova et al., 2021; Flöther, 2023; Sepúlveda et al., 2024; Westminster eForum, 2025). PQ Shield has set an internal five to ten year development and deployment timeline for its quantum-safe cryptography solutions (Westminster eForum, 2025).

The last key problem domain for which quantum computing holds high potential is simulation; the modelling or calculation of how a system changes or behaves during the manipulation of key variables (Rietsche et al., 2022). The removal of binary limitations provides a much more accurate reflection of reality and natural systems, leading quantum computing to be particularly adept at addressing simulation and modelling exercises (IBM, 2023). Quantum computers are proficient at simulating systems that follow the laws of quantum mechanics and static and dynamic behaviours, such as molecules, magnetism, high-energy physics, and astrophysics, that are impossible to simulate using classic computers (Alexeev et al., 2021; Rietsche et al., 2022). As such, quantum computing is promising to the real-world applications of realistic molecular dynamics and material simulation in the fields of material science (Ma et al., 2020). Simulations are key tools within engineering and design, often used to simulate the behaviour and interaction of products with complex processes, such as simulating airflow around an aircraft, thereby reducing the need for and number of physical prototypes and real-world trials (Bayerstadler et al., 2021).

Quantum simulation is already being utilised by a wide array of companies in various sectors. AIRBUS is using simulations to model fluid dynamics, Merck to identify parameters that can control the spread of disease and the development of new drugs and their potential interactions, and Boehringer simulate molecular dynamics within the material science sector (Bayerstadler et al., 2021; Peelam et al., 2024). Areas of potential future simulation include battery design and material requirements, and development of more efficient catalysts, such as those required for the synthesis of ammonia during the Haber-Bosch process, important for producing nitrogen fertilisers. This is an industry that currently consumes 1 to 2 per cent of global energy (Rietsche et al., 2022), therefore simulations such as these have the potential to contribute to net zero targets.

3.3 MATERIAL REQUIREMENTS

A wide range of different raw materials and compounds are required to produce the array of components needed in the different quantum computer technologies. The materials that are selected for a given function in each component are typically chosen based on specific requirements related to particular properties, heterogeneity, impurities, and advantageous defects (de Leon et al., 2021). Many pilot components experience problems when scaled up that were not evident during initial development at a smaller scale. Problems can be caused by quantum states and qubits decaying and becoming incoherent (decoherence). Decoherence, which can be caused by material challenges, such as point defects, grain boundaries, interface, and contamination occurs more rapidly once scaled up (de Leon et al., 2021; Scappucci et al., 2021). Qubit decoherence is one of the major challenges that is slowing the advancement of quantum computing technologies, requiring computer operations or tasks to be completed before qubits lose coherence. One way this can be achieved is by using topological materials, usually comprising one or more heavy elements, to carefully control conduction and thereby delay decoherence and protect qubits (Scappucci et al., 2021).

The elements required for the main quantum computer technologies outlined in Section 3.1 are summarised in Table 8. A full outline of element and material requirements with specific compound, purity and isotopic detail; reasons for choice; and technology readiness levels are provided in Table 24 (Appendix 2). This is not an exhaustive list as many components and comprising materials are company proprietary information and, as such, are not publicly available. The information presented in this section is therefore predominantly based on a review of the scientific literature. Much more information was available on superconducting qubits, quantum dots, and topological qubits. In contrast, only limited information was found for neutral atoms, colour/vacancy centres, and photon technologies (Table 8). Many of the elements indicated for each component are also alternatives based on material or element properties.

This study highlights the element and material requirements of quantum computer components and does not consider the materials and components relating to any classical computer or telecommunications electronics to which the quantum computer is connected. The material requirements and supply chains for these classic computers are already well known and well established. Information relating to the material requirements of servers, networking, memory and storage, network, structure, power, and cooling associated with quantum computers can be found in Section 2.3 and UK supply chains in Section 2.4.

Table 7. Summary of material requirements for components of quantum computer technologies. Sourced from: Ma et al. (2020), Yang et al. (2020), Yang et al. (2021), de Leon et al. (2021), Lordi and Nichol (2021), Scappucci et al. (2021), Wintersperger et al. (2023), Bluvstein et al. (2024), Infleqtion (2025c), Infleqtion (2025b), Lee (2024a), Lee (2024b), Rigetti Computing (2025), Trento (2025), Burnett oral communication (15/12/2025), and Clark oral communication (15/01/2026).

Quantum technology	Component	Material requirements
Superconducting qubits	Josephson Junction	Aluminium (Al), barium (Ba), bismuth (Bi), calcium (Ca), copper (Cu), indium (In), magnesium (Mg), niobium (Nb), oxygen (O), strontium (Sr), tin (Sn), tantalum (Ta), tellurium (Te), titanium (Ti), yttrium (Y)
	Signal traces	Aluminium (Al), indium (In), lead (Pb), niobium (Nb), nitrogen (N), tantalum (Ta), titanium (Ti)
	Memory	Aluminium (Al), niobium (Nb)
	Detectors and sensors	Aluminium (Al), arsenic (As), boron (B), gallium (Ga), germanium (Ge), gold (Au), indium (In), magnesium (Mg), molybdenum (Mo), niobium (Nb), nitrogen (N), phosphorous (P), rhenium (Re), silicon (Si), tantalum (Ta), titanium (Ti), tungsten (W)
	Tunnel barriers	Aluminium (Al), cadmium (Cd), tellurium (Te)
	Substrate	Niobium (Nb), nitrogen (N), sapphire, silicon (Si), tantalum (Ta)
	Capacitors	Tantalum (Ta)
	Cooling	Copper, (Cu), helium (He), oxygen (O), ruthenium (Ru), silver (Ag)
Quantum dots	Quantum cores	Aluminium (Al), caesium (Cs), rubidium (Rb), sapphire, titanium (Ti)

	Heterostructures	Aluminium (Al), arsenic (As), barium (Ba), beryllium (Be), gallium (Ga), germanium (Ge), hydrogen (H), silicon (Si)
	Host	Carbon (C), germanium (Ge), silicon (Si)
	Semiconductors	Aluminium (Al), antimony (Sb), arsenic (As), cadmium (Cd), carbon (C), gallium (Ga), indium (In), mercury (Hg), nitrogen (N), oxygen (O), silicon (Si), tellurium (Te)
	Qubits	Antimony (Sb), arsenic (As), indium (In), silicon (Si)
	Cooling	Copper, (Cu), helium (He), oxygen (O), ruthenium (Ru), silver (Ag)
Trapped ion qubits	Trap	Calcium (Ca), magnesium (Mg), strontium (Sr), ytterbium (Yb)
	Electrodes	Aluminium (Al), argon (Ar), copper (Cu), gold (Au)
	Substrate	Aluminium (Al), diamond (C), oxygen (O), quartz (Si), sapphire, silicon (Si)
	Semiconductors	Ytterbium (Yb)
Neutral atoms	Qubits	Caesium (Cs), rubidium (Rb), strontium (Sr)
Colour/vacancy centres	Host	Carbon (C), diamonds (C), rare earth elements (REE), silicon (Si)
	Surface terminations	Fluorine (F), nitrogen (N), oxygen (O)
Photons	Photons	Nitrogen (N), Silicon (Si)
	Laser crystals	Barium (Ba), erbium (Er), europium (Eu), gallium (Ga), germanium (Ge), lithium (Li), niobium (Nb), praseodymium (Pr), selenium (Se), silver (Ag), sulphur (S)
Topological qubits	Superconductors and semiconductors	Aluminium (Al), antimony (Sb), arsenic (As), bismuth (Bi), cerium (Ce), chromium (Cr), copper (Cu), fluorine (F), gallium (Ga), germanium (Ge), indium (In), iron (Fe), lead (Pb), mercury (Hg), niobium (Nb), nitrogen (N), oxygen (O), selenium (Se), silicon (Si), tellurium (Te), tin (Sn), titanium (Ti)
	Nanowires	Aluminium (Al), antimony (Sb), arsenic (As), germanium (Ge), gold (Au), indium (In), oxygen (O), silicon (Si)
	Substrate	Arsenic (As), gallium (Ga), indium (In), phosphorous (P), sapphire, silicon (Si)
	Catalyst	Gold (Au)
	Insulator	Aluminium (Al), antimony (Sb), arsenic (As), bismuth (Bi), cadmium (Cd), calcium (Ca), chromium (Cr), cobalt (Co), europium (Eu), germanium (Ge), hafnium (Hf), indium (In), iridium (Ir), lanthanum (La), lead (Pb), manganese (Mn), mercury (Hg), molybdenum (Mo), niobium (Nb), oxygen (O), phosphorous (P), platinum (Pt), selenium (Se), sodium (Na), strontium (Sr), sulphur (S), tantalum (Ta) tellurium (Te), tin (Sn), vanadium (V), zirconium (Zr)
	Heterostructures	Aluminium (Al), arsenic (As), gallium (Ga)

3.3.1 Aluminium

Many of the elements required for quantum technologies are also common to data centres (see Figure 4). Aluminium is a very common element found in numerous components of the quantum technologies detailed in Table 8. Due to the thermal properties of aluminium, it can be used with alternating layers of aluminium and aluminium oxide to create a thin insulating thermal barrier within the Josephson Junction Boxes and tunnel barriers of superconducting qubit quantum computers (de Leon et al., 2021; Lee, 2024a; Trento, 2025). Aluminium is also a superconducting material that is simple and predictable to work with and is therefore utilised in topological quantum computers and quantum processor chips (de Leon et al., 2021; Rigetti Computing, 2025; Trento, 2025).

Compounds of aluminium also make very good substrates. Aluminium oxide (Al_2O_3) is used as a substrate within trapped ion technologies, due to its high thermal conductivity, which prevents heating of the chip (de Leon et al., 2021). This same compound is also used in the form of sapphire as a substrate material for superconducting qubits, trapped ion, and topological quantum computers due to its high thermal conductivity, inert nature, and ability to store an electric field, leading to long qubit coherence times (de Leon et al., 2021; Scappucci et al., 2021).

3.3.2 Niobium

Another element that is prolific in many quantum technology components is niobium. The high critical temperature of niobium makes it an ideal element to manufacture insulators for superconducting qubits and superconductors within topological quantum computers (de Leon et al., 2021; Trento, 2025). Niobium is typically combined as compounds, such as NbTiN, $NbSe_2$, NbP, NbRe, and NbSi (de Leon et al., 2021; Lee, 2024b; Scappucci et al., 2021). Josephson junction boxes manufactured with niobium have also been found to have qubits with longer coherence times, due to having higher critical temperatures and being able to withstand higher magnetic fields (de Leon et al., 2021; Lee, 2024b; Scappucci et al., 2021).

3.3.3 Silicon

The use of silicon in quantum computers is ubiquitous across all technologies, except neutral atom (Table 8). The thermal properties of silicon allow silicon-based qubits to operate at higher temperatures (de Leon et al., 2021; Scappucci et al., 2021). The high thermal conductivity of silicon also makes it an ideal element to comprise host or substrate materials in colour centres, trapped ion, quantum dot, and topological quantum computer technologies (de Leon et al., 2021; Lordi and Nichol, 2021; Scappucci et al., 2021). The other main use for silicon is within semiconductors of quantum dots and topological quantum computers (Lee, 2024b; Rigetti Computing, 2025). Although there are better alternatives to silicon-based platforms for many quantum applications, once these technologies are set up and calibrated to silicon, it is hard to pivot the overall manufacturing process and to implement other materials, even despite their more advantageous functional properties (Kazakova oral communications, 03/02/2026).

3.3.4 Trace elements

Quantum computer components require many trace elements in varying quantities. For example, caesium, rubidium, strontium, ytterbium, calcium, and barium, form the basis of both neutral atom and trapped ion quantum modalities (Burnett oral communication, 15/12/2025). The isotope rubidium-87 is used by neutral atom computers within entangling gates, gates that allow qubits to interact and causing the states to become linked or entangled, to create long-lived qubits (Evered, 2023). Arrays of rubidium-87 are also used as optical tweezers to trap ions, such as caesium-133 to form qubits (Wintersperger et al., 2023; Bluvstein et al., 2024). Indium is used to form semiconductors for topological and quantum dot technologies, producing materials such as InAs, InSb and InGaAs (de Leon et al., 2021; Lee, 2024b). Indium is also used to form insulators within topological quantum computers, including In_2Se_3 and $(In,Bi)_2Se_3$ (Scappucci et al., 2021).

Gallium is often used as GaAs compounds to form heterostructures within semiconductor and topological quantum computers due to the high mobility of electrons within the compound (de Leon et al., 2021; Scappucci et al., 2021). Semiconductors within quantum dots and topological quantum computers often use gallium compounds, such as (Al)GaN and GaSb, due to their properties when an electric field is applied (Lee, 2024b; Yang et al., 2021). Technology based on GaN is being actively produced by Cambridge GaN Devices, a company based in the UK that indicates these technologies are more efficient, have a greater power density, and are more compact than similar silicon-based devices (Cambridge GaN Devices, 2026).

Various molybdenum compounds, such as MoSi, MoGe, and MoRe, are used to form superconducting nanowires within superconducting technologies due to their high efficiency (Lee, 2024b). In contrast the bismuth compound, BiSrCaCuO, is used to form qubits within superconducting quantum computers as it is a high temperature superconductor, able to retain its superconducting properties at temperatures much higher than conventional superconductors. These higher temperatures can be obtained by using liquid nitrogen, which is much more cost-effective than liquid helium (Trento, 2025). Any quantum technology that operates below a temperature of 1 kelvin requires cryogenic cooling and the use of a dilution fridge, which utilises helium-3 and helium-4 isotopes, for which there are currently no alternatives (White and Meeson, 2002; Burnett oral communication, 15/12/2025; Willis oral communication, 12/01/2026).

3.3.5 Other materials

Quantum computers are likely to be connected to external components and networks through fibre optics and will therefore need to be integrated with photonic circuits. These quantum networks are likely to require diamonds, silicon carbide (SiC), rare earth element crystals, III-V semiconductors, and non-linear optical crystals (Kazakova oral communications, 03/02/2026). Non-linear optical crystals are materials that exhibit a non-linear dielectric response to intense optical radiation. As the result, they alter the frequency, phase, or polarisation of intense laser light (Kazakova oral communications, 23/02/2026). These crystals are used in various fibre optic, integrated photonic, and quantum technologies to generate single particles of light, alter the properties of light, and manipulate quantum states (Clark oral communication, 15/01/2026). Non-linear materials are required for all quantum missions but are required in greater quantities for quantum networks, sensing and navigation (Kazakova oral communication, 03/02/2026). These crystals are a component of the lasers used in many different quantum technologies and are typically composed of lithium niobate or tantalate, potassium titanyl phosphate, or borate compounds (Paschotta, 2021; Xu, 2022). Alternative materials are currently being investigated. These include $AgGaS_2$ and $BaGa_2GeSe_6$ at the University of Bristol and REE ion doped crystals commonly used in quantum memories (Clark oral communication, 15/01/2026).

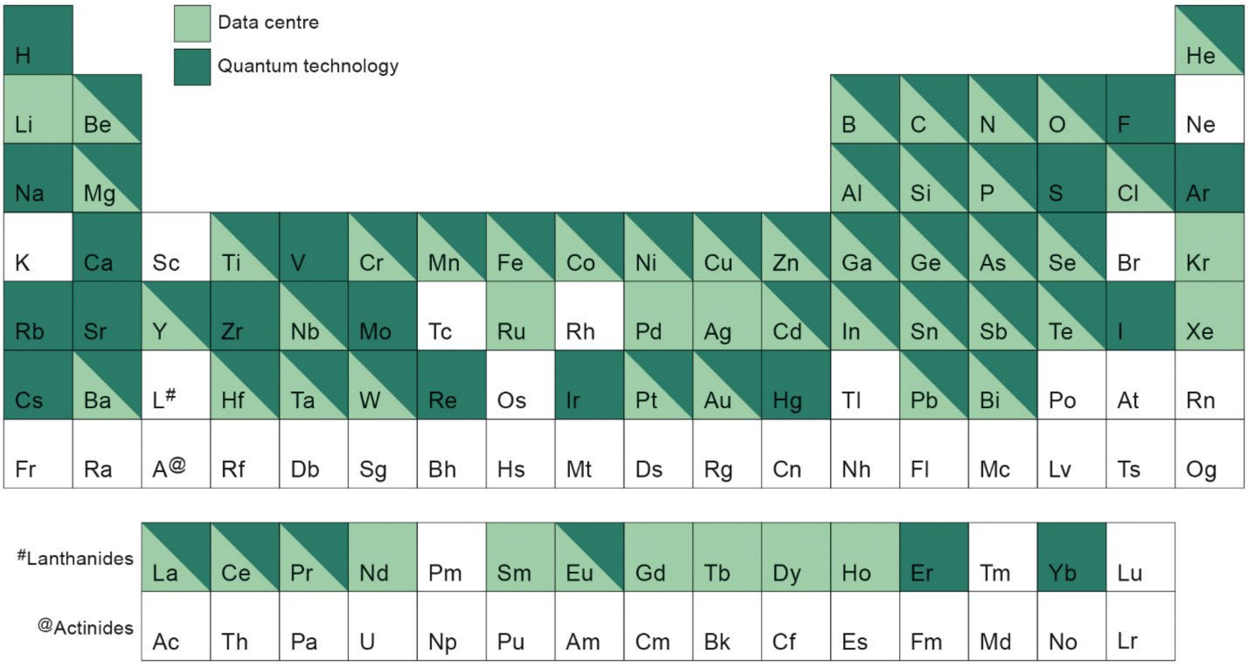


Figure 4. Summary and comparison of the elements required for the manufacture of data centre and quantum technologies. BGS © UKRI 2026.

3.4 QUANTUM COMPUTING SUPPLY CHAINS AND UK CAPABILITY

Quantum computing is currently a nascent industry with most material and component requirements originating from research laboratories. Experimental devices and prototypes only require a small quantity of most of the speciality trace elements indicated in Table 8 and Table 24. As a result, these experiments and systems can operate for multiple years and present low supply chain concerns (Burnett oral communication, 15/12/2025; Clark oral communication, 15/01/2026). Even small quantities of high purity isotopes required for quantum computers are associated with supply risk due to the small number of global suppliers and the geopolitics associated with some of these suppliers (Section 5). Other materials used in larger quantities, such as silicon, are not specific to quantum computers. As such, they already benefit from established supply chains for a range of technologies, such as classic computers and data centres. Each quantum technology or modality requires a different set of materials. Without knowing which of these modalities will be deployed or at what scale, it is hard to predict the future volumes of materials that may be required. Some countries, such as Finland and Australia are focusing on the development of a single modality, whereas the UK is investigating possibilities associated with all of them (Willis oral communication, 12/01/2026).

During the research phase of quantum computing, components were in a constant state of development. However, now that commercial products and pilot computers are available, components can no longer be adjusted and dedicated parts are required to ensure reproducibility and quality. These components are currently unique and made to order for each computer model. As a result, required volumes are low, engineering investment per part is high and established supply chains often do not exist outside of China (Geurtsen oral communication, 23/01/2026). The ordering of bespoke components does not guarantee reproducibility and creates a supply chain with higher risk (Burnett oral communication, 15/12/2025). Until this situation changes and demand for specialist materials and components increases, there will not be an investment case to build and diversify the supply chain, causing long lead times and high prices (Geurtsen oral communication, 23/01/2026).

Where unique components or materials with a specific property are not required, quantum computing does share raw material and component supply chains with other industries, such as semiconductors, photonics, and telecommunications (Burnett oral communication, 15/12/2025). Telecommunications components are cheap, available in large quantities, and easy to acquire but often do not match the needs of the quantum industry (Geurtsen oral communication, 23/01/2026). The vacuum chambers and technology required for quantum computers typically use non-bespoke, off the shelf, components and can therefore utilise the already well-established UK supply chain.

Cryogenics are required for any quantum modality that operates at low temperatures and is a sub-category that is shared with the medical and food processing industries, although, components are not as easily directly translated into quantum computing applications (Mol oral communication, 12/01/2026). The UK has world-leading cryogenic capabilities, with a supply chain that includes companies such as Oxford Instruments and ICEoxford (Mol oral communication, 30/01/2026). However, the main supply risk associated with cryogenics is the supply of helium-3 and helium-4 (Mol oral communication, 12/01/2026). The future demand for helium-3 is predicted to be much greater than current demand (Burnett oral communication, 15/12/2025), with no known alternatives available (Willis oral communication, 12/01/2026). System performance often suffers if lower purity helium-3 is used, therefore many manufacturers will only source and utilise high purity helium-3 (van der Poel oral communication, 13/02/2026). Global volumes of helium-3 are currently small, and companies must bid far in advance to secure the volumes they require, with the potential to limit production and research if volumes are underestimated (van der Poel oral communication, 13/02/2026).

Helium shortages have occurred repeatedly since 2006, with the most recent shortage in 2022 being exacerbated by a reduction in supply from Russia and a temporary shutdown in the US, combined with the war in Ukraine (Bains, 2025). The majority of supply is now being sourced from the USA (see Section 5.2.1.1), this may prove a challenge if future trade embargos or restrictions are placed on the export of helium-3 from the US (van der Poel oral communication, 13/02/2026). There are currently no domestic sources of helium-3 in the UK, however, the presence of nuclear reactors does pose an opportunity for the potential recovery of helium-3, which would provide a reliable domestic supply in addition to exporting into a high demand market (van der Poel oral communication, 13/02/2026).

Although helium-4 has a greater diversity of sources, prices have recently seen a large increase. Helium is typically vented from the system after use; however, this price increase has made it more sustainable to recapture the helium using closed cycle cryogenics, although many universities are not able to afford the initial investment to install such a system (Clark oral communication, 15/01/2026). The combination of high prices and supply risks have the potential to slow research, productivity, and deployment of technologies in the future (Clark oral communication, 15/01/2026).

The UK has a strong photonics research community, with capabilities surrounding design and intellectual property. However, the UK lacks significant manufacturing infrastructure and therefore much of the larger-scale applications are dependent on global supply chains and overseas manufacturing (Mol oral communication, 30/01/2026). While these global photonics supply chains are well-established, components are not always directly translatable to quantum computing (Mol oral communication, 12/01/2026). The sourcing of laser components is seen as the most concerning within the photonics supply chain. Material requirements and sector competition cause long lead times of three to six months on products from some EU companies (Weidner oral communication, 15/01/2026; Paul oral communication, 16/01/2026). These products typically contain non-linear crystals which are currently supplied by China (Clark oral communication, 15/01/2026). REE ion-doped crystals are used in quantum memories but also to amplify optical signals carrying internet traffic within fibre optic systems. Therefore, demand for these crystals will increase significantly if quantum internet is deployed and difficulties sourcing supply may lead to halting or delaying the implementation of such technology (Clark oral communication, 15/01/2026). Diamonds are used in both quantum sensors and memories and whilst the UK does have domestic commercial synthetic diamond production (Element Six, 2026), all subsequent manufacturing is undertaken abroad (Kazakova oral communication, 03/02/2026).

Both caesium and rubidium are required in very small quantities for neutral atom and trapped ion quantum technologies (Burnett oral communication, 15/12/2025). These elements are also required to produce precision atomic clocks, oscillators, cold atom sensors, gyroscopes, and accelerometers (Burnett oral communication, 15/12/2025; Paul oral communication, 16/01/2026). These components can then form part of the supply chain of other quantum computing modalities, beyond neutral atoms. Global demand for caesium and rubidium is very low, and little is known about their very juvenile supply chains. Most of the mines previously producing caesium shut during 2025, three of which were bought by Chinese companies. China is currently the only country actively mining, processing, and purifying caesium. Russia used to be the main supplier of purified rubidium before trade embargoes were put in place in 2022 following the war with Ukraine; there is now a global shortage of isotopically purified rubidium (Paul oral communication, 16/01/2026). China is now the dominate producer and refiner of rubidium (SFA (Oxford), 2025). Data centres and 6G telecommunications fibre exchanges typically use caesium or rubidium-based atomic clocks to avoid synchronisation issues during the transfer of data (Paul oral communication, 16/01/2026). Global demand for data centres is increasing dramatically and potential future upgrades to fibre exchanges in the UK could sharply increase the demand for caesium and rubidium. However, as there is currently no reliable or established supply chain for these elements it creates a significant supply risk. Competition between sectors for specialist materials or bespoke components, typically used only in low volumes, further constrains supply, contributing to delays and increased risk of supply disruption. When quantum computers are deployed in the future and market demand grows, sector competition will also increase. This typically creates opportunities for supply chain diversification, reducing identified risks and making it economically viable for new supplying companies to enter the market.

The UK has considerable expertise in some parts of the global quantum supply chain, including the manufacture of semiconductors, cryogenics, vacuum technology, and photonics (Mol oral communication, 12/01/2026; Willis oral communication, 12/01/2026). The UK semiconductor industry is discussed in Section 2.4.2, but there is also a well-established photonics research community in the UK. Several companies have been established as startup companies leading on from research developed at universities. Kelvin nanotechnology, for example, is a global supplier of advanced photonics and quantum computer components that has been established for over 20 years (Kelvin Nanotechnology, 2021; Burnett oral communication, 15/12/2025; Gwyn oral communication, 15/01/2026) and is affiliated with the University of Glasgow, where there is a strong research presence associated with photonics. Similarly, Covesion, a company associated with the University of Southampton, manufactures magnesium-doped, periodically poled, lithium niobate non-linear crystals that have applications within quantum computers, lasers, medicine, communications, and satellites (Covesion, 2026; Clark oral communication, 15/01/2026). Cornerstone is also affiliated with the University of Southampton, and the University of Glasgow has the James Watt Nanofabrication Facility. These facilities develop and manufacture silicon photonic components as well as bespoke components for applications within quantum computers, sensors, and LiDAR (Cornerstone, 2026; Clark oral communication, 15/01/2026). Although the UK has lost many of its clean rooms and fabrication facilities, smaller facilities have been developed over the past couple of decades that are more agile and able to adapt to bespoke requests, as well as new materials and processes. These facilities are likely to continue to grow as demand increases, investment continues, and infrastructure improves (Geurtsen oral communication, 23/01/2026).

The UK is not currently producing any of the raw materials required for quantum computing. However, the demonstration processing plant at the Trelavour hardrock lithium project in Cornwall was launched in 2024 to produce lithium hydroxide from mica within granite (Cornish

Lithium Ltd, 2026). In addition, this processing plant will produce samples of by-products, such as caesium and rubidium (Brinded, 2022), which are important elements for neutral atom and trapped ion quantum technologies, as well as atomic clocks. Following the successful demonstration of the processing plant, Cornish Lithium plans to build a full-scale processing and refining plant with the ability to produce up to 10 000 tonnes of lithium hydroxide monohydrate, with production expected to start in 2029 (Morgan, 2025).

The quantum community that has been developed in the UK has also been very successful, incorporating collaboration and communication between all parts of the supply and value chain. This integrated and collaborative approach has led to policy developments, quantum programmes, and research hubs that have expediated research and development and continued even as the sector has started commercialising (Geurtsen oral communication, 23/01/2026). A Critical Technologies Supercluster has been established in Scotland to address five key technologies, including photonics, quantum, semiconductors, sensing, and connectivity, rather than in isolation. This supercluster is an integration of industry, academia, and government, consisting of five universities, 41 photonics companies, 17 quantum computing companies, 36 semiconductor companies, 26 sensing and connectivity companies, and five fabrication facilities. The aim of the supercluster is to further research and collaboration, develop a skills base, and attract international talent that will be foundational to the future development of the sector, attract investment, encourage the establishment of more startup companies, and raise the profile of the UK as a competitor within the global technology market (Scotland's Critical Technologies Supercluster, 2025).

4 Global supply chains for selected materials

The manufacture of data centre components and quantum computers requires a wide range of raw materials, many of which are common across the technologies (Table 3, Figure 4). A high proportion of these raw materials have been designated as critical minerals by the UK Government (Mudd et al., 2024a), either produced as by-products of primary commodities or with very concentrated supply chains that increase the risk of supply disruption and vulnerability to political upheaval. This section presents an evaluation of the supply chains of three commodities (tellurium, bismuth, and hafnium) where potential supply risks have been identified.

4.1 TELLURIUM

4.1.1 Background and sources

Tellurium is a scarce element, having a very low crustal abundance of only 0.03 parts per million (ppm) (Hu and Gao, 2008). Tellurium-bearing minerals, known collectively as tellurides, have been identified in numerous gold- and silver-bearing ore deposits across the globe. For example, tellurium is recovered as a co-product during processing of ore at the Kankberg gold-silver deposit in Sweden. However, the overall concentration of tellurium in these deposit types is typically too low to be classed as economic (Goldfarb et al., 2017). Tellurium is found as an impurity in sulphide minerals in some base metal ore deposits, such as pyrite (iron sulphide), where it may reach concentrations up to a few hundred parts per million (Jonasson et al., 2020). There are examples of primary tellurium deposits; however, these are incredibly rare and are mostly located in China and Mexico (Jonasson et al., 2020; Willis et al., 2014). The general low abundance of tellurium in many ore deposits and the rarity of primary deposits, means that tellurium is not typically mined as a primary commodity but is dominantly produced as a by-product of processing base metal ores. Copper ores are a particularly important source of tellurium, accounting for approximately 90 per cent of global tellurium production, whilst the remaining 10 per cent is derived from the processing of lead ores and from recycling (US Geological Survey, 2025).

4.1.2 Extraction

Refined copper is commonly produced via one of two routes: (1) heap-leaching and solvent extraction or (2) smelting and electrolytic refining. The latter is the most important process for tellurium production. During electrolytic refining, impure copper anodes are immersed in a tank containing sulphuric acid. Copper is dissolved from the impure anode and deposited on the cathode as pure copper, whereas impurities are deposited in the bottom of the tank, forming a sludge known as anode slime (Nassar et al., 2022). It is possible to recover tellurium and other metals from the anode slimes by further processing. However, the amount of anode slime generated and the tellurium content of the slimes, can be highly variable. For example, Nassar et al. (2022) reported anode slime generation rates to be in the range of 0.7 to 23 kgs per tonne of copper cathode, with the average being in the range 5 to 5.3 kgs. The tellurium content ranges from 0.07 to 11 per cent, with the average being between 1.4 and 2.3 per cent.

Copper anode slimes typically contain small amounts of copper and other metals, including gold, silver, selenium, tellurium, and sometimes the platinum group metals (PGM). Therefore, the recovery of tellurium can be complex and may require several stages of processing (Figure 5), including pre-treatment to remove copper, roasting, or high-pressure alkaline oxidation of decopperised slimes and finally purification (Knockaert, 2011). Common intermediates include tellurium dioxide, copper telluride, and sodium tellurite. Electrolysis of sodium tellurite is used to produce tellurium cathodes, which are then melted to produce tellurium metal with a purity of approximately 99.9 per cent. To produce very high-purity tellurium (more than 99.99 per cent) further refining must take place, utilising processes such as vacuum distillation and zone refining, leading to purity grades in the range 99.99 to 99.9999 per cent (Knockaert, 2011).

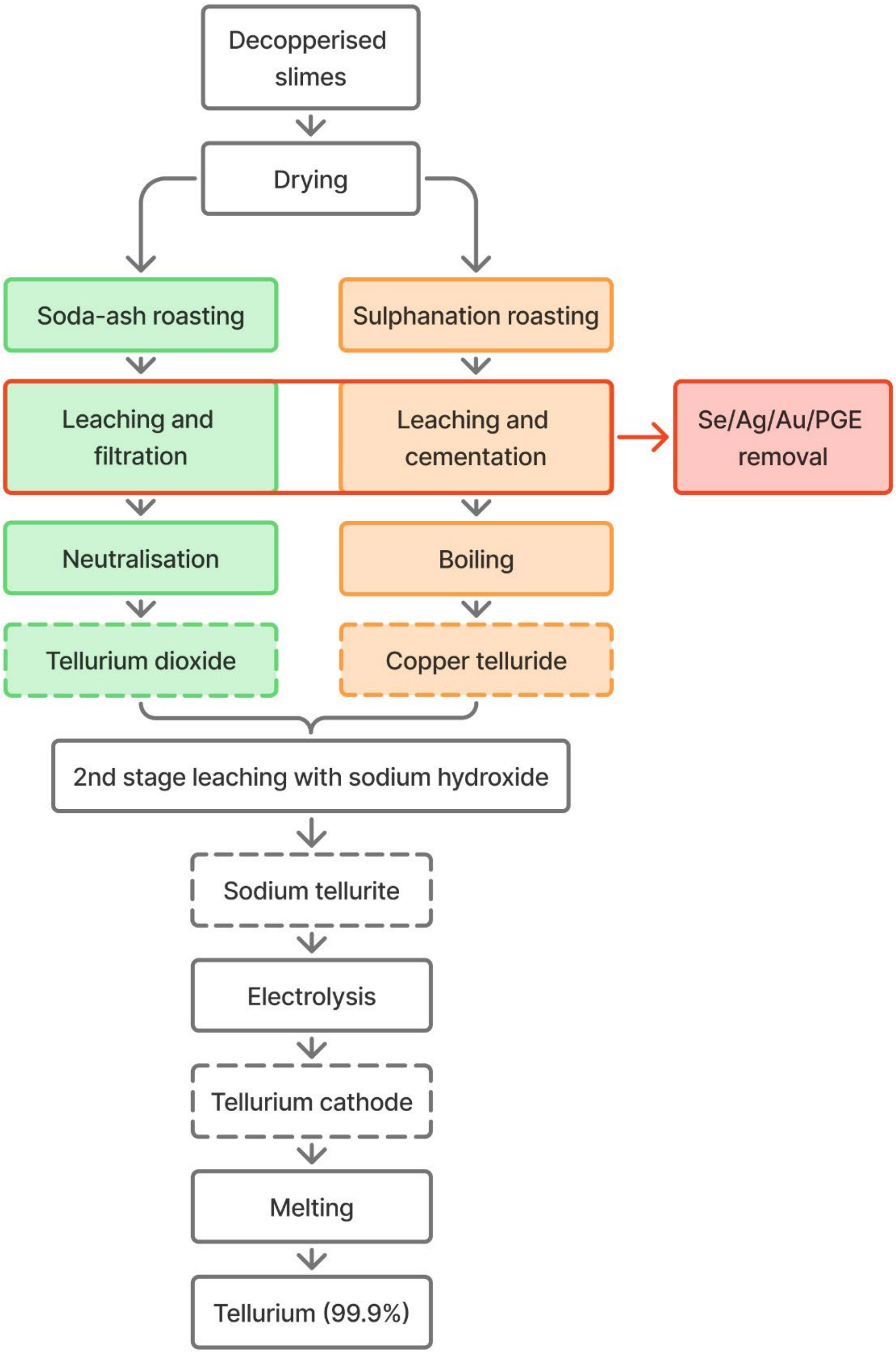


Figure 5. Schematic diagram showing the processing routes for recovering tellurium from copper anode slimes. Boxes with dashed lines are intermediate tellurium products. Selenium (Se), silver (Ag), gold (Au) and platinum group metals (PGM) are typically recovered during the first leaching stage. After Knockaert (2011).

It is common for the processing of anode slimes to happen in a different country to where the mining and refining of copper took place. This creates a complex value chain where the production of refined tellurium may be completely decoupled from the original copper operations. A tellurium refiner may process anode slimes from multiple producers, which further adds to the complexity of assigning tellurium production to a specific country or copper producer. In addition, the production of tellurium intermediates and tellurium metal may also be decoupled. A refiner might be able to process anode slimes into an intermediate product, for example tellurium dioxide, but may lack the capability to produce high purity refined tellurium metal. This further increases the complexity of the supply chain.

4.1.3 Current production and key players

The global output of refined tellurium was approximately 966 tonnes in 2023. Production was dominated by China, which produced 725 tonnes, equating to approximately 75 per cent of global supply. Other producers include Russia, Japan, Canada, USA and Uzbekistan (British Geological Survey, 2025; US Bureau of Mines, Various; US Geological Survey, Various). Only Sweden and Bulgaria produced refined tellurium in Europe during 2023, with a combined output of 37 tonnes. This equated to approximately 4 per cent of global supply in 2023 (Figure 6). However, the output from Sweden (New Boliden Group) is typically sold to China for further refining (Voigt and Falshaw, 2024).

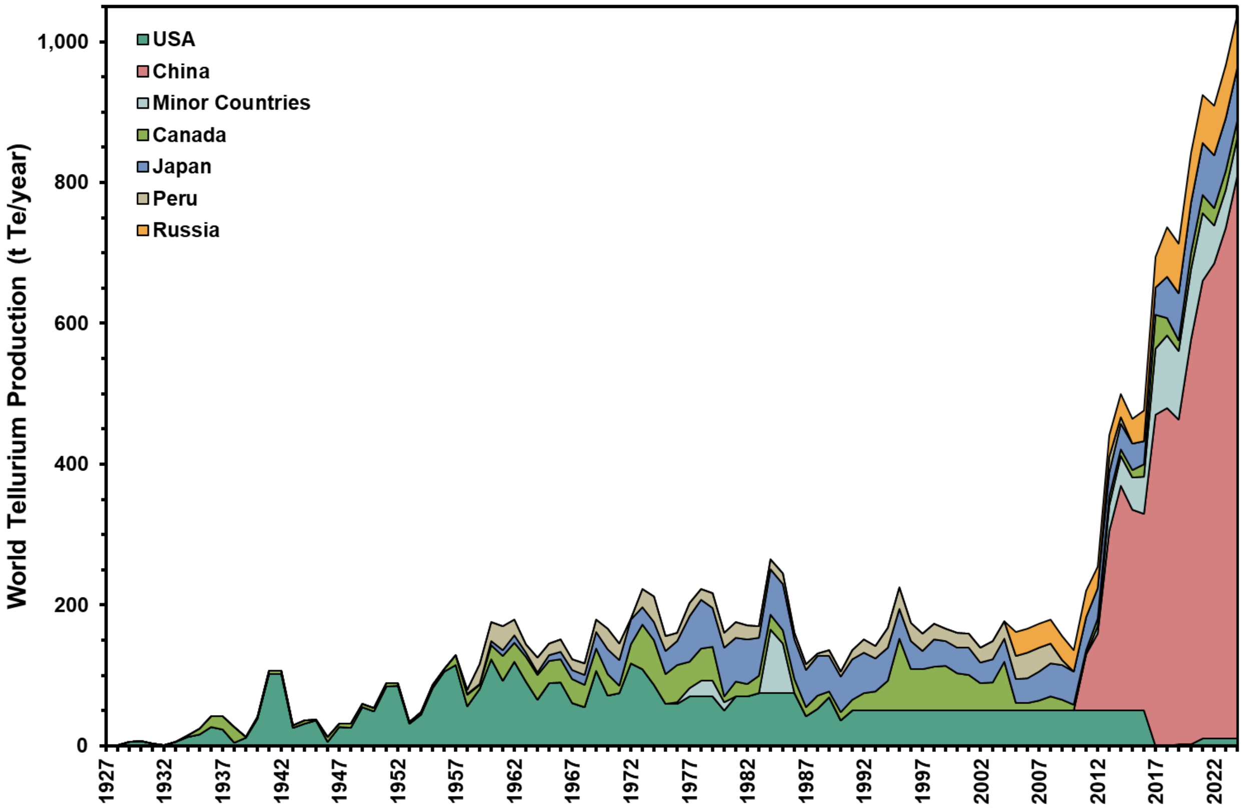


Figure 6. World historical refined tellurium production by principal countries. Created by BGS © UKRI. Data sources: British Geological Survey (2025), US Geological Survey (Various), US Bureau of Mines (Various).

It is difficult to generate a definitive list of tellurium refiners and equally difficult to find reported production or capacity figures for those that are known. At least 26 tellurium refineries were reported as operating in 2011 by Willis et al. (2014), with an estimated combined output of 450 to 470 tonnes of tellurium. Current information indicates that some of the companies listed no longer produce tellurium, for example Kazakhmys, Kazakhstan; KGHM, Poland; Pasar, Philippines; and Sumitomo, Japan. Selected tellurium producing companies that are currently active are listed in Table 9, including mining companies (e.g. Rio Tinto), refining companies (e.g. LS MnM), recyclers (e.g. Umicore) and integrated mining and refining companies (e.g. New Boliden Group). Vital Metals and Kosaka Smelting and Refining Co are two of the companies listed that are producing refined tellurium products from the processing of e-waste and CdTe batteries. Over half of the twenty companies listed in Table 9, are based in China and Japan.

Table 8. Selected global tellurium refiners, showing form and purity where reported. Sources: [a] 5N Plus (2025); b Almalyk Mining and Metallurgical Complex (2025); [c] Anhui Fitech Materials (2025); [d] Aurubis (2025); [e] Glencore (2025b); f Iwatani (2025); [g] JX Materials (2025); [h] Kisan Kinzoku Chemicals Co (2025); [i] Kosaka Smelting & Refining Co (2025); [j] LS MnM (2025); [k] Voigt and Falsahw (2024); [l] Noah Chemicals (2025); [m] Pan Pacific Copper (2025); [n] Rio Tinto (2025b); [o] Shandong Humon Smelting Ltd (2025); [p] ECHEMI (2025); [q] Umicore (2025); [k] Vital Materials (2025); [s] Zhuzhou Keneng New Material Co (2025); [t] Zijin Mining (2025). In addition to the companies listed, the Ural Mining and Metallurgical Company in Russia and Jiangxi Copper in China are also believed to be producing tellurium metal

Company	Country	Tellurium form	Notes
5N Plus [a]	USA	Various	Inc. cadmium and zinc telluride and oxide
Almalyk Mining and Metallurgical Complex [b]	Uzbekistan	Metal powder	99.95% purity
Anhui Fitech Materials [c]	China	Metal & oxide	Up to 99.999% purity
Aurubis [d]	Germany	Metal & oxide	Min. 99.995% purity
Glencore [e]	Canada	Oxide	
Iwatani [f]	Japan	Various	Inc. telluric acid
JX Advanced Metals [g]	Japan	Metal	99.99% purity or higher
Kisan Kinzoku Chemicals Co. [h]	Japan	Various	Inc. telluric acid & Na tellurite
Kosaka Smelting & Refining Co. [i]	Japan	Metal	From e-waste
LS MnM [j]	South Korea	Metal	Up to 99.99% purity
New Boliden Group [k]	Sweden	Cement	Sold to China for further refining
Noah Chemicals [l]	USA	Various	Inc. sodium tellurite & tellurium chloride
Pan Pacific Copper [m]	Japan	Metal	99.99% purity or higher
Rio Tinto [n]	USA	Cu telluride	Sent to 5N Plus for further refining
Shandong Humon Smelting Ltd. [o]	China	Metal	Up to 99.99999% purity
Sichuan Xinlong Tellurium Industry Co. [p]	China	Metal powder	Up to 99.99999% purity
Umicore [q]	Belgium	Various	
Vital Materials [r]	China	Various	Up to 99.999% purity; from e-waste and CdTe batteries
Zhuzhou Keneng New Material Co. [s]	China	Metal & oxide	Up to 99.99999% purity
Zijin Mining [m]	China	Metal	

4.1.4 Future supply potential

The future supply of tellurium will largely be driven by economics, global demand and market conditions. It is difficult to forecast future supply accurately without considering these factors. However, there is broad consensus that significant potential exists to expand production capacity in the future.

Various studies (for example Buchert et al., 2009; Green, 2013; McNulty et al., 2022; Nassar et al., 2022) have attempted to estimate global tellurium production based on copper cathode production data. The results varied considerably, between 777 and 2,770 tonnes, compared to reported production figures, which averaged 562 tonnes per year. Anode slime generation rates were estimated by Nassar et al. (2022) to be between 0.7 to 28 kgs of anode slime per tonne of copper cathode, with the average being approximately 5 kgs. Whilst the tellurium content of slime ranges between 0.07 to 11 per cent, the average is approximately 1.4 per cent.

The present study has used two different methods to estimate future tellurium production capacity. Both methods are based solely on production rates as a function of time with no adjustments for other variables, such as market conditions and recovery rates. The first estimate applies a linear regression to reported tellurium production for the years 2003 to 2023 and then extrapolates the trend out to 2050. This results in a theoretical tellurium production capacity of approximately 2,000 tonnes in 2050 (Figure 7a). The second method applies a linear regression to copper cathode data for the same period and then extrapolates the trend out to 2050. This results in an estimated copper cathode production capacity of 25 million tonnes in 2050 (Figure 7b). The average slime generation rate and tellurium content figures reported by Nassar et al. (2022) can then be used to estimate a tellurium production capacity of 2,450 tonnes of tellurium by 2050, assuming recovery from anode slimes keeps pace with copper cathode production.

The estimated tellurium capacity of 2000 to 2450 tonnes per year by 2050 based on Nassar et al. (2022) lies within the range of other estimates indicated above (777 to 2770 tonnes). Estimates provided in this chapter are, however, likely to be conservative, as they do not consider tellurium production from lead smelting, gold processing, or e-waste recycling. Figures from this study and others (for example McNulty et al., 2022), highlight that global tellurium production during the past 20 years has only been a fraction of the potential capacity.

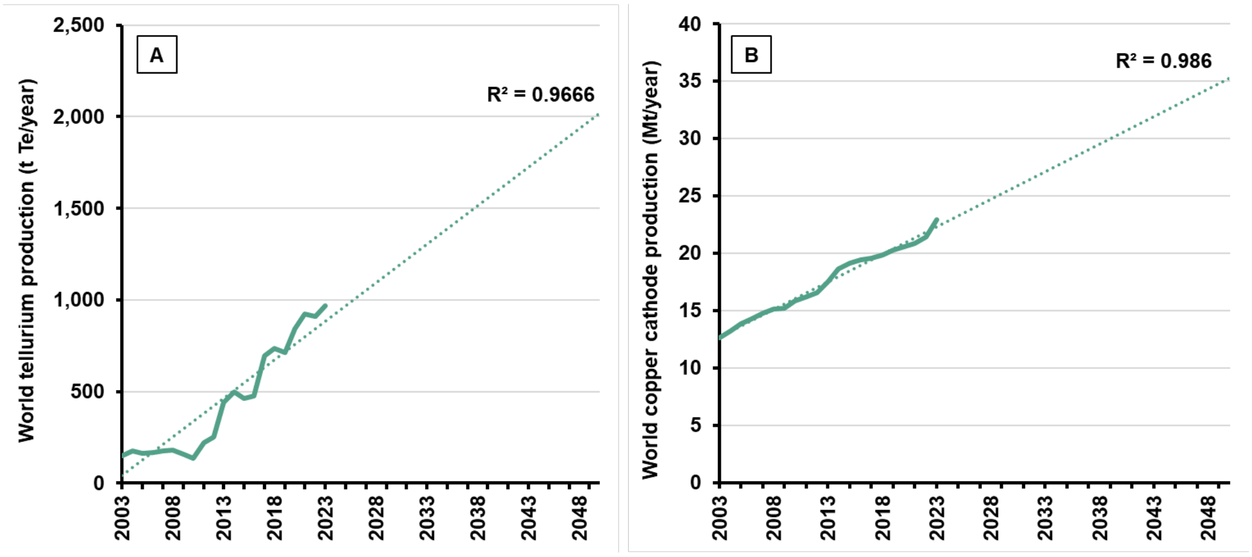


Figure 7. Linear regression plots for (A) tellurium and (B) copper cathode showing forecast production up to 2050. Tellurium data from British Geological Survey (2025), US Geological Survey (Various) and US Bureau of Mines (Various) with copper cathode data from British Geological Survey (2025).

In terms of the geography of future supply, any country producing copper cathodes, could in theory produce tellurium from its anode slimes. However, this would require capital investment to install tellurium recovery circuits and refining capacity. For example, there are currently two countries that produce tellurium in Europe, Bulgaria and Sweden, with a combined output of 37 tonnes in 2023. Of that, 36 tonnes were sold to China for further refining. If all of Europe's copper cathode producing countries installed tellurium recovery circuits, the region could produce almost 200 tonnes per annum, almost a fifth of global supply (Table 10).

Table 9. Missed potential tellurium production in Europe based on copper cathode production. The slime generation rate and tellurium content used to calculate theoretical production are taken from Nassar et al. (2022), copper cathode figures are from Idoine et al. (2025a). Text in bold signifies active tellurium producers.

Country	2023 copper cathode (t)	Anode slimes (t)	Missed potential tellurium production (t)
Austria	109 000	545	8
Belgium	377 500	1 888	26
Bulgaria	**229 070**	**1 145**	**16**
Finland	135 203	676	9
Germany	609 000	3 045	43
Italy	9 900	50	<1
North Macedonia	640	3	<1
Norway	18 475	92	1.3
Poland	586 006	2 930	41
Serbia	24 665	123	1.7
Spain	297 900	1 490	21
Sweden	**217 779**	**1 089**	**15**
Turkey	134 600	673	9
Ukraine	2 400	12	<1
		Europe total	193

4.2 BISMUTH

4.2.1 Background and sources

Bismuth is a relatively scarce element in the Earth's crust, with an abundance of only 0.23 ppm (Hu and Gao, 2008). Bismuth is found in a wide range of minerals in nature that are most commonly associated with magmatic-hydrothermal systems, where they can be subdivided into four key groups. These include gold and silver alloys; sulphides (e.g. bismuthinite); oxides (e.g. bismutite); and complex selenides and tellurides. Bismuth can also be found as a native metal in some mineral deposits (Deady et al., 2022). In some parts of the world, such as Bolivia and China, bismuth is extracted as a primary commodity. However, it is predominantly extracted as a by-product of mining other metals, such as lead, copper, tungsten, tin, molybdenum or gold. Complex polymetallic (cobalt-nickel-bismuth-silver-arsenic) mineral deposits, where bismuth occurs as a native metal, were historically important sources of production in countries such as Germany, Czechia, and Switzerland (Deady et al., 2022). Currently, lead and tungsten ores are the largest source of bismuth production, with approximately 50 to 60 per cent of bismuth being obtained as a by-product of processing lead ores and the remainder coming from the processing of tungsten ores (Willis et al., 2014). Bismuth is also recovered from the processing of other metal ores, such as zinc, tin, copper and precious metals. However, the amount captured from these sources is likely to be very small.

4.2.2 Extraction

Bismuth production is closely associated with the production of lead. Bismuth can be recovered from lead concentrates via a sintering process that results in the formation of lead bullion (an impure lead alloy) enriched in bismuth. The lead bullion is then subjected to either pyrometallurgical refining through the Betterton-Kroll process, or electrolytic refining using the Betts process, to remove impurities, such as bismuth. During the Betterton-Kroll process, calcium and magnesium are added to the molten lead, which results in the formation of a bismuth-rich crust (approximately 6 per cent bismuth). Waste from the Betts process takes the form of anode slime, which typically contains between 2 and 4 per cent bismuth. These waste materials can be further treated to recover bismuth and other valuable metals. Additional pyrometallurgical refining is required to produce high-purity bismuth metal (Figure 8), which is a precursor to the production of bismuth compounds and alloys (Krüger et al., 2003). Where bismuth is produced from other sources, for example tungsten or zinc ores, alternative processing routes are utilised, the details of which are not given here.

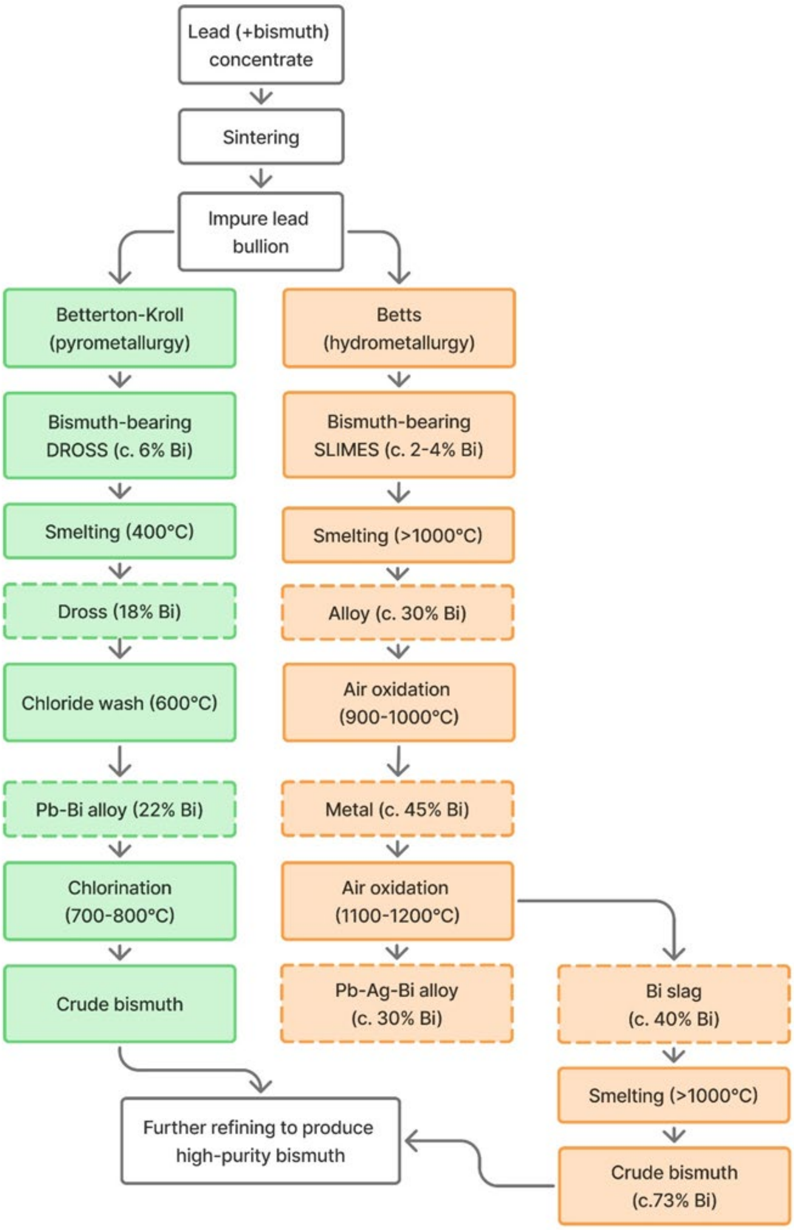


Figure 8. Schematic diagram showing the processing routes for recovering bismuth from lead processing. Boxes with dashed lines are intermediate products. After Krüger et al. (2003).

4.2.3 Current production and key players

Bismuth global mine production was 4000 tonnes (contained metal) in 2023. Production is dominated by three countries, China, Vietnam, and Japan, accounting for 85 per cent of global supply, of which China holds the largest share at 45 per cent. Other producing nations include Bolivia, Peru, Russia, Bulgaria, and Kazakhstan. European production is currently limited to Bulgaria (Figure 9), which produces approximately 50 tonnes per year (Idoine et al., 2025a). Annual global production has been between 3000 and 5000 tonnes for the last twenty years, with a peak of nearly 6500 tonnes in 2018. Production in China and Japan has been remarkably consistent during the past twenty years. However, for other countries, notably Mexico and Canada, production has declined to almost zero. Vietnam has increased its bismuth mine production during the past ten years, peaking at just over 3000 tonnes in 2018 (Idoine et al., 2025b).

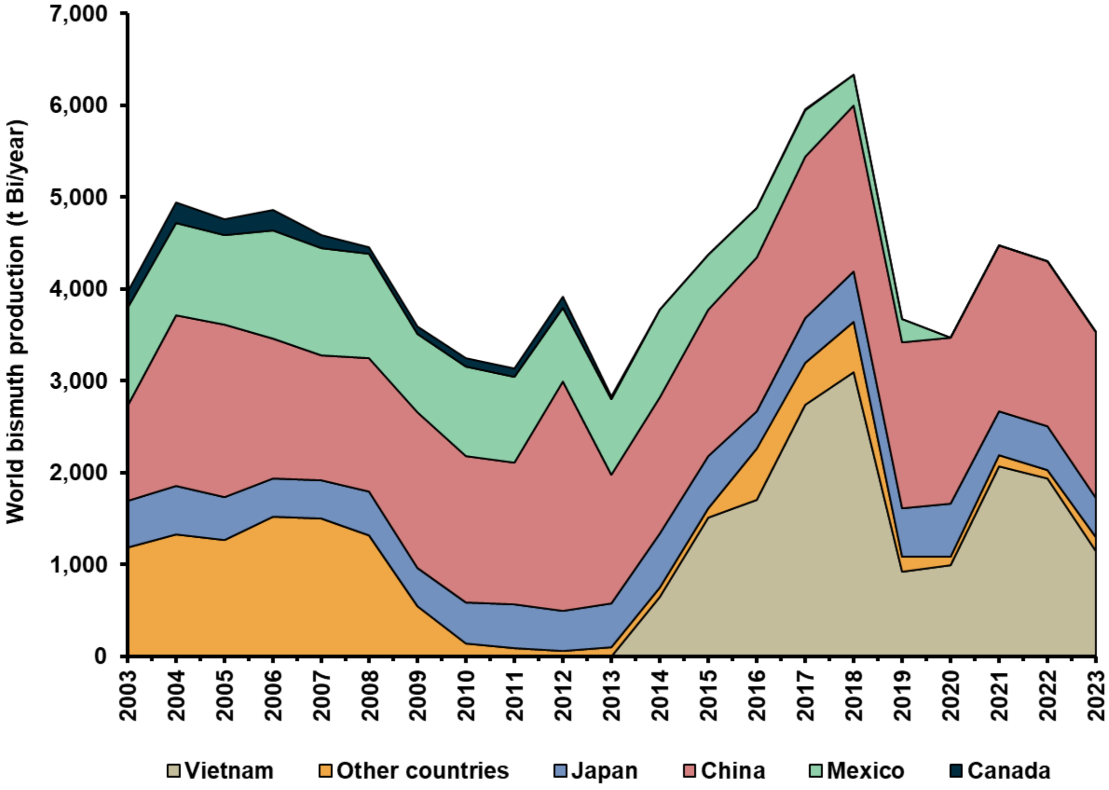


Figure 9. World historical bismuth mine (contained metal) production by principal countries. Created by BGS © UKRI. Data source (British Geological Survey, 2025). World historical bismuth mine (contained metal) production by principal countries. BGS © UKRI 2026. Data source: British Geological Survey (2025).

Due to bismuth predominantly being produced as a by-product of mining and refining other commodities, it has a highly complex supply chain. It is therefore very difficult to generate a complete list of bismuth producers, especially for refined bismuth metal, alloys and compounds. Although Table 11 is not exhaustive, it includes a selection of current actors in the bismuth supply chain, including miners, refiners, recyclers, and speciality metal traders. Table 11 also highlights the diversity of bismuth-bearing materials that are produced and traded, including: bismuth-bearing concentrates from mining; bismuth cement and impure alloys derived from tungsten and lead refining; refined bismuth metal; and a wide-variety of bismuth-bearing chemicals. It is worth noting there are several minor metal traders based in the UK that have a strong presence in the global bismuth supply chain, including Advent Research Materials, Westbrook Resources, Lambert Metals International Ltd, and William Rowland (Table 11).

Table 10. Selected global bismuth producers, showing annual capacity, form and purity where reported. Sources: [a] 5N Plus (2025); [b] Advent Research Materials (2025); [c] Aurubis (2025); [d] China Minmetals Corporation (2025); [e] Compañía Minera Antamina SA (2010); [f] Kazzinc (2025); [g] KCM 2000 Group (2019); [h] Lambert Metals International Ltd (2025); [i] Masan High-Tech Materials Corporation (2024); [j] Umicore (2025); [k] Vital Materials (2025); [l] Westbrook Resources Ltd (2025); [n] William Rowland (2025); [n] Xianyang Yuehua Bismuth Industry Co (2025).

Company	Country	Bismuth form	Notes
5N Plus [a]	US	Bismuth metal & chemicals	Up to 99.999 % purity
Advent Research Materials [b]	UK	Bismuth metal	Speciality metal trader
Aurubis [c]	Germany	Lead-bismuth alloy (6-12 % bismuth)	
China Minmetals Corporation [d]	China	Bismuth sulphide concentrate	
Compañía Minera Antamina S.A. [e]	Peru	Bismuth-lead concentrate	
Kazzinc [f]	Kazakhstan	Bismuth anode alloy	By-product of copper and lead refining. Capacity of ~300 tonnes per year.
KCM 2000 Group [g]	Bulgaria	Lead-bismuth alloy (7 % bismuth)	By-product of lead refining.
Lambert Metals International Ltd. [h]	UK	Bismuth metal	Speciality metal trader
Masan High-Tech Materials [i]	Vietnam	Bismuth cement	By-product of tungsten refining.
Umicore [j]	Belgium	Bismuth metal	Recovered from lead bullion.
Vital Materials [k]	China	Bismuth metal & chemicals	Up to 99.9999 % purity
Westbrook Resources [l]	UK	Bismuth metal	Speciality metal trader & producer
William Rowland [m]	UK	Bismuth metal	Speciality metal trader & producer
Xianyang Yuehua Bismuth Industry Co. [n]	China	Bismuth metal & chemicals	Bismuth-oxide production capacity of ~100 tons per month

4.2.4 Future supply potential

Estimating future supply of bismuth and the potential to expand capacity is challenging due to the supply chain complexity and the decoupled nature of production; refining and mining typically occur in different locations. It is also difficult to accurately forecast future supply without considering demand, market conditions, and economics. However, as with many by-product metals, it is highly likely there is potential to increase production.

There are not many published future supply forecasts for bismuth, although figures by McNulty et al. (2022) indicate that one third of the world's copper refiners (approximately 32 operations) could have recovered more than 1600 tonnes of bismuth in 2019. Empirical data that describe the amount of waste generated during the processing of key metal ores, such as lead, zinc, and tungsten, and the associated bismuth content of those waste streams, are scarce. There are several studies that report these types of data (Table 12). However, they are based on a limited number of samples from a single operation. Therefore, using these figures to forecast global bismuth supply potential is subject to very high uncertainty.

Table 11. Range of waste generation figures and bismuth contents per tonne of refined lead, zinc, tungsten and copper.

Host metal	Kg waste per tonne of refined metal	Bismuth content of waste (%)	References
Lead	12 to 18	4.5	Dong et al. (2024) Gu et al. (2026)
Zinc	30 to 50	14 to 20	Fan et al. (2020) Tan et al. (2025)
Tungsten	700 to 800	2.4	Deng et al. (2023)
Copper	0.7 to 28	7	Nassar et al. (2022) Li et al. (2023)

Trying to forecast future bismuth supply from currently reported data is problematic. Fitting a simple linear regression to reported production data for the period 2003 to 2023 results in a very low R^2 value (0.0001), although the reasons for this poor fit are not entirely clear. One reason may be shifting market dynamics, such as decreasing production in Peru and Mexico and increasing production in Vietnam (Idoine et al., 2025b). There is also uncertainty about data reporting. For example, Japanese production is reported as mine production, however Japan imports bismuth-bearing mineral concentrates from elsewhere for refining (Idoine et al., 2025b). It is therefore not possible to forecast future supply by extrapolating bismuth production forward to 2050 based on the fitted linear regression.

Attempting to forecast future bismuth supply from lead production is also challenging. This is partly due to the scarcity of published waste generation rates and bismuth content data, but also due to a lack of information about the proportion of lead that is produced via the different processes described above (i.e. electrolytic versus pyrometallurgical). As such, no forecast is made here. Despite the challenges in estimating future supply, it seems highly likely, given the diversity of feedstock materials, that future bismuth supply could be expanded. As with other metals, the degree to which future supply is developed will depend on demand, economics and market dynamics.

4.3 HAFNIUM

4.3.1 Background and sources

Hafnium (Hf) is a rare, lustrous, silver-grey metal used in major industrial sectors. Properties of hafnium that are desirable to a variety of industrial sectors include corrosion resistance, neutron absorption, and high di-electric properties (Nielsen, 2013). These properties make hafnium a key ingredient in the manufacture of superalloys for the aerospace sector (rocket nozzles, hypersonic engines for jets, and missiles), rods employed to control the rate of fission reactions in the nuclear sector, and semi-conductors (Nielsen, 2013).

Commonly qualified as a refractory incompatible element, hafnium does not fit within the structure of most common minerals. It possesses very similar geochemical properties to the more abundant element zirconium (Zr), and is therefore mostly found as a trace element in zirconium minerals, such as zircons ($ZrSiO_4$, approximately 2 per cent hafnium by weight) and, to a lesser extent, baddeleyite (ZrO_2) (Nielsen, 2013). These two minerals commonly form as accessory phases in igneous rocks (Schaltegger and Davies, 2017).

Due to its extremely low natural abundance in the Earth’s crust (3 to 4.8 ppm), refractory nature, and chemical substitution within zirconium minerals, production of hafnium is intimately linked to that of zirconium as a by-product (Haygarth and Graham, 1999). The largest primary deposits of zirconium (and hafnium) are associated with alkaline igneous intrusions, such as pegmatites (Brazil, Malawi), carbonatites (Mount Weld, Western Australia), or more rarely as trachyte tuffs containing hafnium-rich eudialyte (Dubbo, New South Wales, Australia) (Haygarth and Graham, 1999). Baddeleyite is produced as a by-product of magnetite and apatite mining in the Kola Peninsula, Russia (Jones III et al., 2017). Globally, heavy mineral sands are the main ore deposit for zirconium from which hafnium is derived. Heavy mineral sands are a secondary deposit formed by weathering and erosion of pre-existing igneous rocks and the concentration of high-density minerals, such as zircon, ilmenite, rutile, garnet, chromite, and monazite, during sedimentary processes. Notably, coastal environments are particularly efficient at sorting particles by density through repeated wind, wave, and tidal processes, leading to economically important accumulations in shallow offshore settings (Jones III et al., 2017).

4.3.2 Extraction

Extracting hafnium follows a three-step process: (1) conversion of the hard mineral into chemically active intermediates, (2) separation of hafnium from zirconium, and (3) chemical reduction and refinement of hafnium metal to high purity (Nielsen, 2013).

The first stage converts refractory zircon (a chemically stable mineral) into compounds that can be handled in subsequent steps. One common industrial route includes the process of carbochlorination, which involves reacting milled zircon with carbon and chlorine gas at approximately 1,100 °C to make volatile zirconium/hafnium tetrachloride and silicon tetrachloride as a by-product. A second potential industrial process is fluorosilicate fusion, in which zircon is fused with potassium fluoro-compounds at approximately 700 °C to create soluble fluoride salts ($K_2[ZrHf]F_6$) containing zirconium, hafnium, and silica. The product is cooled, crushed and leached with acidified hot water, filtered to remove silica, then cooled further to form a crystalline fluoride salt (Nielsen, 2013).

The second stage separates hafnium from zirconium. The two elements behave almost identically chemically; therefore, industrial separation relies on incremental differences and multi-stage processing. Industrial methods include liquid–liquid extraction, molten-salt extractive distillation, and repeated crystallisation of fluoride salts. In liquid–liquid extraction, the dissolved metal mixture is contacted with an immiscible organic solvent that binds hafnium more strongly than zirconium, causing hafnium to transfer into the organic layer, which can then be separated and processed to recover hafnium. In molten-salt extractive distillation, the metal tetrachlorides are vapourised into a heated molten-salt bath where small differences in volatility allow hafnium to concentrate in the rising vapour stream, which is collected and condensed to produce a hafnium-enriched fraction. In fluorozirconate crystallisation, the metals are converted into soluble fluoride salts and the solution is cooled so that the less soluble, zirconium-rich crystals form first, leaving a liquid that is comparatively enriched in hafnium and can be isolated for further purification (Nielsen, 2013).

The third stage converts purified hafnium compounds into metal and then further purifies the metal. The Kroll process reduces hafnium tetrachloride with liquid magnesium to produce a porous ‘sponge’ of hafnium metal, which is then washed and vacuum-distilled to remove magnesium residues and produce a consolidated, but still impure, metal product. Iodide-based vapour transport (van Arkel–de Boer process) reacts hafnium with iodine to form volatile hafnium tetraiodide, which is driven to a hot filament where it decomposes and deposits very pure hafnium metal on the filament. Vacuum electron-beam melting purifies hafnium by heating and melting it in a high vacuum so that volatile impurities evaporate away, producing a dense, high-purity metal for aerospace or electronics (Nielsen, 2013).

4.3.3 Current production and key players

Production data for hafnium is scarce. Given hafnium’s close geochemical association with zirconium, zirconium mine output is used as a rough proxy for potential hafnium supply. This is an imperfect indicator as zirconium production does not automatically translate into hafnium production. However, it can help suggest where hafnium output is most likely and which countries are key players (Figure 10). Global mine production of zirconium was 1.30 Mt in 2023 (Figure 10), with production concentrated in Australia (36 per cent) and South Africa (31 per cent), with notable producers including Mozambique, Indonesia, China, Senegal, and the USA. There is minimal production of zirconium in Europe, with Ukraine ceasing production after 2022 (Idoine et al., 2025a). Production of zirconium has remained relatively stable since 2014, with peak production in 2016 at 1.37 Mt (Figure 10). Key players that operate zirconium mines include Rio Tinto, Iluka Resources, and Kenmare Resources (Table 13).

Global refined hafnium production from 2016 to 2020 is estimated at 71 tonnes per year with France and the US dominating refining output at 49 per cent and 44 per cent respectively. Both China and Russia produce approximately 3 per cent of refined hafnium and Ukraine 1 per cent (SCCREEN, 2024). These figures are likely out of date, as publicly available data on hafnium refining is sparse. Key hafnium refiners include Framatome and ATI, producing approximately 93 per cent refined hafnium globally (Table 13). Stakeholder engagement highlighted the creation of a dedicated hafnium refinery in China with a production capacity of 30 tonnes per year, not yet captured in open datasets due to market and reporting opacity. This additional capacity, roughly equal to 40 per cent global hafnium production cannot currently be tracked. It is, however, likely ingested by Chinese consumption and strategic stockpiling.

The supply of secondary hafnium feedstock from recycling is difficult to quantify. Nonetheless, there are multiple specialist companies that recycle hafnium containing products. Recycling companies operate in multiple countries, including the UK (Advanced Alloy Services LTD., Avon Specialty Metals), the USA (Quest), and Germany (RS-Recycling GmBH).

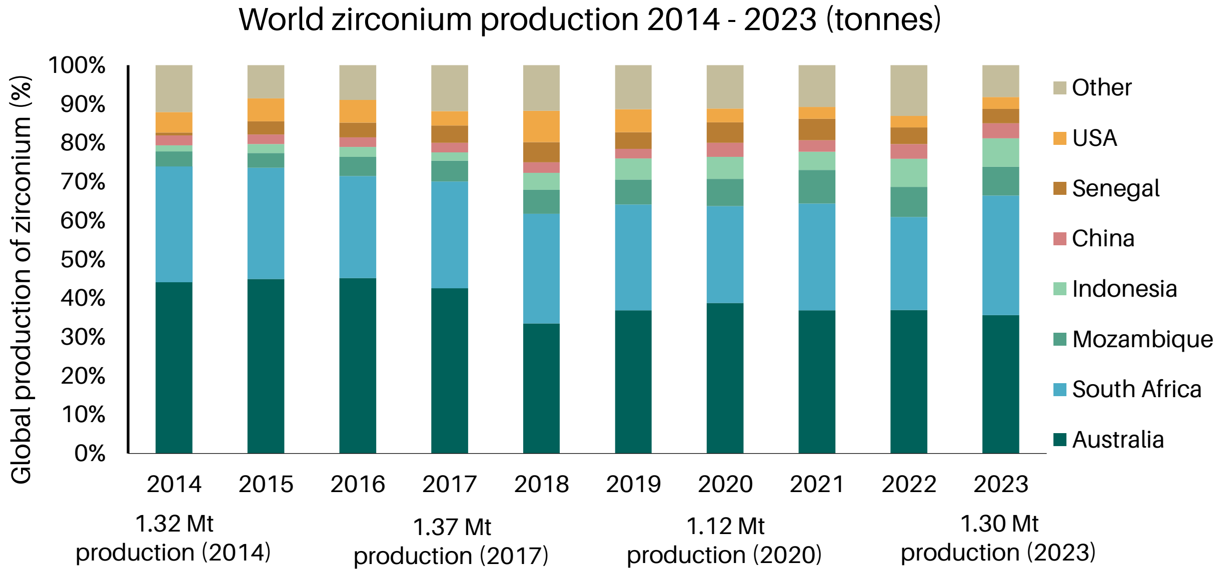


Figure 10. Country level zircon mineral production data, 2014 – 2023. Zircon mine output is used as a proxy for potential hafnium production (noting very little zircon is processed exclusively for hafnium production). Data source: (Brown et al., 2020; Idoine et al., 2025a).

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Table 12. Selected key players of hafnium production and refining, showing output volumes where reported. Sources: [a] Iluka Resources (2025), [b] Kenmare Resources Plc (2025), [c] Rio Tinto (2025a), [d] Rio Tinto (2025c), [e] Eramet (2025b), [f] Tronox (2025), [g] Framatome (2025), [h] Gambogi (2025), [l] ATI Materials (2025), [j] Neo Materials (2025), [k] CMP (2025), [l] Mordor Intelligence (2025a), and [m] MMTA (2016).

Company	Country	Estimated production	Notes
Mining			
Iluka Resources[a]	Australia	Zircon at 1 Mt per year	Major zircon miner (hafnium by-product)
Kenmare Resources[b]	Mozambique	Zircon at 1.2 Mt per year	Moma mineral sands (zircon, ilmenite, rutile)
Rio Tinto (RBM)[c]	South Africa	Zircon at 2 Mt per year	Richards Bay Minerals (zircon, ilmenite, rutile)
Rio Tinto (QMM)[d]	Madagascar	Ilmenite at >1 Mt per year	Ilmenite with zircon by-product
Eramet (GCO)[e]	Senegal	Ilmenite at 0.7 Mt per year	Grande Côte Operations (ilmenite, zircon)
Tronox[f]	South Africa/USA	-	Integrated mineral sands producer
Refining/separation			
Framatome (Jarrie)[g]	France	Hafnium at 30 t per year[l]	Zirconium-hafnium separation; hafnium oxide/metal
Westinghouse (Western Zirconium)[h]	USA (Utah)	-	Zirconium processing; hafnium streams
ATI SA&C (Wah Chang)[i]	USA (Oregon)	Hafnium at 40 t per year[m]	Hafnium metal/alloys; zirconium refining
Neo Performance Materials – Silmet[j]	Estonia	-	Hafnium metal/compounds
ChMP (TVEL/Rosatom)[k]	Russia	-	Zirconium/hafnium metals for nuclear
Orient Zirconic[l]	China	-	Zirconium chemicals; hafnium chemicals

4.3.4 Future supply potential

Predicting future demand for hafnium is challenging due to its diverse applications. Currently, aerospace accounts for over half of annual hafnium consumption (Morace, 2025; Nielsen, 2013). Demand from this sector is expected to rise considerably following Rolls-Royce's announcement in 2024 of next-generation aircraft engines utilising hafnium-based superalloys (MMR, 2025). Demand for hafnium from the nuclear industry is also projected to grow steadily, with an estimated annual increase of 4 per cent (Metalnomist, 2025). The semiconductor industry is a growing source of demand, making use of hafnium's dielectric properties for the production of micro-chips (Nielsen, 2013). The growing need for memory capacity in data centres, particularly for AI applications, is expected to accelerate consumption further (Belda, 2025a). Overall, global hafnium demand is forecast to increase by nearly 40 per cent by 2030, reaching approximately 180 tonnes (Belda, 2025b).

In terms of supply, the total physical availability of hafnium is not considered a major constraint. Zircon typically contains around 2 wt. per cent hafnium (Nielsen, 2013). This means that zirconium production in 2023 (Idoine et al., 2025a) could have yielded up to 26,000 tonnes of contained hafnium. Yet only a minor fraction (less than 1 per cent) of the hafnium contained in zirconium ores is extracted (Matos et al., 2021). Global reserves of hafnium are estimated at around 1 million tonnes (Matos et al., 2021). Compared to the projected demand of 180 tonnes by 2030, the challenge lies not in resource scarcity, but in the capacity to refine hafnium from zirconium.

Plans to expand hafnium production are underway. China is reportedly considering increasing its refining capacity by an amount roughly equivalent to current global demand. Although this may be optimistic, it signals potential for significant additional supply (Matheson and Stratton, 2024). Whilst this could mitigate potential future supply shortages, it does not address supply risks because it also increases dependency on China. Meanwhile, France's leading producer aims to boost output from 30 tonnes per year to 45 tonnes per year during 2026 (Belda, 2025b).

Several factors could constrain future hafnium supply. The adoption of more-enriched nuclear fuels reduces the frequency of fuel-rod replacement, lowering demand for new zirconium cladding (Matheson and Stratton, 2024). As hafnium is recovered as a by-product of zirconium refinement, any reduction in zirconium demand has the potential to reduce hafnium supplies.

Although the nuclear sector is projected to grow (Metalnomist, 2025), this growth does not necessarily translate directly into increased zirconium demand. Efficiency gains, such as higher fuel enrichment, will offset some of the increased demand for zirconium cladding. As a result, hafnium supply may not increase by as much as implied by a growing nuclear sector. However, rising hafnium prices could incentivise the development of dedicated separation facilities to recover hafnium beyond nuclear industry requirements.

Secondary feedstock is another opportunity to secure further supply of hafnium. The aerospace sector is efficient in closed-loop recycling, with nearly 95 per cent of used jet turbines now recyclable and approximately half of recovered material suitable for new engine components (Singh et al., 2023). Outside of such closed-loop systems, however, less than 1 per cent of end-of-life hafnium-containing products are recycled (United Nations Environment Programme et al., 2013). This is likely attributed to contamination from the nuclear industry and low hafnium content in superalloys (SCCREEN, 2024).

5 High purity chemical and isotopic material requirements

This section examines the trade supply of key elements and isotopes used in quantum technologies, specifically carbon, nitrogen, gallium, germanium, and arsenic. Section 4 described upstream mining and production across all purity levels. This section disaggregates refining by purity, mapping where low-purity and high-purity materials are processed. The latter are required for electronic and quantum-grade applications, demanding far greater chemical purification and targeted isotopic enrichment. Processes are technologically specialised, often geographically concentrated, and cause different supply-chain vulnerabilities. Understanding where and how these elements are refined to electronic or quantum grade, and where and how they are isotopically enriched, will help identify challenges and opportunities to strengthen the UK's supply-chain resilience for digital technologies.

5.1 HIGH CHEMICAL PURITY MATERIALS

Chemical purity is often expressed as number of nines: 4N = 99.99 per cent, 5N = 99.999 per cent, 6N = 99.9999 per cent, and 8N = 99.999999 per cent. In a similar manner, 5N5 would refer to 99.9995 per cent purity. These grades describe the fraction of the target element present by mass, with the remaining parts comprising of parts per million (ppm) to parts per billion (ppb) scale impurities. For device performance, impurities at parts per million and even parts per billion levels may potentially result in performance loss or even complete failure (Isshiki et al., 2011). For example, just 20 ppm (0.002 per cent) of thallium can be enough to short circuit a gold plated transistor (Goodman, 1986).

Producing electronic-grade metals typically requires multiple complementary chemical and physical stages, often performed in specialised facilities. First, the raw material, in the form of residues or concentrates, is dissolved to form soluble metal ions. Chemical methods, such as solvent extraction and ion-exchange, then separate the desired metal from other elements. Metals can be recovered from solution through electrowinning, a process that utilises electricity to deposit metals as a solid on a cathode. Oxides and salts are commonly reverted to a metallic form by chemical reducers, such as hydrogen or carbon. Next, the metal is physically refined through melting and treated under controlled conditions to remove gases, oxides and other unwanted elements. Common processes at this stage include vacuum distillation, electron-beam or vacuum-arc remelting, and plasma/arc melting (Isshiki et al., 2011). Finally, impurities are removed by controlled fractional crystallisation using zone or floating zone refining methods (Isshiki et al., 2011) or crystal-growth techniques, such as the Czochralski method (Wang et al., 2023). These methods push trace impurities to one end of a piece of metal or produce perfect single crystals for electronic devices. The exact mix and order of steps depend on the metal involved and the level of purity required (Isshiki et al., 2011).

5.1.1 Carbon

Methane (CH_4) and carbon monoxide (CO) are the primary sources of carbon, both of which can be sourced from natural gas (George, 2001; International Energy Agency, 2025b). Global liquefied natural gas (LNG) is typically 87 per cent to greater than 99 per cent methane (Kuczyński et al., 2020). The USA produced approximately 22 per cent, , Russia 12 per cent, China 9 per cent, and the UK 2 per cent of the global liquified natural gas supply in 2023 (International Energy Agency, 2025a).

The purity of methane required to produce synthetic diamonds for quantum computing requires a grade of 6N (99.9999 per cent) (Zhang et al., 2021). Specialty gas producers, such as Nippon Gases, achieve this through a multi-stage purification process. Activated carbon and molecular sieve beds remove sulphur species, moisture, carbon dioxide (CO_2), and other impurities. Subsequent cryogenic distillation removes residual heavier hydrocarbons, such as ethane (Nippon Gases, 2025).

Commercial carbon monoxide is typically a co-product of synthetic gas (carbon monoxide plus hydrogen mix) production. Although the purity of carbon monoxide is below the grades required for electronic purposes (≥99.99 per cent) and requires further refinement. This is typically done through processes such as cryogenic distillation or pressure swing adsorption (George, 2001).

High-purity products are specialised materials and companies may treat their production volumes as proprietary or commercially sensitive. Consequently, there is little published data on the production of high-purity methane and carbon monoxide. Market reports of high-purity products indicate that North America produced the largest proportion of high purity methane in 2024 at 36 per cent, followed by Asia-Pacific (27 per cent), Europe (22 per cent) and South America (6 per cent). Key market players in 2024 include Linde Plc (Ireland), Osaka Gas Liquid Co., Ltd (Japan), Air Liquide S.A (France), Messer Group GmbH (Germany), Matheson Tri-Gas, Inc. (US), Coregas (Australia) and Gruppo SIAD (Italy) (Industry Arc, 2025).

5.1.2 Nitrogen

Nitrogen (N) is acquired from the atmosphere using air separation units (ASUs) through three main methods: cryogenic distillation, pressure swing adsorption, and membrane separation. Cryogenic distillation is the most dominant and efficient method for producing high volume and high purity nitrogen (Castle, 2002), capable of producing ultra-high purity nitrogen up to 6N (Ivanova and Lewis, 2012). Whereas pressure swing adsorption can only produce up to 5N5 (99.9995 per cent) purity. Membrane separation typically produces the lowest purity nitrogen, typically up to 2N5 (Ivanova and Lewis, 2012). The purity of nitrogen required in the semiconductor industry ranges from 4N to 6N purity for critical semiconductor processes and advanced chips (AriesPro, 2025).

Nitrogen gas is traded under the Harmonious System (HS) code 280430. Based on the UN Comtrade database and geographical area in 2024, Europe and North America are the top producers. Belgium is the top exporter of nitrogen gas (approximately 290 million m^3), followed by the US (approximately 220 million m^3), and Germany (approximately 130 million m^3). Other notable exporters include Poland, Serbia, Sweden, and Ireland (United Nations Statistics Division, 2025a). The UK predominantly imports nitrogen under HS 280430 from Ireland (8.6 million m^3), the USA (4.16 million m^3), and France (1.4 million m^3) (United Nations Statistics Division, 2025a). Whilst the UN Comtrade database does not provide national-level production statistics, it is still a useful tool for inferring the top producing countries. Moreover, the dataset does not provide specific detail regarding the purity of nitrogen gas.

Linde plc is a global player in the nitrogen market, suppling air separation plants and industrial gases. The Linde plc plant at Roethenbach, Germany, has a liquid nitrogen capacity of 18 280 Nm^3/h, with impurity levels of less than 0.5 ppb (Linde plc, 2025). A UK-based subsidiary of Linde, known as the British Oxygen Company (BOC), operates several ASUs throughout the UK (BOC, 2025) capable of separating nitrogen using cryogenic distillation to produce high-purity nitrogen (Dawson, 2010).

Specific volume data of key players for nitrogen are not published, but key companies producing high purity nitrogen include Air Liquide (France), Linde (Ireland), Air Products and Chemicals (USA), Messer Group GmbH (Germany), Atlas Copco (Sweden), and Taiyo Nippon Sanso (Japan) (Verified Markets Research, 2025).

5.1.3 Silicon

Silicon (Si) is the second most abundant element on Earth at 28.8 per cent in continental crust (Hans Wedepohl, 1995). Quartz (SiO_2) is the most common form of silicon found in nature. Despite the prevalence of silicon and quartz, deposits of high-purity quartz (purity of ≥4N5) used in electronic products and manufacturing of high-purity silicon metal, are rarely found in nature (Müller et al., 2012). Spruce Pine, North Carolina dominates the production of high-purity quartz, producing approximately 90 per cent of current global supply (Ma et al., 2025). Other important deposits and suppliers can be found in Norway, Russia, Australia, and Mauritania (Zhang et al., 2023). Large commercial players include Sibelco (US), TQC (The Quartz Corp, Norway), Russian Quartz LLC (Russia), Pacific Quartz (China), and Fudong Quartz (China).

Metallurgical-grade silicon metal is classified as approximately 98.5 per cent purity (Ciftja et al., 2008). It is produced in electric-arc furnaces from quartz and a carbon reductant. Silicon cannot be produced from quartz sand as its finer particle size means that it clogs the furnace; instead the quartz used is typically 5 to 100 mm in size (Elkem, 2025). Such quartz can be sourced from pegmatites (coarse grained igneous rocks), such as the Spruce Pine granite pegmatites (USA) from which Sibelco obtains its raw materials, or the Kyshtym quartz vein (Russia) which is a source for Russian Quartz LLC (Ma et al., 2025). Silicon metal used in semiconductor production must have a purity of at least 9N (Ciftja et al., 2008; Roussilhe et al., 2025). Consequently metallurgical-grade silicon requires further refining to achieve this level of purity. The silicon metal is first converted into a silicon hydride (SiH_4) which is then further purified using fractional distillation. The hydride is subsequently decomposed to produce pure silicon metal by either reductive pyrolysis or chemical vapour deposition (Ciftja et al., 2008).

Both the production of silicon metal (≥98.5 per cent) and solar grade silicon metal ≥6N purity (Yadav et al., 2017) is geographically concentrated in China, producing 4.8 Mt (US Geological Survey, 2026) and 1.8 Mt (International Energy Agency, 2025b), respectively in 2024 (Figure 11). China accounts for 94.7 per cent of global solar-grade silicon production (OECD, 2026). Semiconductor manufacturing requires ≥11N purity silicon, less than 10 per cent of which is produced by China and 65 per cent produced by the US and Germany, with other significant producers located in Japan and Korea (OECD, 2026). Polysilicon factories outside of China are currently being developed. This includes a 10 kilotonne (kt) facility in Malaysia operated by the Japanese firm Tokuyama Corporation and South Korean firm OCI (Bellini, 2025). Additionally, a 100 kt facility is being developed by United Solar in Oman (Lawder, 2025) and RESiLICON has entered the engineering phase for a new polysilicon plant in the Netherlands, although, neither the anticipated production start date nor the planned capacity have been disclosed (RESiLICON, 2025). However, REC Silicon's US plant is scheduled to cease polysilicon production in 2025 due to persistent challenges in meeting required purity standards (Blois, 2025).

The secondary supply of silicon is still a nascent industry, with recycled silicon reaching 5N purity, insufficient for both solar photovoltaic (PV) cells and semiconductor purposes. Despite this, planned production is growing. Output of secondary silicon is anticipated to reach 40 kt in France, 30 kt in Germany, and 10 kt in Spain in the near future (International Energy Agency, 2025b).

Electronic grade silicon metal is traded under the UK combined nomenclature (CN) code 38180010 and defined as highly refined, doped silicon intended for electrical use, in forms such as discs, wafers, cylinders or rods. The UK imported silicon used in electronics primarily from Europe (approximately 90 tonnes), followed by Taiwan (approximately 15 tonnes), China (approximately 15 tonnes), and the USA (approximately 11 tonnes) in 2024 (Figure 12). The UK also exported similar quantities of silicon used in electronics in 2024 (Figure 12). Exports were to Europe (approximately 91 tonnes), USA (approximately 34 tonnes), and China (approximately 13 tonnes) (United Nations Statistics Division, 2025b).

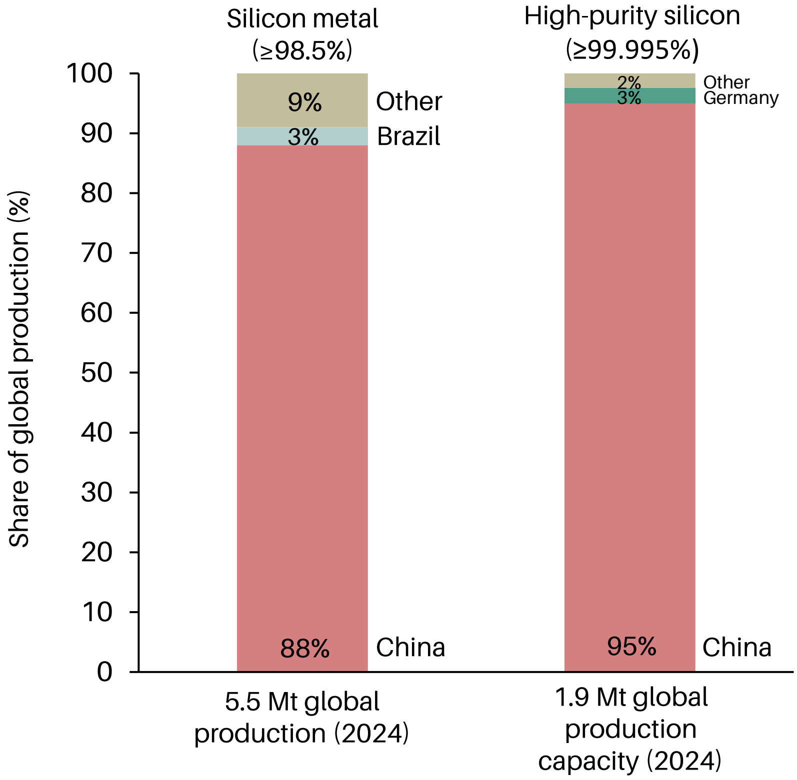


Figure 11. Global production of silicon metal at ≥98.5% (Ciftja et al., 2008) and production capacity for high-purity silicon metal used in solar photovoltaic cells at ≥6N purity (Yadav et al., 2017). Data for silicon metal production after US Geological Survey (2026) and high-purity silicon production capacity after International Energy Agency (2025b).

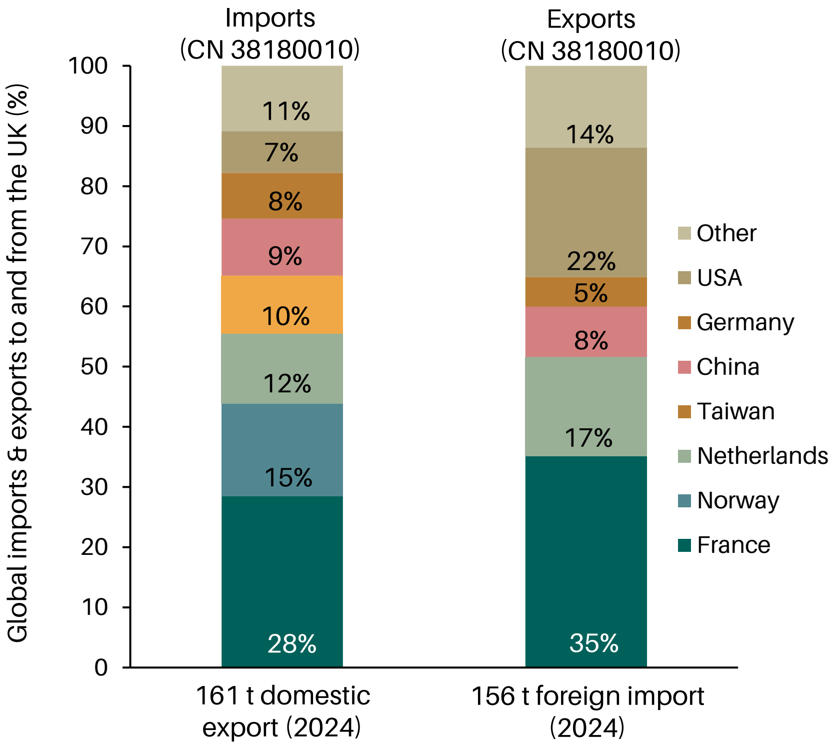


Figure 12. Global exports and imports of electronic grade silicon to and from the UK under CN 38180010. Data source: United Nations Statistics Division (2025b).

5.1.4 Gallium

Gallium (Ga) is relatively abundant in the Earth's crust at approximately 19 ppm, but rarely occurs in concentrated, mineable ores. Instead, it is found as a trace element hosted in other minerals, such as sphalerite, and is therefore produced almost exclusively as a by-product of other metal processing, predominantly bauxite and zinc ore (Butcher and Brown, 2014).

Approximately 90 to 96 per cent of gallium is recovered from the Bayer process waste streams, generated during aluminium oxide production (Wesselkaemper et al., 2025). In the Bayer process, bauxite is treated with caustic soda to dissolve aluminium oxides and produce an alkaline solution commonly called Bayer liquor. That liquor typically contains approximately 100 to 125 ppm gallium, which is separated using proprietary adsorption and ion-exchange methods and then purified further (Butcher and Brown, 2014).

Gallium is produced as a by-product, therefore reserves and production are not tightly coupled. For example, although some countries, such as the Republic of Guinea, hold a large share of global bauxite reserves. This equates to 23.3 per cent or 399 kt of global gallium reserves, however, they generally export raw bauxite rather than operating downstream processing plants that recover gallium. Australia and Brazil both host considerable proportions of global gallium reserves, at 17.9 per cent (307 kt) and 8.5 per cent (146 kt) respectively in 2021 (Han et al., 2024). These countries use the Bayer process (Butcher and Brown, 2014), but do not report gallium production data (Idoine et al., 2025a). As a result, a country's share of global gallium is decoupled from its share of reserves. For example, China hosted only 2.2 per cent of global gallium reserves in 2021, but has come to dominate gallium supply, producing 97 per cent of the global supply of low-purity gallium in 2024 (Figure 13) due to the country's large, integrated bauxite refining industry (Han et al., 2024).

Recycling and secondary supply present an emerging opportunity to increase global gallium supply. The amount of gallium contained in products has grown rapidly, approximately 19-fold between 2000 and 2021. This has been driven by use in light emitting diodes, mobile phones, computers, photovoltaics, and other electronics. The annual outflow of gallium in end-of-life products rose from approximately 21.3 tonnes per year in 2005 to approximately 99.6 tonnes per year in 2021 (Han et al., 2024). However, a negligible quantity of gallium is currently recovered through end-of-life recycling (Han et al., 2024).

Gallium recovered directly from Bayer liquor or from scrap is typically in the 3N purity range (99.9 per cent). Electronic and semiconductor applications require much higher purity (commonly 6N to 8N) and therefore require additional refining steps. The process of electrolytic refining can reach approximately 4N, followed by fractional crystallisation or zone refining to exceed 6N (Butcher and Brown, 2014; Moskalyk, 2003). High-purity gallium production is not as geographically concentrated as low-purity gallium (Figure 13), with the majority originating from China in 2024 (approximately 250 tonnes), followed by Japan (approximately 110 t), Slovakia (approximately 25 t), Canada (approximately 15 t), the USA (approximately 10 t), and Hungary (approximately 5 t) (Nassar et al., 2024).

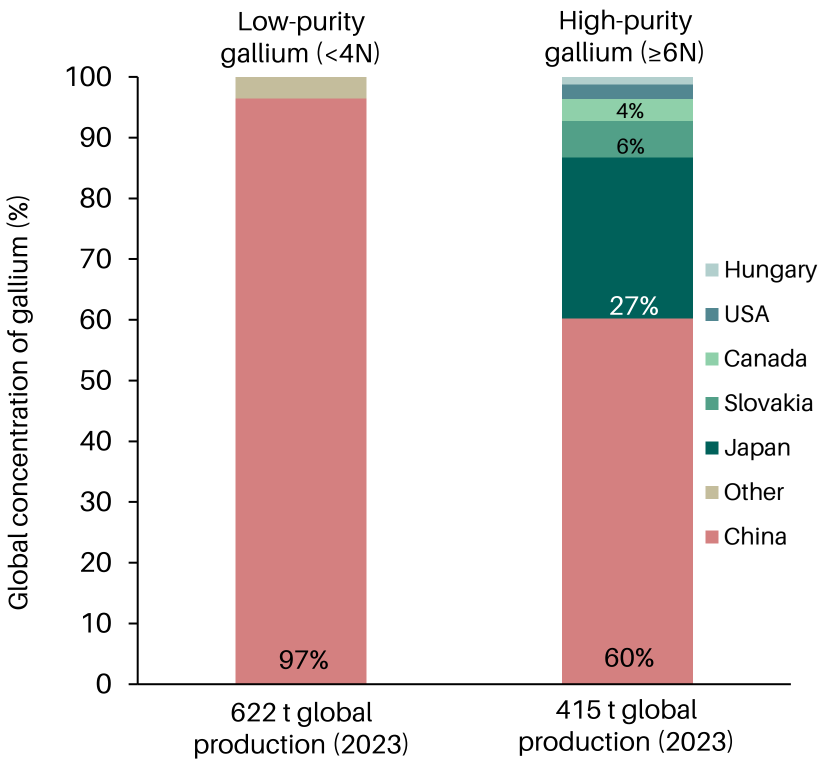


Figure 13. Global concentration of low-purity gallium and high-purity gallium represented as a percentage. Data of low-purity gallium production sourced from Idoine et al. (2025) and high-purity gallium from Nassar et al. (2024).

5.1.5 Germanium

Germanium (Ge) is a trace element in the Earth's crust at a concentration of approximately 1.6 ppm, that rarely forms primary ore bodies. Germanium typically substitutes into sulphide minerals, predominantly sphalerite, wurtzite, and chalcopyrite, and accumulates in organic-rich materials, such as lignite and coal fly ash (Melcher and Buchholz, 2014). Commercial germanium is therefore recovered almost exclusively as a by-product, mainly from the leaching of zinc residues or coal fly ash (Shanks III et al., 2017).

Germanium global reserves are estimated to be 119 kt, 112 kt of which are hosted in coal. Russia has a potential resource of 17.5 kt of germanium across seven deposits, and China 4.2 kt. Other active and potential sources of germanium include the Democratic Republic of the Congo (3.75 kt zinc ore), the USA (2.3 kt zinc ore), and smaller sources in Canada, Mexico, Namibia, Ukraine, and Uzbekistan (Patel and Karamalidis, 2021). Approximately 62 per cent of the world's germanium production is sourced from zinc processing (RFC Ambrian, 2025), although efficient and effective recovery of germanium is a challenge. Outside of China and Russia, only 12 per cent of germanium contained in zinc concentrate or refinery residue is refined. Combining the USA, India, and Australia, only 40-45 t of germanium was recovered out of a potential 336 t of germanium contained in the zinc ores mined during 2011 (Patel and Karamalidis, 2021). This is partly because processing germanium can have a negative impact on zinc recovery (European Commission, 2014).

Approximately 211 tonnes of germanium metal was produced in 2023, with China accounting for approximately 95 per cent of production, followed by the USA (approximately 3 per cent) and Russia (approximately 2 per cent) (Figure 14). Germanium may also be recovered in Canada, Belgium, Germany, Japan, and Ukraine but data is scarce (Idoine et al., 2025a). The Lubumbashi copper-cobalt tailings project in the Democratic Republic of the Congo has the capacity to produce 30 tonnes of germanium per year since 2024, with the concentrate sent to Belgium for refining. Additionally, the USA plans to increase expansion of the Clarksville zinc smelter in Tennessee, potentially adding 30 tonnes per year capacity. Moreover, the Chinese-owned Tsumeb mine in Namibia may add a germanium line at its copper smelter (RFC Ambrian, 2025)

Germanium is recovered by first concentrating it from industrial residues through a series of heating and separation steps, such as retorting, roasting, flotation, and pyrometallurgy, to produce a germanium-rich concentrate. This concentrate is converted into germanium tetrachloride ($GeCl_4$) and further refined by fractional distillation, hydrolysed to germanium oxide (GeO_2) and reduced via reductive pyrolysis to metal powder that is melted into bars (Shanks III et al., 2017). For electronics and detector uses, further purification processes, such as zone refining, fractional crystallisation, and crystal growth, produces ultra-high-purity germanium (≥4N to more than 13N) (Melcher and Buchholz, 2014). Germanium used in semiconductors or solar cells are produced by zone refined germanium metal grown into crystals, sliced into wafers and polished (RFC Ambrian, 2025). Data for high-purity germanium (≥4N) are scarce, and available sources do not identify the key refining countries or players. However, the total germanium production outlined in Idoine et al. (2025a) indicates that China is a dominant producer of high-purity germanium.

Recycling for germanium accounted for approximately 30 per cent of the total global supply in 2021, typically from reclaimed scrap generated during the manufacture of fibre-optic cables and infrared optics (Tolcin, 2025). Recycling end-of-life products is difficult and typically proprietary (RFC Ambrian, 2025). Umicore, a Belgium refiner, has a recycling plant in Olen that recycles germanium-containing end-of-life products, such as optical fibres (Tolcin, 2025). The availability of germanium scrap will increase in the next two decades as aging products, such as fibre optics, solar cells, and military vehicles, reach end-of-life and are taken out of service (Tolcin, 2025). This will provide an opportunity to recover more germanium secondary feedstock.

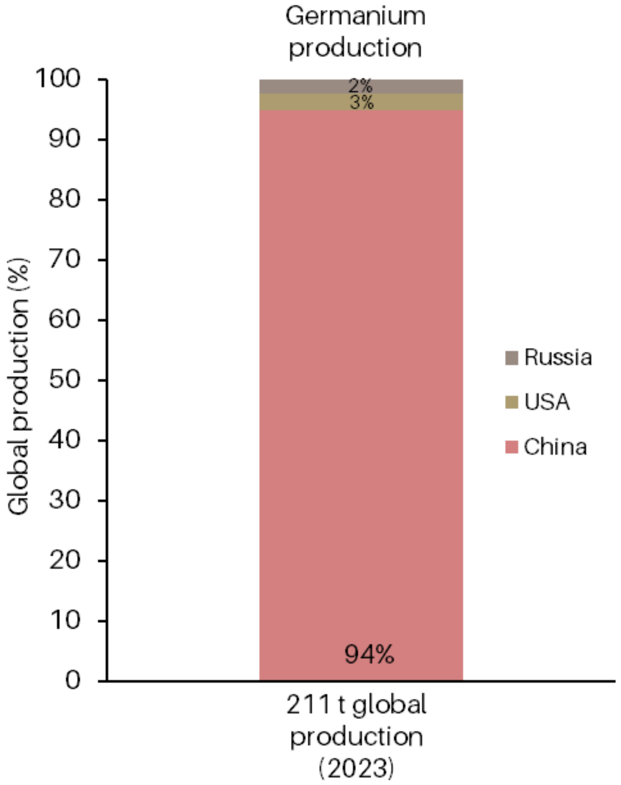


Figure 14. Global concentration of germanium production. Global germanium production and country statistics after Idoine et al. (2025a).

5.1.6 Arsenic

Arsenic (As) has a low crustal abundance of 1.0 to 1.8 ppm and often occurs as a trace element substitute in common sulphide minerals, substituting for iron and/or sulphur in pyrite and sphalerite. Arsenic can also be a major element within minerals such as arsenopyrite (FeAsS), enargite (Cu_3AsS_4), orpiment (As_2S_3), and realgar (As_4S_4). Arsenic is commonly found in gold deposits and ores containing copper, tin, nickel, lead, uranium, zinc, cobalt, platinum, or the borate mineral colemanite (Henke, 2009). The US Geological survey estimated global arsenic reserves at over 900 kt in 2024 (US Geological Survey, 2024b). However, China reported reserves at 3977 kt in 2003 (Xiao Xi-yuan, 2008), highlighting the uncertainty and large disparity surrounding global arsenic reserve estimates and reporting. It is unlikely that arsenic supply is at risk, because arsenic is widely distributed and occurs as a by-product of processing numerous copper, lead, and gold deposits, meaning that if demand increases, additional arsenic could be recovered from other mineral deposits (US Geological Survey, 2025).

Arsenic is refined by two basic industrial routes. The simpler, common route heats arsenic-bearing sulphide ore so the arsenic oxidises to arsenic trioxide (As_2O_3), the vapour is captured and condensed, and the collected oxide is then reduced to produce metallic arsenic (Fedorov et al., 2023). High-purity arsenic metal at 5N5 grade (Roussilhe et al., 2025) is used to produce gallium-arsenic semiconductors (US Geological Survey, 2025). For high purity, arsenic trioxide is converted to arsenic trichloride ($AsCl_3$), which is purified by distillation and adsorption, then converted to arsine (AsH_3) gas and decomposed to deposit ultra-pure arsenic metal (Fedorov et al., 2023).

Peru accounted for 31 162 tonnes of primary arsenic production in 2023, equating to approximately 50 per cent of global supply (largely as As_2O_3), followed by China (38 per cent) and Morocco (10 per cent) (Idoine et al., 2025a). Approximately 95 per cent of arsenic produced is in the form of arsenic trioxide and other combined compounds (Agency for Toxic Substances and Disease Registry, 2007). Therefore, the remaining 5 per cent can be inferred to be arsenic metal equating to approximately 3.1 kt relative to total arsenic production. However, the derived figure of 3.1 kt does not separate high-purity arsenic metal used in electronics from arsenic metal used in nonferrous alloys, ammunition, solders, and other applications (George, 2021). Production volumes of high-purity arsenic metal are difficult to find and may be proprietary information, resulting in our analyses likely underestimating the true quantity of high-purity arsenic production. Additionally, some countries, such as Russia, likely produce high-purity arsenic metal, but do not report any quantities, resulting in their absence in our calculations (Chemical Prom, 2025). Where production volumes are available, it is expected that China produces more than 90 per cent of high purity arsenic metal, with smaller contributions from Japan and Germany (Figure 15).

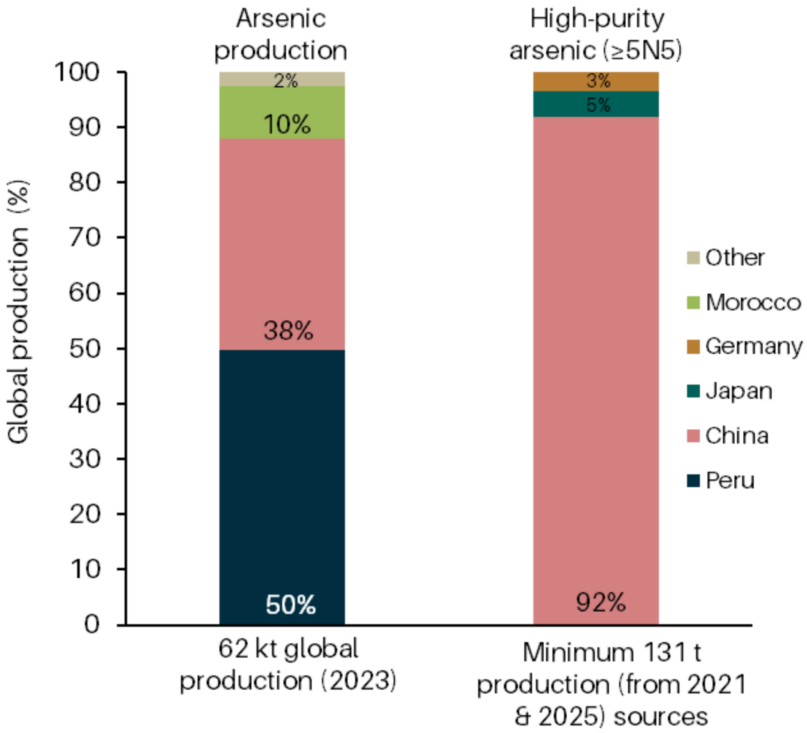


Figure 15. Global concentration of arsenic production and high-purity arsenic (more than 5N5) production. Global arsenic production sourced from Idoine et al. (2025a). Data for high-purity arsenic metal production compiled for Germany and Japan is sourced from Business Research Insights (2025). Data for China sourced from Asian Metal (2021) and Jiangxi Haichen Optoelectronic (2025). Note, high-purity arsenic metal data for China is not exhaustive and production is likely to be higher than reported here.

5.1.7 UK trade supply of high-purity materials

The UK lacks domestic refining capability to produce many of the high-purity elements reviewed in Section 5.1 and instead imports from specialised international refineries and gas suppliers (Table 14). Those supply chains are concentrated in a few countries, particularly China, for silicon (International Energy Agency, 2025b), gallium (Nassar et al., 2024), germanium (Idoine et al., 2025a), and arsenic (Asian Metal, 2021; Business Research Insights, 2025; Jiangxi Haichen Optoelectronic, 2025), creating clear import dependency and supply-chain vulnerability. High-purity gases and processing are supplied by specialist industrial-gas companies, such as Nippon Gases and Linde, but no UK producers of high-purity methane or carbon monoxide were identified (Linde plc, 2025; Nippon Gases, 2025). The exception of this is BOC, a subsidiary of Linde, that has several air separation units (ASUs) in the UK (BOC, 2025) capable of producing high-purity nitrogen (Dawson, 2010).

Table 13. Summary of key country level suppliers of carbon, nitrogen, silicon, gallium, germanium and arsenic. The table identifies upstream sources of the materials, followed by where they are initially refined, then further processed to produce high-purity materials required for electronics.

Element	Upstream	Refining (low-purity grade)	High-purity refining (electronic grade)
Carbon	Primarily obtained from natural gas, sourced through domestic production and imports from Norway and the USA (Jackman, 2025)	No data available, but key country level producers include North America and Europe (Industry Arc, 2025)	
Nitrogen	The UK, Europe, and the US produce nitrogen from ASUs (Castle, 2002)	BOC has several ASUs in the UK (BOC, 2025). Top UK import sources in 2024 were Ireland (8.6 million m$^{3)}$, the USA (4.16 million m^3), and France (1.4 million m^3) (United Nations Statistics Division, 2025a)	
Silicon	Principal high-purity quartz obtained from Spruce Pine (USA) and the Kyshtym vein quartz (Russia) (Ma et al., 2025)	China dominates, produced approximately 85 % global refined silicon (approximately 98.5 % purity) in 2024 (US Geological Survey, 2025)	China dominates, produced approximately 95 % global high-purity silicon (≥ 6N) in 2024 (International Energy Agency, 2025b)
Gallium	By-product from bauxite refining (Bayer process) (Wesselkaemper et al., 2025) with the largest reserves hosted in the Republic of Guinea, Vietnam, and Australia (Han et al., 2024)	China dominates, produced approximately 97 % global refined gallium (approximately 3N purity) in 2023 (Idoine et al., 2025a)	China dominates, produced approximately 60 % global high-purity gallium (≥ 6N) in 2023 (Nassar et al., 2024)
Germanium	By-product of zinc processing and coal-fly ash (Melcher and Buchholz, 2014) with substantial deposits found in China, Russia and the USA (US Geological Survey, 2024b)	China dominates, produced approximately 94 % global germanium in 2023 (Idoine et al., 2025a)	No data
Arsenic	By-product of copper, lead, and gold ores (Henke, 2009). Arsenic reserves unknown but global players include Peru, China, and Morocco (Idoine et al., 2025b)	Peru dominates, produced approximately 50 % global arsenic trioxide in 2023 (Idoine et al., 2025a)	China dominates, produced approximately 92 % global high-purity arsenic metal (≥ 5N5 purity) from 2021 and 2025 (Asian Metal, 2021; Business Research Insights, 2025; Jiangxi Haichen Optoelectronic, 2025)

5.1.8 UK production and capability of high-purity material

The UK's capability in high-purity materials is limited upstream but stronger downstream. Whilst the UK retains significant strengths in semiconductor device fabrication and epitaxy (IQE, 2025;

Wafer Technology Ltd., 2025), it lacks domestic production of most high-purity materials (Table 15).

The UK produces approximately 1.8 per cent of the global supply of natural gas, (International Energy Agency, 2025a), although no facilities were identified for producing high-purity methane. Industrial gas suppliers, such as Linde, operate in the UK but their high-purity production facilities are located in Europe (Linde plc, 2025). Engineering companies, such as ReiCat, Germany, possess the technical expertise to design and install methane purification units (ReiCat, 2025), suggesting that domestic capability could be developed if demand emerges. By contrast, high-purity nitrogen is produced domestically at several ASUs operated by BOC (BOC, 2025; Dawson, 2010).

Primary refining capacity in the UK is absent for semiconductor-relevant elements, such as silicon, gallium, germanium, and arsenic, with the UK ceasing high-purity gallium production in 2018 (US Geological Survey, 2023), and now relying on international trade. Nonetheless, the UK retains its downstream fabrication and epitaxy capability. The Government acquisition of a semiconductor fabrication facility at Newton Aycliffe, County Durham (Octric Semiconductors UK), provides a domestic capacity to manufacture GaAs semiconductor materials (Trueman, 2024b). Commercial companies, such as IQE plc, its subsidiary Wafer Technology Ltd., and Cambridge GaN Devies, manufacture and supply semiconductor materials, including GaAs, GaN, SiGe, and germanium epitaxy (Cambridge GaN Devices, 2026; IQE, 2025; Wafer Technology Ltd., 2025). Whilst upstream refining of elements such as silicon, gallium, germanium, and arsenic, is not currently domestic, the UK has strong downstream capabilities to manufacture semiconductor materials. Moreover, the nascent recycling sector for silicon, gallium, and germanium offer the UK an opportunity to develop domestic secondary feedstocks, lower import dependence, and support mid-stream semiconductor capability (Han et al., 2024; International Energy Agency, 2025b; Patel and Karamalidis, 2021).

The UK demonstrates strong downstream capabilities and could integrate domestic production if a reliable supply stream were established. However, the lack of domestic producers for high-purity methane, silicon, gallium, germanium, and arsenic exposes supply chain vulnerabilities and ongoing dependency on imports. Despite these gaps, the presence of engineering companies capable of installing air separation and gas-enrichment systems, alongside Urenco's operations, the existing semiconductor industry, and opportunities to advance recycling technologies, indicate that the UK has opportunities to strengthen its domestic supply chain.

Table 14. The UK capability in producing, refining, and manufacturing materials critical to quantum technologies and data centres. References in table are as follows; [a] International Energy Agency (2025a), [b] Linde plc (2025), [c] after BOC (2025) and Dawson (2010), [d] Trueman (2024b), [e] IQE (2025), [f] Wafer Technology Ltd. (2025), [g] U.S. Geological Survey (2023).

Element	Upstream	Refining	Manufacturers
Carbon	Produces ~1.8 % of global natural gas[a]	Linde Plc. has head office in UK, there are no domestic facilities[b]	Absent
Nitrogen	BOC has several ASUs throughout the UK able to produce high purity nitrogen[c]		Absent
Silicon	Absent	Absent	Octric semiconductors UK[d], IQE[e] and Wafer Technology Ltd.[f]
Gallium	Absent	Absent. Ceased high-purity refining in 2018[g]	IQE[e] and Wafer Technology Ltd.[f]
Germanium	Absent	Absent	IQE[e] and Wafer Technology Ltd.[f]
Arsenic	Absent	Absent	Octric semiconductors UK[d], IQE[e] and Wafer Technology Ltd.[f]

5.1.9 Future demand for high-purity material

This study has discussed the future of critical technologies, the material requirements for these, and the supply chains for high-purity materials. The following section provides an estimate of the future demand of high-purity materials.

The growing adoption of quantum computing, AI, and the construction of data centres is expected to increase demand for materials critical to their manufacture, such as high-purity silicon. However, the expansion of clean energy technologies, particularly solar photovoltaics and batteries, is projected to be a stronger driver of demand. Global demand for high-purity silicon is forecast to rise from approximately 5 Mt in 2024 to approximately 7 to 7.5 Mt by 2050 (International Energy Agency, 2025b). This increase will be primarily driven by its use in solar PV, batteries, semiconductors, silicones, and alloys. The semiconductor industry will contribute to growing demand, although its share remains relatively small compared to that from the clean energy sector.

To estimate the potential effects of data centre growth on high-purity material demand, two complementary methods were applied. Method 1 scales material demand based on the proportion of data centre electricity consumption relative to total UK electricity generation, whilst method 2 scales demand according to the projected increase in data centre electricity consumption over time. Both methods use electricity projections from the National Energy System Operator (2025) under four scenarios: (1) holistic transition, (2) electric engagement, (3) hydrogen evolution, and (4) falling behind. Each method is anchored to 2023 (and 2024 for silicon) baseline production levels (Table 16) to generate future demand estimates.

Both approaches indicate that global demand will rise rapidly. Relative to 2023/2024 production, projected demand increases by approximately 150 to 330 per cent by 2030, 160 to 720 per cent by 2040, and 160 to 930 per cent by 2050 (Figure 16). These estimates are intentionally simple and assume that UK electricity trends reflect global patterns. They do not account for supply-side constraints, material substitution, or increasing efficiency of technology. Nevertheless, the models indicate that data centre growth could drive substantial increases and, in extreme cases, an order of magnitude rise in demand for high-purity materials over the coming decades.

Table 15. Estimated production of high purity materials (gallium, germanium, silicon, and arsenic) based on the global production and the estimated fraction used in electronics. Global production statistics for gallium, germanium, and arsenic sourced from Idoine et al. (2025a) and silicon from US Geological Survey (2025). Estimated fraction of materials used in electronics for gallium sourced from Cui et al. (2016), germanium from Patel and Karamalidis (2021), silicon from SCRREEN (2023), and arsenic from US Geological Survey (2025).

Metal	Fraction used in electronics (%)	Global production (kt)	Estimated volume used in electronics (t)
Gallium	50	0.622 (2023)	311
Germanium	15	0.211 (2023)	32
Silicon	2	4600 (2024)	92,000
Arsenic	5	62 (2023)	3,100

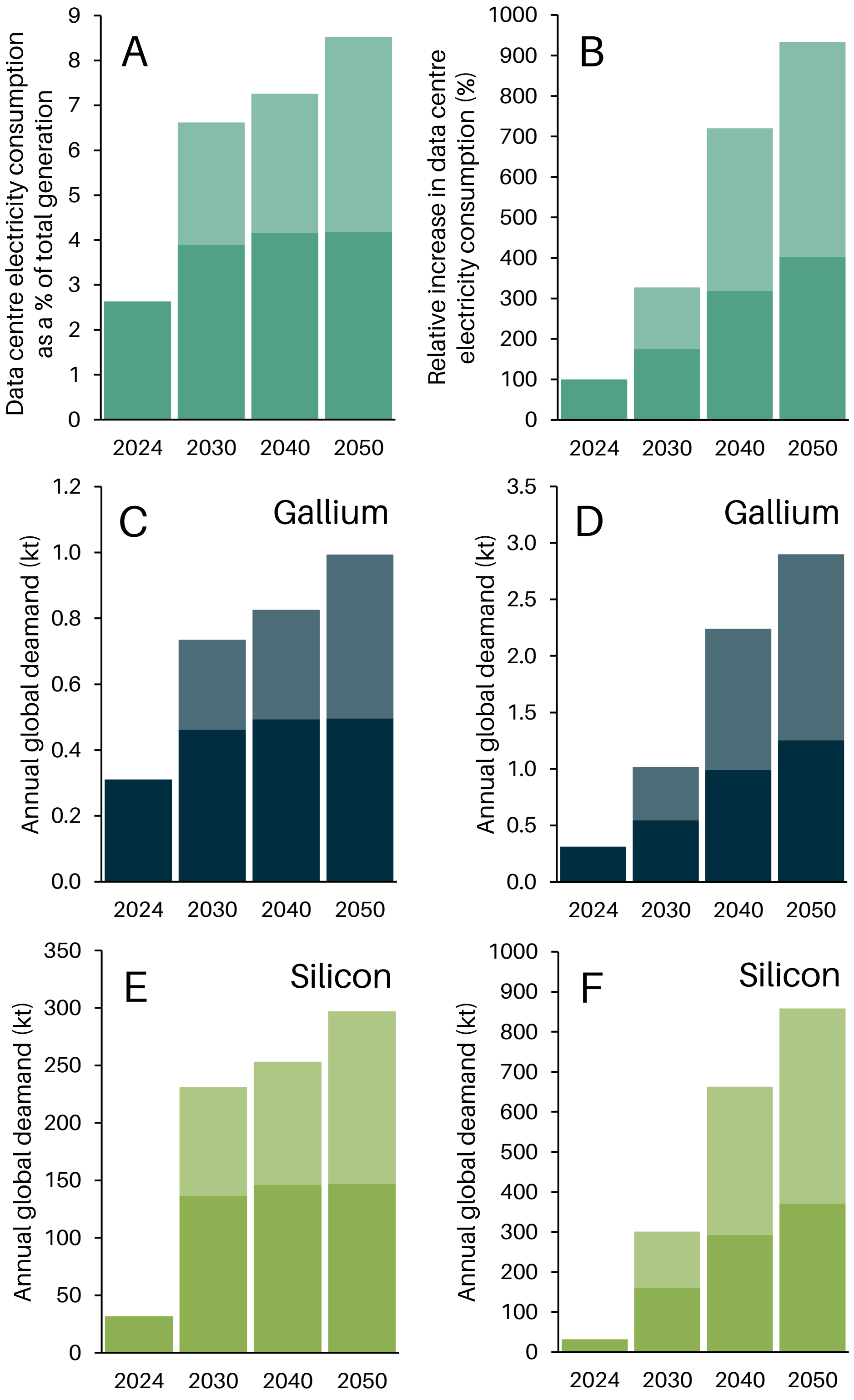


Figure 16. Projected effect of data centre growth on high-purity material demand. (A, B) UK electricity-consumption scenarios for data centres. Estimated global annual demand for gallium (C, D) and silicon (E, F), scaled from 2023/2024 production using Method 1 (left) and Method 2 (right). Both approaches use National Energy System Operator (2025) electricity projections future scenarios, with darker and lighter colours marking minimum and maximum values. Baseline 2024 (gallium uses 2023 value assuming the same for 2024) values from Table 16.

5.2 ISOTOPICALLY PURE MATERIALS

Isotopes are atoms that contain the same number of protons but differ in the number of neutrons. Isotopes can be denoted in the form ${}^{m}_{n}E$ where "*m*" is the mass number and "*n*" is the number of neutrons contained in the nucleus of element E (Hoefs, 2021). Using an example, carbon is typically denoted as ${}^{12}_{6}C$, comprising of six neutrons and six protons, resulting in a total mass of 12. Carbon-12 (^{12}C) is the most commonly found stable isotope of carbon, but it can also occur naturally as carbon-13 (^{13}C) (Wagner et al., 2018), consisting of seven neutrons and six protons (${}^{13}_{6}C$).

The structure of an atom is responsible for both the chemical and physical properties of an element. Generally, the arrangement of electrons around the nucleus determines the chemical behaviour of an element, whereas the number of neutrons and protons in the nucleus determines its physical properties. As such, the variations in the number of neutrons between isotopes of an element can give rise to differences in both chemical and physical properties (Hoefs, 2021). One such property includes nuclear spin, which occurs when the spins of protons and neutrons don't cancel each other out, giving the nucleus a tiny magnetic moment. Isotopes with non-zero nuclear spins, such as carbon-13, therefore, act like magnets that create fluctuating magnetic fields.

Nuclear spins can have a dual effect on quantum technologies. The nuclear spins of vacancy centres within an isotopically pure medium can be used as well-shielded, long-lived qubits or quantum memories, for example the nitrogen vacancy centre in an isotopically purified carbon-12 diamond (Waldherr et al., 2014). However, element or isotope impurities within a medium can have nuclear spins that generate fluctuating magnetic fields, acting as a source of magnetic noise that cause decoherence upon interacting with qubits (Jing and Wu, 2018). By contrast, spin-zero isotopes, such as carbon-12, provide a host lattice that minimises magnetic noise and thereby preserves coherence of nearby qubits (Balasubramanian et al., 2009).

The use of ultra-high purity materials avoids these challenges by removing impurities at the parts per million to parts per billion levels. Quantum technologies often also require specific isotopic enrichment of the host element. Meeting these requirements depends on isotope separation techniques rather than standard metallurgical refining. Isotope separation techniques cover diverse physical and chemical methods to exploit the different isotopic properties. Each technique differs in how they separate isotopes, the quantity produced, and operational cost. Separation techniques include, but are not limited to, the following:

- **Cryogenic distillation:** separation of isotopes in distillation columns utilising differences in volatility properties. Lighter isotopes separate into vapour phases, whereas heavier isotopes concentrate in liquid phases (McInteer, 1980).
- **Thermal diffusion:** laboratory-scale method involving the use of a temperature gradient to separate isotopes within a gas, with heavier isotopes diffusing in the direction of decreasing temperature and lighter isotopes diffusing in the direction of higher temperatures (Chapman and Dootson, 1917; Eriksen, 2015).
- **Gaseous diffusion:** separation of isotopes by taking advantage of differences in thermal velocities of molecules in a gas (Wooldridge and Smythe, 1936) by forcing a gas through a porous barrier under a pressure difference. Lighter isotopes move faster and therefore encounter holes in the barrier more often, creating a light isotope-enriched gas (Krass et al., 1983). This method is now obsolete and replaced by the more efficient gas centrifuge techniques (Peachey, 2013).
- **Gas centrifugation:** a high-speed rotating cylinder is used to separate isotopes in a gas based on mass difference, with heavier isotopes pushed toward the outer wall and lighter isotopes remaining closer to the centre. Multiple separation stages can be built into a single unit to achieve the desired isotopic purity (Roberts, 1989).
- **Aerodynamic separation:** a technique similar to gas centrifugation, during which a high-speed gas flow in a curved path is used to create a pressure gradient. Lighter isotopes are

carried to the centre of the flow and heavier isotopes driven to the outer regions (ASP Isotopes, 2025a; Ronander et al., 2012).

- **Ion exchange:** a sodium hydroxide liquid solvent is fed into a column packed with strongly acidic cation exchange resin with adsorbed ammonium ions. Nitrogen-14 is enriched at the front of the ammonium boundary, whereas nitrogen-15 is enriched at the rear of the boundary (Ding et al., 2008; Spedding et al., 1955).
- **Chemical exchange:** uses the tendency of different isotopes to naturally concentrate into different compounds. Refluxing of a packed column builds an isotopic gradient for effective separation of the isotopes into different compounds (Begun et al., 1957).
- **Electromagnetic isotope separation (EMIS):** a low quantity method involving vaporisation of material into a gas phase that is then ionised and focused into an ion beam. Channelling of the ion beam through a magnetic field causes isotopes with different mass to charge ratios to travel along different trajectories, allowing them to be focused into separation collection pockets, where they can be recovered (Perović, 1983).
- **Laser isotope separation:** method involving the excitation of specific isotopes by a laser tuned to a particular wavelength (Parvin et al., 2004). The excited and unexcited molecules respond differently in a flow, allowing the separation of an isotopically enriched product (Lyman, 2005; Snyder, 2016). Advanced laser stable isotope separation uses ultraviolet fibre lasers to breakdown compounds containing a particular isotope, leaving the remaining compounds preferentially enriched in other isotopes (Jeong et al., 2018).

5.2.1 Global isotopes supply

Materials enriched in specific isotopes are a requirement for many critical technologies and future demand is predicted to increase (Colwell, 2025). Therefore, it is important to analyse the global supply chains of isotopically enriched materials, to determine any challenges or opportunities relating to their production and supply chains. Data relating to the quantity of isotopes produced is typically proprietary or confidential information, leading to challenges in examining the trade of these materials. Approximate values are provided where data can be determined, however this information may be dated. For example, reported values of carbon-13 production by Cambridge Isotope Laboratories in 2018 (Table 23) likely underestimate the true value since the expansion of their operations with the North Star project in 2024 (Cambridge Isotope Laboratories, 2024). Therefore, this section focuses on the key corporate players and their location to better understand isotope supply chains.

This section focuses on the isotopes of helium, carbon, nitrogen, silicon, germanium, and barium. Arsenic is excluded because it has only one stable isotope (^{75}As) (Vasiliu and Dixon, 2018). Gallium is also omitted as its two stable isotopes (^{69}Ga and ^{71}Ga) both have a 3/2 nuclear spin and therefore exhibit similar properties, providing no justification for enriching either isotope (Humayun, 2018).

5.2.1.1 Helium-3 and helium-4

Helium-3 and helium-4 are the only two stable isotopes of helium and have a natural abundance of 0.000137 per cent and 99.999863 per cent, respectively (McGregor and Shultis, 2020). Both helium-3 and helium-4 are used in quantum computing to power cryogenic systems that cool quantum processors to the extremely low temperature required for stable qubit operations (see section 3.4). Dilution refrigerators use a mixture of helium-3 and helium-4 to provide continuous cooling down to the millikelvin (<0.1 K) temperature range required by many quantum processors. The cooling is a result of the thermodynamic behaviour of the helium-isotope mixture, which allows steady extraction of heat to below 0.1 K (Zu et al., 2022).

Helium-4 is produced at a commercial scale as a by-product of natural-gas processing, with the USA producing approximately 44 per cent (approximately 12,870 tonnes per year) of global supply, followed by Qatar at approximately 35 per cent (US Geological Survey, 2025). Helium-3 is extremely scarce, and commercial production typically comes from the radioactive decay of tritium generated in heavy-water nuclear reactors or in a few natural gas-fields. Helium-3 is enriched using pre-enrichment methods, such as gas chromatography, combined with cryogenic distillation and other methods, such as superfluid titration and adsorption, to achieve up to 99.9 per cent isotopic purity (Niculescu et al., 2025). There are only a few commercial producers of helium-3 globally, with the volume of helium-3 produced typically confidential (Table 17). There are currently no manufacturers of helium-3 within Europe.

Table 16. Helium-3 manufacturers. Volume data, where available, are reported together with the year. ‘Producing’ indicates companies that produce an isotope but do not report volume quantities. Companies that do not produce the isotope are denoted as ‘-‘. Data sources: [a] Lurentis Energy Partners (2021), [b] Juyal (2024), and [c] Savannah River Site (2026).

Country	Manufacturer	Method of production	Volume (Mm^3 ^{3}He/yr)
Canada	Laurentis Energy Partners[a]	Radioactive decay of tritium	Producing
China	China National Nuclear Corporation[b]	Radioactive decay of tritium	In development
Russia	Isotope JSC (Rosatom)[b]	Radioactive decay of tritium (BGS assumption)	Producing
USA	Savannah River Site (Department of Energy)[c]	Radioactive decay of tritium	Producing (likely dominant producer)[b]

5.2.1.2 CARBON-12 AND CARBON-13

The stables isotopes of carbon include carbon-12 and carbon-13, comprising 98.89 per cent and 1.11 per cent respectively of the carbon on Earth (Wagner et al., 2018). Both isotopes are used in quantum technologies. Carbon-12 has no nuclear spin, and reducing the fraction of spin-carrying carbon-13 in a diamond lattice minimises background magnetic noise caused by nuclear spins and increases coherence times of qubits generated by nitrogen vacancy centres. By contrast, carbon-13 carries a nuclear spin and can itself act as a controllable qubit or quantum memory. Hence both isotopes are essential to different quantum applications (Waldherr et al., 2014).

Cryogenic distillation accounts for approximately 99 per cent of carbon-13 production since 2018 (Khoroshilov, 2018). Cambridge Isotope Labs is one of the world's largest manufacturers and suppliers of stable isotopes, producing quantum grade carbon-12 (99.99 per cent) and high-purity carbon-13 (99.9 per cent) methane (Cambridge Isotope Laboratories, 2021). Manufacturers of carbon isotopes are concentrated within the US, Russia, and east Asia, with the USA being the top producer (Table 18). There are currently no manufacturers of carbon isotopes within Europe.

Table 17. Isotope carbon-12 and carbon-13 manufacturers. Volume data, where available, are reported together with the year. 'Producing' indicates companies that produce an isotope but do not report volume quantities Companies that do not produce the isotope are denoted as '-'. Data sources: [a] Khoroshilov (2018), [b] ASP Isotopes (2025a), [c] Sakurai et al. (2022), and [d] QuTope (2025).

Country	Manufacturer	Method of production	Volume (kg ^{13}C/yr)	Volume (kg ^{12}C/yr)
USA	Isotec, Inc.[a]	Carbon monoxide cryogenic distillation	100 (2018)	Producing
	Cambridge Isotope Laboratories, Inc.[a]	Carbon monoxide / methane cryogenic distillation	420 (2018)	Producing
	ASP isotopes[b]	Aerodynamic separation	Producing	Producing
China	Jiangsu Zhengnen Isotope Co., Ltd.[a]	Carbon monoxide cryogenic distillation	Projected 600 (2018)	-
Russia	Kurchatov Institute[a]	Carbon monoxide cryogenic distillation	Producing	-
	SC "PA Electrochemical Plant" (Rosatom)[a]	Gas centrifugal separation	~5 (2018)	-
Japan	Tokyo Gas Company[a]	Methane cryogenic distillation	100 (2018)	-
	TAIYO NIPPON SANSO[c]	Methane cryogenic distillation	Projected	-
South Korea	QuTope[d]	Laser separation (ALSIS)	Producing	Producing

5.2.1.3 NITROGEN-14 AND NITROGEN-15

The stables isotopes of nitrogen include nitrogen-14 and nitrogen-15, comprising 99.632 per cent and 0.368 per cent respectively of natural nitrogen (Cartigny and Busigny, 2018). Both isotopes are useful in the manufacturing of nitrogen vacancy centre diamonds due to nitrogen-14 having a nuclear spin of 1, whilst nitrogen-15 has a nuclear spin of ½ and can be used as quantum qubits (Gulka et al., 2021).

Commercialised production of nitrogen isotopes typically uses chemical exchange, cryogenic distillation, and centrifugation (Table 19). Whilst many facilities produce nitrogen-15, it is often unclear whether they also manufacture or market nitrogen-14. Isotopic separation methods inherently generate a nitrogen-14 enriched fraction; however, it is uncertain whether this by-product is refined or made available commercially (Table 23). Alternatively, as nitrogen-14 is so abundant relative to nitrogen-15, there may not be a need to isotopically enrich nitrogen-14 further. The manufacture of isotopes is concentrated in North America and east Asia with some European capability (Table 19).

Table 18. Isotope nitrogen-14 and nitrogen-15 manufacturers. Volume data, where available, are reported together with the year. 'Producing' indicates companies that produce an isotope but do not report volume quantities. Companies that do not produce the isotope are denoted as '-'. Data sources: [a] Khoroshilov (2018), [b] CPI Georgia (2025), and [c] China Isotope Development Centre (2025a). NHTCG – National High Technology Centre of Georgia, INCDTIM – National Institute for Research and Development of Isotopic and Molecular Technologies, SRICI – Shanghai Research Institute of Chemical Industry.

Country	Manufacturer	Method of production	Volume (kg ^{14}N/yr)	Volume (kg ^{15}N/yr)
Georgia	NHTCG[a]	Chemical Exchange NO-HNO_3	-	Producing
	CPI Georgia[b]	NO cryogenic distillation	-	Producing
USA	Isotec, Inc[a]	NO cryogenic distillation	-	Producing
	CIL, Inc[a]	NO cryogenic distillation	-	16 (2018)
	ICON, Los Alamos National Laboratory[a]	NO cryogenic distillation	-	Producing
Romania	INCDTIM[a]	Chemical Exchange NO-HNO_3	-	Producing
China	SRICI Co., Ltd[a]	Chemical Exchange NO-HNO_3	-	30 (2018)
	China Isotope Development Co Ltd[c]	Cryogenic distillation & Chemical exchange NH_3-HNO_3	-	Producing
Japan	SHOKO Science Co., Ltd[a] (SI Science Co., Ltd)	Chemical Exchange NO-HNO_3	-	5 (2018)

5.2.1.4 SILICON-28

There are three stable isotopes of silicon: silicon-28, silicon-29, and silicon-30, with natural abundances of 92.23 per cent, 4.67 per cent, and 3.1 per cent respectively (Shahar, 2018). Silicon-29 is the only stable isotope of silicon with a nuclear spin (Itoh and Watanabe, 2014). Nuclear spin can act as a source of magnetic noise, interfering with quantum information and reducing the performance of silicon-based qubits (Lo and Morton, 2014). Consequently, developers of semiconductor spin qubit technologies preferentially use isotopically enriched silicon-28 substrates to minimise decoherence arising from host nuclear spins (Itoh and Watanabe, 2014). Ideally, quantum applications require a purity of at least 99.99 per cent silicon-28, (Lee, 2024a).

Urenco is one of the world's largest producers of isotopically enriched material, utilising gas centrifuges to produce enriched silicon-28 (Table 20). Although the UK holds a one-third ownership stake in Urenco (Urenco, 2025b), production facilities are located outside the UK, in the Netherlands (Urenco, 2025a). Only the enrichment facilities of the Russian TVEL Fuel Company, a subsidiary of the state-owned Rosatom group, have a similar production capacity to Urenco. Both Urenco and TVEL have demonstrated the ability to enrich $^{28}SiF_4$ to an isotopic purity of up to 6N (Ernst et al., 2024).

Silicon is typically enriched in gas centrifuges as silicon tetrafluoride (SiF_4) that is then converted to silane (SiH_4) and further converted into thin silicon-28 layers by chemical vapour deposition (Ernst et al., 2024). While not yet commercial, other ongoing research to produce silicon-28 include SILEX at a purity of approximately 4N8 silicon-28 (Silex Systems Limited, 2025) and the National Institute of Standards and Technology producing more than 6N6 silicon-28 using an electromagnetic isotope separator (EMIS) (NIST, 2014). Isotopically enriched silicon manufacturing is concentrated in Europe and South Africa, with capability being developed in Australia and North America (Lee, 2024a). It is worth noting that ASP isotopes is a US based company, but the isotopic enrichment plants are in South Africa (ASP Isotopes, 2025d).

Table 19. Isotope silicon-28 manufacturers. Volume data, where available, are reported together with the year. 'Producing' indicates companies that produce an isotope but do not report volume quantities. Data sources: [a] ASP Isotopes (2025d), [b] Urenco (2025c), [c] Silex Systems Limited (2025), [d] Colwell (2025), [e] Ernst et al. (2024), [f] Orano Group (2025a), and [g] China Isotope Development Centre (2025a).

Country	Manufacturer	Method of production	Volume (kg ^{28}Si/yr)
South Africa	ASP isotopes[a]	Aerodynamic separation	Estimate: 80 (2025)
UK/Germany/ Netherlands	Urenco[b]	Gas centrifuge	Estimate: 100's[d] (2024)
Australia	Silex[c]	Laser separation (SILEX)	Estimate: 20 by 2027
Russia	TVEL (Rosatom)[e]	Gas centrifuge	Similar to Urenco[e] (2024)
France	Orano Group[f]	Gas centrifuge	Producing
China	China Isotope Development Co Ltd[g]	Gas centrifuge (BGS interpretation)	Producing

5.2.1.5 Depleted germanium-73

Germanium has five stable isotopes, including germanium-70 (20.57 per cent), germanium-72 (27.45 per cent), germanium-73 (7.75 per cent), germanium-74 (36.50 per cent), and germanium-76 (7.73 per cent; Derry, 2018). Germanium-73 is the only isotope with a nuclear spin, which can result in decoherence of qubits within quantum computing applications (Hendrickx et al., 2024).

Isotopically depleted germanium-73 can be achieved by the centrifugation of monogermane (GeH_4), followed by cryogenic distillation. The purified monogermane is turned into polycrystalline germanium-72 through pyrolysis, a type of thermal decomposition, and then further purified by zone crystallisation (Troshin et al., 2023). Manufacturers of depleted germanium-73 are based in South Africa, Europe, and east Asia (Table 21).

Data on the commercial production capacities for the isotopic enrichment of germanium are difficult to obtain. However, the LEGEND-1000 physics programme, requires roughly 1,000 kg of germanium-76 enriched to approximately 92 per cent and, envisages a production of approximately 200 kg of germanium-76 per year (Radford, 2023). Although the producer(s) and the wider global capacity data are not available, the LEGEND-1000 project provides a useful lower-bound estimate of isotopically enriched germanium that could be in the order of 100's of kg annually.

Table 20. Germanium isotopic manufacturers. Volume data, where available, are reported together with the year. 'Producing' indicates companies that produce an isotope but do not report volume quantities. Data sources: [a] ASP Isotopes (2025b), [b] Urenco (2025c), [c] Orano Group (2025b), [d] Isotope JSC (2025), and [e] China Isotope Development Centre (2025b).

Country	Manufacturer	Method of production	Volume (kg ^{xx}Ge/yr)
South Africa	ASP isotopes[a]	Aerodynamic separation	Production expected for 2025
UK/Germany/ Netherlands	Urenco[b]	Gas centrifuge	Producing
France	Orano[c]	Gas centrifuge	Producing
Russia	Isotope JSC (Rosatom)[d]	Gas centrifuge (BGS interpretation)	Producing
China	China Development Centre Co Ltd[e]	Gas centrifuge (BGS interpretation)	Producing

5.2.1.6 BARIUM-137

Barium has seven stable isotopes, including barium-130 (0.11 per cent), barium-132 (0.10 per cent), barium-134 (2.42 per cent), barium-135 (6.59 per cent), barium-136 (7.85 per cent), barium-137 (11.23 per cent), and barium-138 (71.70%; Eugster et al., 1969). Barium-137 is of particular interest in trapped ion quantum computing because the nucleus carries a non-zero spin (I = 3/2) whilst offering practical advantages over other ions, such as ytterbium-171, that make it suitable for use as both qubits (An et al., 2022) and higher-dimensional quantum digits (qudits) (Low et al., 2025).

Enriched barium-137 is typically initially supplied as a chemical feedstock, such as $BaCO_3$, BaO, $BaCl_2$, or barium metal, that is vaporised and then isotopes are separated by laser isotope separation (ASP Isotopes, 2025c) or mass separation methods, such as EMIS (Carney et al., 2013). Barium-137 is also noted to be produced by centrifugation, but there are some uncertainties as to what this method entails (Greenberg Enterprises, 2026). High purity barium-137 (>99.9%) is offered by only a few manufacturers (Table 22), and openly available data on production volumes are limited. Available estimates indicate that global enrichment capacity for barium-137 is small (below 100 kg per year), with the majority produced by Russian facilities, however, these figures are uncertain and should be treated cautiously (Greenberg Enterprises, 2026). The recent emergence of commercial laser-separation entrants, such as Quantum Leap Energy (subsidiary of ASP Isotopes), may broaden supply options (ASP Isotopes, 2025c).

Table 21. Barium isotopic manufacturers. Volume data, where available, are reported together with the year. ‘Producing’ indicates companies that produce an isotope but do not report volume quantities. Data sources [a] ASP Isotopes (2025c), and [b] Greenberg Enterprises (2026).

Country	Manufacturer	Method of production	Volume (kg ^{137}Ba/yr)
South Africa	Quantum Leap Energy (ASP isotopes)[a]	Laser isotope separation	Production expected for 2026
UK/Germany/ Netherlands	Urenco[b]	Gas centrifuge	Producing (on request)
Russia	Isotope JSC (Rosatom)[b]	Gas centrifuge	Producing (likely dominant producer)
USA	NIDC[b]	Mass separator (EMIS)	Producing
	AE Isotopes[b]	N/A	Producing

5.2.2 UK capability and trade of isotopically enriched materials

Isotopically enriched materials are essential for quantum computing and advanced semiconductors. Global production patterns for isotopically enriched materials vary by element, with helium-3 isotope production concentrated in the USA; carbon and nitrogen isotopes produced mainly by the USA, Russia, and China; silicon and germanium isotopes produced by Europe, Russia, and China; and barium isotopes predominantly produced by Russia (Table 23). The UK currently lacks domestic enrichment capacity, relying on foreign imports from a small number of suppliers. This dependency poses strategic risks amid global competition and supply chain vulnerability. The UK has the knowledge to undertake isotopic purification but lacks the facilities and infrastructure for domestic production to occur on a commercial scale. Small-scale academic capability does exist in the UK; for example, the University of Manchester and the Surrey Ion Beam Centre have demonstrated laboratory-scale depletion and enrichment of silicon isotopes (Acharya et al., 2024; Schneider and England, 2023).

Although academic demonstrations are promising for research-scale quantum component fabrication, they do not yet constitute commercial-scale isotope production. The only isotope production affiliated with the UK is that of Urenco's stable isotope operations in the Netherlands (Urenco, 2025a), in which the UK holds a one third ownership stake (Urenco, 2025b). Urenco's stable isotope facility produces a range of isotopes, including cadmium, germanium, iridium, molybdenum, selenium, tellurium, titanium, tungsten, xenon, and zinc (including Cd, Ge, Ir, Mo, Se, Te, Ti, W, Xe, and Zn; Urenco, 2025a). Urenco recently commissioned the Blaise Pascal installation, expanding stable-isotope production capacity, including germanium and silicon (Urenco, 2025d). Whilst the UK has no identified domestic facility for stable isotope enrichment, the UK's direct stake in an established enrichment provider (Urenco, 2025b) offers the UK a foothold in the isotope separation supply chain for a range of elements. However, the purification of other isotopes that are important in the manufacture of critical technologies, such as carbon and nitrogen, must be sourced through global supply chains.

Table 22. Summary of key country and corporate level suppliers of carbon, nitrogen, silicon, and germanium isotopes. The table identifies the dominant methods of isotopic separation used in industry today, the top producing countries and key players. Data sources: [a] Niculescu et al. (2025), [b] Savannah River Site (2026), [c] US Geological Survey (2025), [d] ExxonMobil (2022), [e] Reuters (2025a), [f] Khoroshilov (2018), [g] Colwell (2025), [h] Orano Group (2025a), [i] Orano Group (2025b), [j] Greenberg Enterprises (2026), and [k] ASP Isotopes (2025c)

Isotope	Typical separation method(s)	Top producing countries	Production (kg/yr)	Key producers
Helium-3	Gas chromatography and cryogenic distillation [a]	USA [b]	No data available	Savannah River Site (Department of Energy, USA) [b]
Helium-4	Natural abundance means none is required	USA [c]	Approximately 12.87 million [c]	ExxonMobil (USA) [d]
		Qatar [c]	Approximately 10.84 million [c]	QatarEnergy (Qatar) [e]

Carbon-12	Cryogenic distillation [f]	US and China are thought to be top producing countries (BGS interpretation)	No data available	Cambridge Isotope Labs (USA) [f] Jiangsu Zhengnen Isotope (China) [f]
Carbon-13	Cryogenic distillation [f]	USA [f]	Approximately 500 (2018) [f]	Cambridge Isotope Labs (USA) [f]
		China [f]	Approximately 600 (2018) [f]	Jiangsu Zhengnen Isotope (China) [f]
Nitrogen-14	Cryogenic distillation [f] Chemical exchange [f]	USA and China are thought to be top producing countries (BGS interpretation)	No data available	Cambridge Isotope Labs (USA) [f] Jiangsu Zhengnen Isotope (China) [f]
Nitrogen-15	Cryogenic distillation [f] Chemical exchange [f]	China [f]	Approximately 30 (2018) [f]	SRICI (China) [f]
		USA [f]	Approximately 18 (2018) [f]	Cambridge Isotope Labs (USA) [f]
Silicon-28	Gas centrifuge [f, g, h]	Europe [g]	100s (2024) [g]	Urenco (Europe) [g]
		Russia [g]	100s (2024) [g]	TVEL (Rosatom, Russia) [g]
Depleted germanium-73	Gas centrifuge [g, i]	Europe, Russia and China are thought to be key producing countries (BGS interpretation).	No data available	Urenco (Europe) Isotope JSC (Rosatom, Russia) China Isotope Development Centre
Barium-137	Gas centrifuge [j] Laser mass separation [k]	Russia	No data available	Isotope JSC (Russia) [j]

5.2.3 Future demand of isotopically enriched materials

Predicting future demand for isotopically enriched materials is difficult because production volumes are not well reported and future demand is dependent on the successful scaling of technologies that use isotopically enriched materials. Data centre growth is a driver for the demand of high-purity materials, but it does not generally require isotopically enriched materials. Some studies show increased efficiencies for isotopically purified materials, such as the improved thermal conductivity of silicon-28, yet these approaches are small scale, high cost and not viable as mass-adopted solutions (Ci et al., 2022).

Today, most demand for isotopically enriched materials is for research and medicine, but quantum technologies represent an emerging sector that require high levels of isotopic purity (de Leon et al., 2021). The future deployment of quantum computers and associated systems, such as quantum navigation and networking, could cause the demand for particular enriched isotopes to increase rapidly. These isotopes include:

- Helium-3 (with helium-4) for dilution refrigeration to lower operating temperatures to millikelvin levels, required for several quantum modalities (Niculescu et al., 2025).
- Spin-free isotopes, such as carbon-12, nitrogen-14, silicon-28 and germanium-74, to reduce magnetic noise and enhance qubit coherence (de Leon et al., 2021).
- Spin-active isotopes, such as carbon-13 and barium-137, where nuclear spins are deliberately used as qubits. Barium-137 is of particular interest in trapped ion architectures and may also support higher dimensional quantum digits (qudits) (An et al., 2022; Low et al., 2025).

The future demand for helium-3 is closely associated with the demand for cryogenics and dilution refrigerators deployed across research and industrial systems (Niculescu et al., 2025). Helium-3 supply is limited because it is only produced at few facilities and not manufactured in Europe (Table 17), therefore even modest growth could cause supply chain challenges.

Historical trends for carbon-13, nitrogen-15, and oxygen-18 reported by Khoroshilov (2018) suggest a tenfold increase in the demand for these isotopes every 20 years. Assuming this trend continues and is extrapolated from 2025 to 2050, this could result in the demand for isotopically enriched materials increasing by eight times current production in 2025. Whilst this assumption is an oversimplification, it nonetheless demonstrates that the increase in the demand for isotopically enriched materials could rise rapidly.

Estimates of silicon-28 demand indicate that annual requirements for 4N-purity silicon-28 could reach approximately 1 000 to 5 000 kg by 2035 (Colwell, 2025), compared to current production which is estimated at hundreds of kilograms (Table 20), resulting in a tenfold increase. Published capacity volumes of germanium isotopes are difficult to find, with one source suggesting production in the hundreds of kgs per year (Radford, 2023). Both silicon and germanium isotopes are used in quantum modalities, such as quantum dots, therefore it is plausible that demand for isotopically enriched germanium could rise along a similar trajectory to silicon (Colwell, 2025).

Barium-137 is an example of an isotope with very small current supply (less than 100 kg/yr) and few manufacturers (Greenberg Enterprises, 2026). Barium-137 is a key material requirement of the trapped ion quantum modality and production of higher-dimensional quantum digits (qudits) (Low et al., 2025), therefore commercial adoption of those technologies could trigger sharp increases in demand for barium-137, although new laser separation producers may increase supply diversity (ASP Isotopes, 2025c).

These indications of future demand for isotopically enriched materials are speculative and depend on technology choices and manufacturing practices. Quantum devices face material and engineering challenges (de Leon et al., 2021) and their large-scale practical applicability remains uncertain. Quantum computers are not being designed to replace classic computers but are a new type of computer that is designed to solve particular highly complex problems. Therefore, the use of quantum computers will not be as pervasive as that of classic computers, which may limit the demand for isotopically enriched materials. Regardless, continued advancement in quantum computing and adoption in specific sectors, such as medicine, finance, and sensing, would drive increased demand for specific, high-purity isotopes (Westminster eForum, 2025).

6 Synthesis: challenges and opportunities for the UK

6.1 FUTURE DEMAND AND SECTOR COMPETITION

Technological developments in the fields of AI, data centres, and quantum computing have been moving forward at an exponential pace in recent years. These technologies have transitioned from concepts and research topics to being integrated into daily life within a very short period of time. The integration of these technologies into our society and economy as more general-purpose tools means they are being applied to an ever-increasing number of challenges within industry, science, and manufacturing. As demand grows for AI, the data centres that sustain it, and quantum computers to solve increasingly complicated challenges, so too does the demand for raw materials to create them.

The raw materials required for AI, data centres (Section 2.3), and quantum computers (Section 3.3) have been summarised in this report. As technologies are developing and adapting to tackle increasingly complicated functions and applications, the number of materials utilised in their manufacture is also increasing. Many of these are minor or trace elements that had limited applications in the past but are now relied upon for specialised functions (Nassar et al., 2015), and therefore production is low and supply chains relatively juvenile. The demand for isotopically enriched materials is uncertain, and whilst it will almost certainly increase in line with enhanced demand for these technologies, it is unsure how much demand will grow (Section 5.2.3). The majority of the raw materials required to manufacture these technologies have been categorised as critical minerals by the UK Government (Figure 17) (Mudd et al., 2024a). The risks of not being able to source these raw materials may have a large impact on the UK economy. There are many factors that contribute to the categorisation of a raw material as being critical, including production concentration (discussed in Section 6.3) and production as a co-product or by-product of a primary commodity (discussed in Section 6.2).

Many of the elements required in the manufacture of data centres, AI, and quantum computers are also important constituents of technologies required by other sectors, such as defence, construction, aviation, and clean energy (Figure 17). Therefore, the current and future expansion of data centres as well as the adoption of AI and quantum computers are going to cause future sector competition for the majority of critical minerals, which are vulnerable to geopolitical disruptions and trade issues. One of the largest areas of competition is likely to be battery minerals. Data centres must demonstrate their ability to maintain an uninterrupted power supply to main operations, should an unexpected event occur (Clark, 2025). One of the reliable backup power supplies being used is batteries, which typically require a range of raw materials, such as lithium, cobalt, graphite, and manganese (Mudd et al., 2024a). However, these same raw materials are also required to manufacture the batteries needed for portable electronics, electric vehicles, and renewable energy. The UK battery manufacture demand by 2050, relative to current global mine production, is already estimated at 8 per cent lithium, 5.5 per cent graphite, 3 per cent cobalt, and 2 per cent nickel (Petavratzi et al., 2024c).

The expansion of data centres alone is expected to cause an 11 per cent increase in gallium demand, 2 per cent increase in both copper and silicon demand, and 3 per cent increase in rare earth element demand, relative to current production levels (International Energy Agency, 2025c). Copper in particular is seeing an increase in demand from other sectors, especially decarbonisation technologies, with an estimated requirement of 1.35 million tonnes of copper for heat pump manufacture, 626 000 tonnes for traction motors, and 402 000 tonnes for wind turbine manufacture (Petavratzi et al., 2024a). Silicon demand from decarbonisation technologies is tied to the manufacture of solar panels, which will require an estimated 192 thousand tonnes by 2050 (Petavratzi et al., 2024b), and 91 000 tonnes will be required for anode materials within batteries (Petavratzi et al., 2024c; Petavratzi et al., 2024b). The highest demand for rare earth elements is in the manufacture of permanent magnets, to be used in data centres, quantum computers, decarbonisation technologies, and portable electronics. The 2050 demand for rare earth elements in permanent magnets is estimated to reach 28 000 tonnes for wind turbines, 21 000 tonnes for traction motors, and 8 000 tonnes for heat pumps (Petavratzi et al., 2024a). However, rare earth elements also have important applications to military technologies, such as guidance, weapons, and communication systems (Mancheri et al., 2019).

Many of the elements and materials required for critical technologies are specialised, required in small quantities, and sourced from typically juvenile supply chains (Section 6.2). Due to the low volume demand for these materials and components, and typically restricted range of suppliers (Sections 4 and 5), supply is unresponsive to demand, causing long lead times and high supply risks. Sector competition for these low demand volume specialist materials or bespoke components therefore hinders the supply chain, increasing risks and delays to supply. Materials and components that are not bespoke or unique to data centres or quantum technologies are able to utilise pre-existing and well-established supply chains, such as photonics or semiconductors (Section 3.4). Whilst the sector competition on these supply chains will increase, this typically leads to opportunities for supply chain diversification to reduce the identified risks, making the setup of new companies more economically viable. Superconducting quantum technologies often make use of simpler and more readily available materials, such as niobium and aluminium. While the film growth is largely done in the UK, it requires high-purity material targets. For example, the niobium material supply chain is heavily dominated by China, leading to supply risks and vulnerability. (Kazakova oral communication, 03/02/2026).

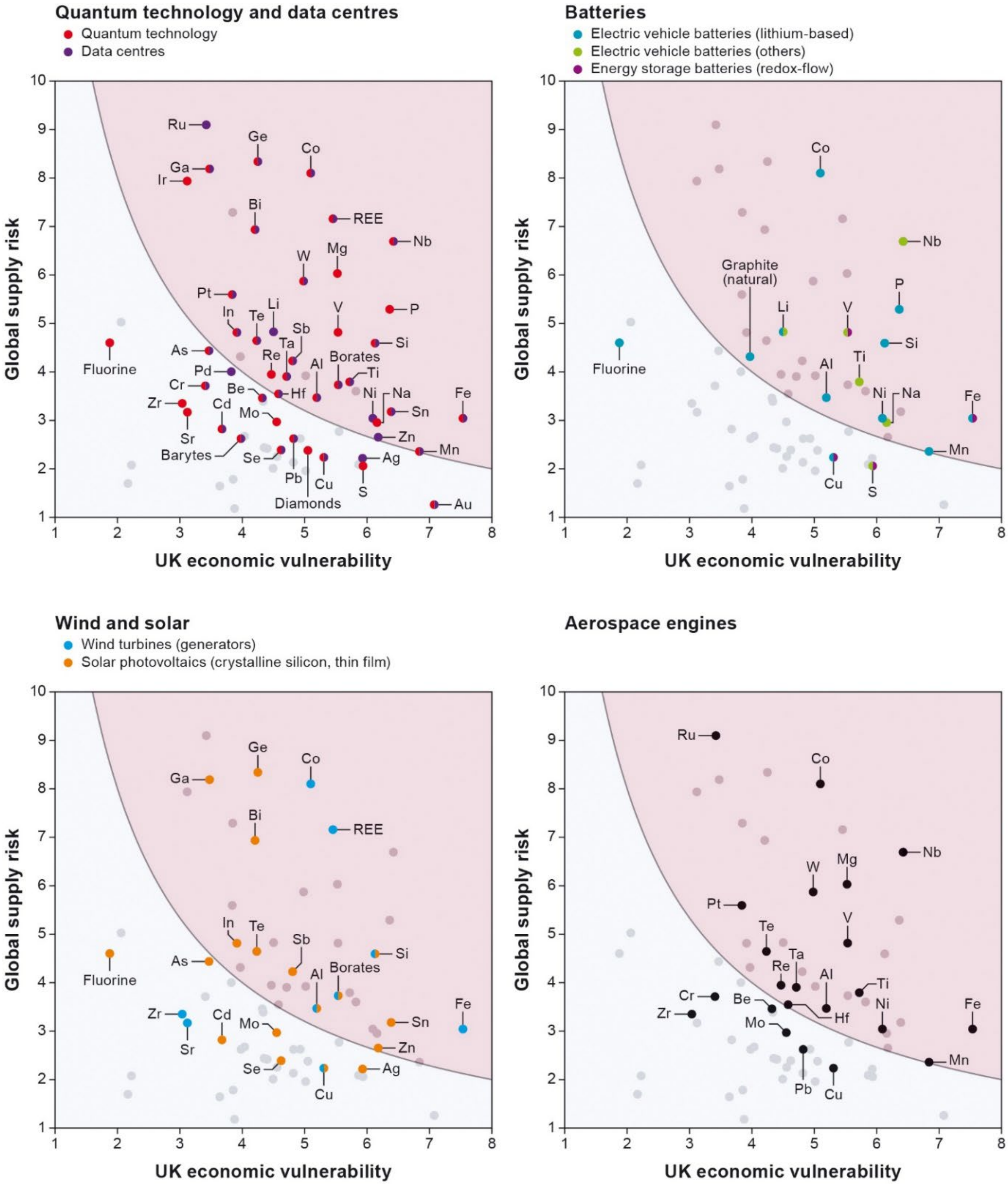
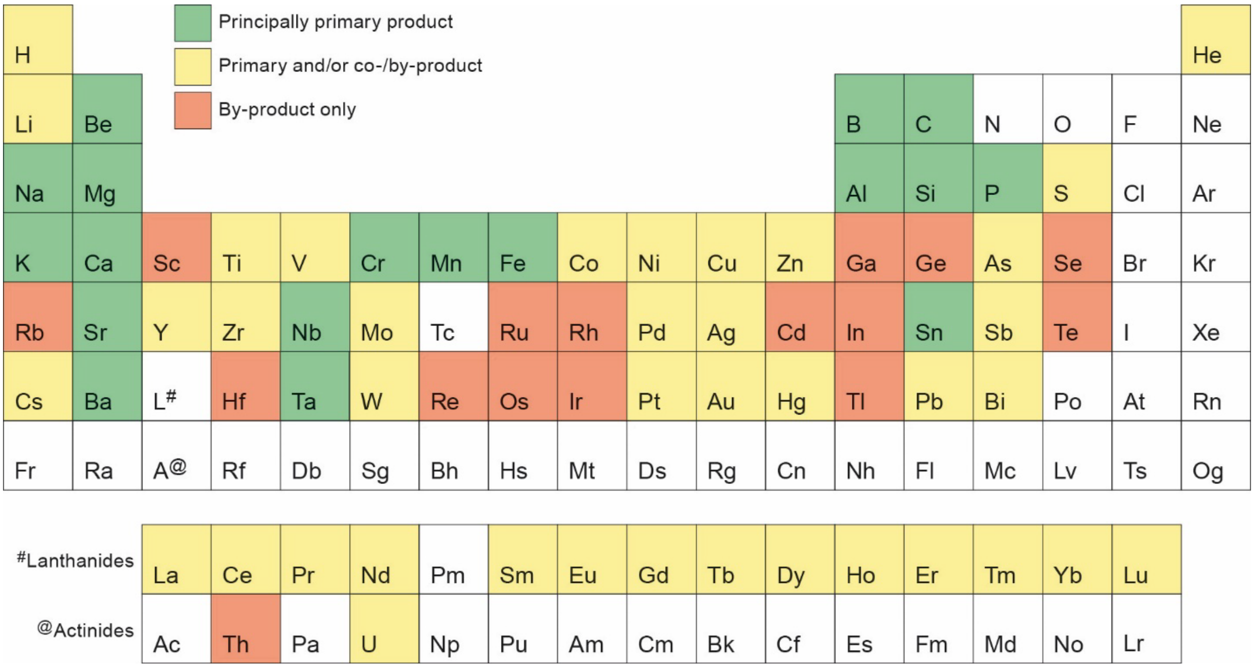


Figure 17. Comparison of materials required for selected technologies displayed through the use of the UK 2024 criticality assessment plot, indicating where sector competition may occur. Adapted from Mudd et al. (2024a). BGS © UKRI

6.2 BY-PRODUCT MATERIAL REQUIREMENTS

The supply of materials for modern technologies and infrastructure begins with the extraction of raw materials through mining, followed by smelting and refining to pure mineral forms or metals, conversion to specific forms, such as alloys, shapes or combinations thereof, and finally, synthesis to a final product or technology, such as a digital computer. A small number of raw materials, such as iron, copper, aluminium, and gold (Figure 18), can be considered primary commodities, where they are the predominant target of extraction and the main revenue generator of a project (Nassar et al., 2015). Deposits do not only consist of one element, however, and can often host multiple minor and trace elements within their mineral structures. These are called companion metals, such as tellurium, indium, cadmium, and hafnium, which can be recovered as co-products or by-products during smelting or refining processes of the primary commodity (Figure 5 and Figure 8).



🟩 Principally primary product
🟨 Primary and/or co-/by-product
🟥 By-product only

🟨 H																	🟨 He
🟨 Li	🟩 Be											🟩 B	🟩 C	N	O	F	Ne
🟩 Na	🟩 Mg											🟩 Al	🟩 Si	🟩 P	🟨 S	Cl	Ar
🟩 K	🟩 Ca	🟥 Sc	🟨 Ti	🟨 V	🟩 Cr	🟩 Mn	🟩 Fe	🟨 Co	🟨 Ni	🟨 Cu	🟨 Zn	🟥 Ga	🟥 Ge	🟨 As	🟥 Se	Br	Kr
🟥 Rb	🟩 Sr	🟨 Y	🟨 Zr	🟩 Nb	🟨 Mo	Tc	🟥 Ru	🟥 Rh	🟨 Pd	🟨 Ag	🟥 Cd	🟥 In	🟩 Sn	🟨 Sb	🟥 Te	I	Xe
🟨 Cs	🟩 Ba	L#	🟥 Hf	🟩 Ta	🟨 W	🟥 Re	🟥 Os	🟥 Ir	🟨 Pt	🟨 Au	🟨 Hg	🟥 Tl	🟨 Pb	🟨 Bi	Po	At	Rn
Fr	Ra	A@	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

#Lanthanides	🟨 La	🟨 Ce	🟨 Pr	🟨 Nd	Pm	🟨 Sm	🟨 Eu	🟨 Gd	🟨 Tb	🟨 Dy	🟨 Ho	🟨 Er	🟨 Tm	🟨 Yb	🟨 Lu
@Actinides	Ac	🟥 Th	Pa	🟨 U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Figure 18. Primary, co-product, or by-product status of most elements, based on expert knowledge of the CMIC team and key studies, such as Nassar et al. (2015) BGS © 2025 UKRI.

An important observation is that many of the elements required for data centre and quantum computing components are by-products, meaning their supply is dependent on the primary extraction and refining of a host metal. As such, production of these by-products is intrinsically linked to extraction levels of the associated primary commodity. Supply of these by-product elements is therefore less responsive to demand fluctuations than that of primary commodities, often creating discrepancies between supply and demand that can have a large impact on manufacturing and markets (Mudd et al., 2024a).

Some important examples of by-product materials used in digital technologies include gallium and germanium. These are both important raw materials for the manufacture of data centre servers and quantum computer detectors, sensors, heterostructures, and semiconductors, whilst also being used in solar panels, permanent magnets within decarbonisation technologies, and in military applications (Mudd et al., 2024a). However, gallium is produced as a by-product of the aluminium and zinc industry, whereas germanium is produced as a by-product of zinc processing and from coal fly ash (Mudd et al., 2024a). Tellurium is also used for data centre servers and quantum computer semiconductors and insulators but is predominantly recovered during the refining of copper and, to a minor extent, gold.

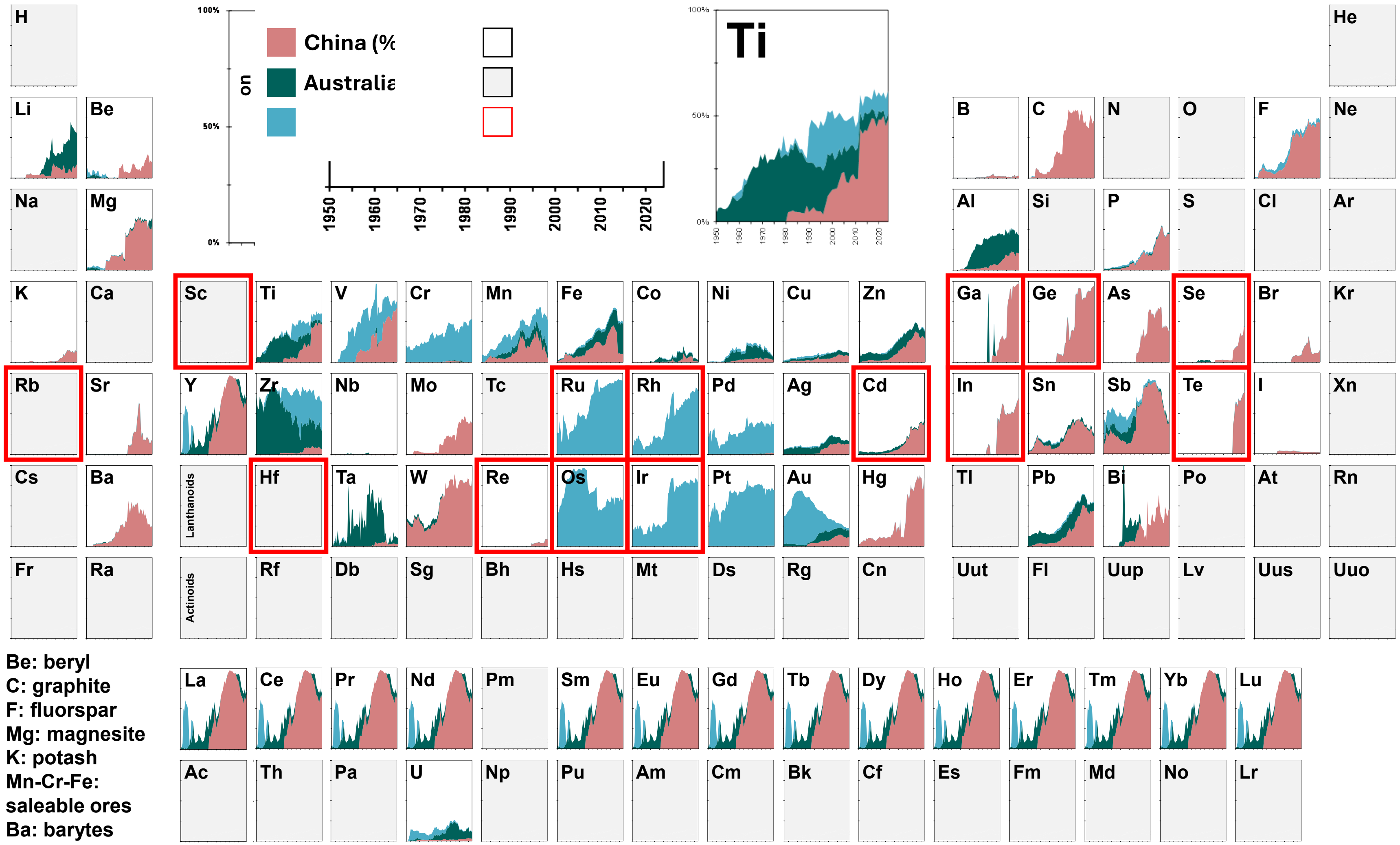
6.3 CONCENTRATED SUPPLY CHAINS

Mining and refining for the majority of critical raw materials is dominated by three or fewer countries (Petavratzi et al., 2024a), creating highly concentrated supply chains that lead to geopolitical and trade vulnerabilities. This concentration can be the result of geological processes leading to an accumulation of mineral deposits in a particular area, historical production centres, policies, and regulations (Mudd et al., 2024a). Supply chain domination and the potential for resulting disruption is a major factor taken into consideration when assessing the criticality of a raw material, expressed by the production concentration indicator in the UK criticality assessment (Mudd et al., 2024a).

The majority of materials needed for data centres, AI, and quantum computers are obtained as by-products of primary commodities. The recovery of many by-products is dominated by China, which is linked to their extensive smelting and refining infrastructure (Mudd et al., 2024a).

To explore this further, this study compiled global mineral production from 1950 to 2024, which shows the proportional roles of China, Australia, and South Africa as leading mining producer nations, as well as highlighting those elements that are by-product only (Figure 19). China is the dominant producer of many by-products, such as gallium, germanium, and tellurium, although it does not produce other by-products, such as the platinum group metals (rhodium, ruthenium, osmium, iridium), for which South Africa dominates production, and rhenium, where Chile dominates (data not shown). For some elements, there is insufficient data to show any trends, such as caesium or rubidium, although it should be noted that the Chinese company Sinomine owns two of the world’s principal caesium producers at TANCO in Manitoba, Canada, and Bikita in Zimbabwe (Sinomine, 2025). Both the Bikita and TANCO mines are mainly lithium producers, with caesium being a by-product, whilst Bikita can also extract tantalum and beryllium (Sinomine, 2025).

A further issue of importance is the proportion of smelting and refining of the primary metals that occurs in China. For example, from 2020 to 2024 China produced 8.3 per cent of world copper mine production but smelted 50.7 per cent and refined 43.4 per cent of world copper output (data after Idoine et al. (2025a) and US Geological Survey (2025)). Where available, data has been compiled to show the proportional roles of China, Australia, and South Africa in mining, smelting, and refining of the primary metals (Figure 20), which facilitate the recovery of various by-product elements. For example, tellurium and selenium can be recovered during copper refining; gallium during alumina refining; and cadmium, indium, and germanium can be recovered from zinc refining. China has developed a dominant global share of production for all these elements (Figure 19).



Be: beryl
C: graphite
F: fluorspar
Mg: magnesite
K: potash
Mn-Cr-Fe: saleable ores
Ba: barytes

Figure 19. Global mineral production from 1950 to 2024 showing the proportion of China (red), Australia (green), and South Africa (blue). Red outlines of boxes show by-product only elements, presented through a visualisation of the periodic table. Data combined from Idoine et al. (2025a), US Bureau of Mines (Various), and US Geological Survey (2024c), including historical editions. BGS © 2025 UKRI.

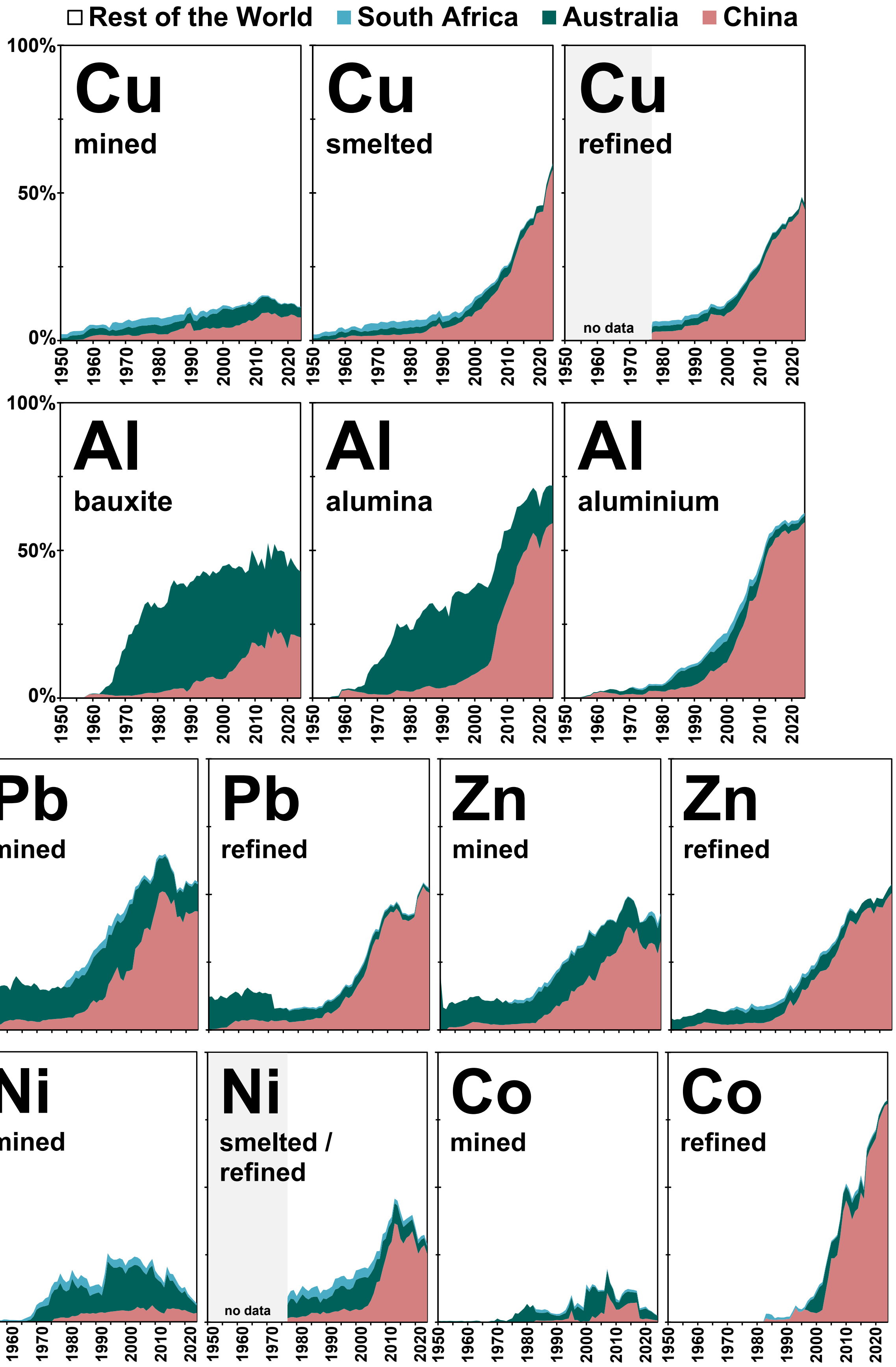


Figure 20. The proportional roles of China, South Africa, and Australia in world mining, smelting and refining of key primary metals. Data combined from Idoine et al. (2025a), US Bureau of Mines (Various), and US Geological Survey (2024c), including historical editions. BGS © 2025 UKRI

In the case of niobium (not shown in Figure 19 or 20), Brazil accounted for 91 per cent of world mine production and 86.6 per cent of smelted ferroniobium during the period 2020 to 2023 (data after Idoine et al. (2025a)). This production is sourced from two mines; the largest is Araxá which is operated by Companhia Brasileira de Metalurgia e Mineração (CBMM) and the smaller Boa Vista mine at Catalão is owned by the Chinese company, CMOC Group Ltd. A Chinese consortium bought 15 per cent of CBMM during 2011 and, when combined with niobium oxide production at Catalão, Chinese companies are responsible for approximately 78 per cent of world niobium mine production (data combined from Medeiros (2025) and US Geological Survey (2025)). The third largest niobium mine in the world is at Niobec in Quebec, Canada, and is owned by Magris Performance Materials Inc, representing approximately 3 per cent of world niobium production in 2024 (US Geological Survey, 2025). This highlights that niobium is one of the most concentrated minerals in the world with just a few mines and companies producing almost all niobium mine production in 2024, with very minor amounts also mined in the Congo region of central Africa and in Russia.

Although China's proportion of world mine production of rare earth elements is declining (Figure 19), mainly due to increased production from the USA, Australia, and Myanmar, China remains the predominant refiner of rare earth elements at approximately 90 per cent (Mudd et al., 2024a). The Democratic Republic of the Congo (DRC) mines the majority of the world's cobalt as a by-product of copper mining, but China is the world's largest refiner of cobalt (Figure 20). Most of the cobalt mined in the DRC is produced by Chinese mining companies, such as the large Tenke Fungurume mine owned by CMOC Group Limited and other companies such as MMG Limited, JCHX Mining Management Co. Limited, Jinchuan International Resources Group Limited, Zijin Mining Limited, and Crystal Mining Limited. Overall, it remains important to understand where world mineral production occurs across the principal stages of mining, smelting, and refining as well as the companies who control this production.

The supply chains for AI, data centres, and quantum computers need to consider bottlenecks further downstream than the mining, smelting, and refining stages. The supply of isotopically pure elements is also highly restricted, with isotopes of helium being of particular concern (Kazakova, 2026) due to the USA and Russia being the only countries currently producing helium-3 (Table 17 and Table 23). Many of the specialist compound materials, such as bismuth, indium, and lithium compounds (Clark oral communication, 15/01/2026; Paul oral communication, 16/01/2026), required to manufacture components for both quantum computers and data centres have no or very restricted supply chains outside of China. Lithium niobate is an important material for all quantum missions in the UK, including computers, communications, sensors, and navigation (Kazakova, 2026), as well as having photonics applications in data centres and other technologies. China is currently retaliating to US trade restrictions by implementing export bans on minerals and materials that are key to the manufacture of critical technologies, such as semiconductors and non-linear crystals (Baskaran, 2024); Paul oral communication, 16/01/2026). Lithium niobate should therefore be highlighted as a material with a particularly high risk to supply.

Changes in the supply chain resilience of elements and compounds, such as gallium, germanium, indium, has also been seen for all businesses and users since China instigated export controls in 2023, including significant delays to importing them into the UK. These trade interventions are causing many global companies to rely on non-Chinese suppliers, causing a large increase in lead times for obtaining these materials. Companies that previously relied on 'just in time policies' are now having to forecast more prudently and consider storing more stock (Davies oral communication, 03/02/2026).

The manufacture of semiconductors is predominantly within Asia, including Taiwan and China (Department for Science Innovation and Technology, 2024; Woods and Gajjar, 2024). Without large fabrication facilities, the UK must rely on imports for most processing units and memory, especially AI processing chips that are in high demand. Reliance on international imports creates uncertainty in the domestic manufacture of data centre and quantum computer technologies, leaving the supply chains vulnerable to long lead times and geopolitical risks. The UK Government has established a £10 million fund to support UK companies to develop and innovate in the field of semiconductors, to accelerate their technology readiness level to market-ready and to establish the UK as a competitor within the global supply chain (Department for Science Innovation and Technology, 2025b).

6.4 RECOVERY AND RECYCLING OF MATERIALS

The recycling of end-of-life products to recover metals is a potential supply of secondary materials that supplements primary supply generated from mining. Recycling diversifies the supply chain of a raw material, reducing reliance on imports and effectively generating a domestic supply of a material that may not be extracted in the UK, therefore reducing risks and vulnerability within the supply chain (Mudd et al., 2024a). However, many of the materials used in the construction of data centre and quantum computer technologies are minor metals, which are either not economically viable to recover or are downcycled to lower-quality products during recycling, and are therefore unsuitable for their original applications and unable to replace their primary feedstock (Mudd et al., 2024a). If this lower-quality product must then be shipped elsewhere to be refined to quality and purity levels required for technology applications, the UK would still be reliant on imports.

Data centres need to replace hardware frequently to keep up to date with AI requirements, leading to retiring of processing units and servers. Worldwide, generative AI could produce approximately 5 million tonnes of electronic waste by 2030 (Zero Tech Waste, 2025). However, quantum computer and data centre components are complicated technologies, requiring a multitude of raw materials in their manufacture (Sections 2.3 and 3.3). The recovery of metals from these technologies is challenging (Mudd et al., 2024a) because technology design is predominantly focused on function and efficiency rather than recycling and metal recovery. Implementation of these digital technologies is relatively recent and many of their trace element constituents lack historic industrial applications. Time is therefore required for digital technologies to reach end of life and build sufficient waste product feedstocks to make recycling and recovery of these trace elements economic and efficient.

Data centres must demonstrate that they are able to provide an uninterruptable power supply, which may involve integration of batteries. The UK is currently actively growing its battery supply chain, which is able to facilitate the requirements of multiple industrial sectors, including electric vehicles, renewable energy, and data centres. Altilium is constructing the UK’s first large-scale electric vehicle battery recycling and refining plant in Plymouth, which will be capable of processing 24 000 electric vehicles per year (Altilium Metals, 2025). Over 20 per cent of battery metals required for UK battery cell production by 2040 could come from a secondary supply obtained by recycling end-of life batteries (Keating, 2022), thus creating a secondary domestic supply of these metals and reducing the UK’s reliance on imports for a number of critical raw materials. Other ventures that aim to create this domestic battery supply chain include the RECOVAS recycling project and deals involving battery manufactures, such as Britishvolt, Glencore, Veolia, and Technology Minerals (Keating, 2022).

Points of waste and scrap generation should also be identified within the supply chain to provide an understanding of where materials may be recovered during the manufacture process. For example, the recycling of gallium is very limited globally, however, the thinning of gallium and indium-based epiwafers causes up to 80 per cent of material to be lost during the device manufacturing process for electronic and photonic devices, into a waste slurry. Both gallium and indium could be recovered from this waste stream and used as a secondary supply. Although this recovery is likely to be more expensive than importing these materials from countries such as China, it could provide a reliable domestic supply that is much less reliant on high-risk global supply chains (Davies oral communication, 03/02/2026).

6.5 UK CRITICAL TECHNOLOGIES SKILLS SITUATION

Whilst the demand for data centres and AI continues to rise and the global race toward employing quantum computers accelerates; there is growing concern regarding skills shortages relating to these critical technologies. Digital technologies have been highlighted as the sector with the second highest additional employment demand in the UK between 2025 and 2030, with the majority requiring Level 4 education (for example, certificate of higher education or higher apprenticeship) or higher (Skills England, 2025b). Despite considerable national investment of approximately £1.1 billion since 2014 and more than 600 PhD students trained through the UK's National Quantum Technology Programme, skills remain a limiting factor, particularly the engineering workforce that will be needed to build quantum technology (Westminster eForum, 2025). Skills shortages account for 36 per cent of vacancies in AI-related job roles and AI careers are expected to grow twice as fast as other careers up to 2035, although UK quantum companies, meanwhile, are typically SMEs with a small number of employees (Skills England, 2025a). The SME-heavy landscape reinforces the need for long term investment and translational support, so firms can scale domestically and retain talent and intellectual property in the UK (Westminster eForum, 2025).

There are currently five quantum-related Centres for Doctoral Training across the UK; however, there are far more applicants than there are available studentships (Clark oral communication, 15/01/2026), reflecting the appetite for training in quantum science and technologies in the UK. Domestic students are hard to recruit into these positions, however, with the majority of applicants being international students, making it harder to retain skilled professionals within the UK (Weidner, oral communication, 15/01/2026). Scotland's Critical Technologies Supercluster is aiming to create 6 600 jobs by 2035 (Scotland's Critical Technologies Supercluster, 2026), but there are concerns regarding who will fill these vacancies (Gwyn oral communication, 15/01/2026). This concern reflects recent sector dynamics, due to an approximate 67 per cent increase in new quantum companies between 2024 and 2025 that has led to expanding vacancies outpacing the domestic talent pipeline (Westminster eForum, 2025). Unfortunately, this is not a problem solely within the UK, but a global phenomenon in most countries (Paul oral communication, 16/01/2026).

The number of employees involved in the UK semiconductor supply chain currently stands at 27 245 individuals and the number of UK graduates with relevant skills and qualifications has plateaued, whilst the industry continues to grow. As such, there is strong global competition for skilled workers, creating the risk that talent may be lost to overseas employers and hindering the UK's ability to meet semiconductor industry expansion ambitions (Perspective Economics, 2025). The UK Government is investing in the development of skilled designers, aiming for 12,000 new processing chip designers by 2030 (Trueman, 2025a). Initiatives such as ARIA's Scaling Compute Programme and chip design hubs aim to convert UK intellectual property into manufactured components (Advanced Research & Invention Agency, 2025).

As the AI, data centre, and quantum computing sectors are expanding, there are increasing numbers of mid-skilled roles becoming available, such as mechanical engineers and laboratory technicians, that can be filled as graduate positions or apprenticeships (Skills England, 2025b; Weidner, oral communication, 15/01/2026). Support is therefore likely to be required to help SMEs within both the quantum and AI sectors to be able to invest in and offer apprenticeships, re-skill existing workforce, and provide vocational certification to ensure that UK digital technologies are not held back by a lack of skilled future workers (Westminster eForum, 2025).

6.6 OPPORTUNITIES FOR THE UK

Data centre demand is growing to support the increasing need to store and process vast amounts of data and facilitate the adoption of AI into everyday lives. Quantum computing is moving from a research concept towards early-stage industrial applications, with growing potential to address complex challenges across a range of industry sectors. It is therefore important to consider how the UK might establish a foothold within the supply chains of all three technologies, both to sustain economic and social competitiveness, and to mitigate cyber security risks associated with quantum decoding of security protocols.

Whilst the UK has the potential to develop domestic supplies of certain critical mineral raw materials and components, it is unlikely to achieve self-reliance and cannot become a specialist in all sections of the supply chain. As such, access to global supply chains, international collaboration, and strategic partnerships remain important. There is an opportunity for the UK to enhance its portfolio of distinctive capabilities, including skills, materials, components, and processes that can be deployed to enhance its position within these partnerships. The UK already hosts considerable expertise within the fields of quantum computing (Section 3.1) and data centres (Section 2.4), providing a strong foundation for further development. Important opportunities include:

- Opportunity exists to undertake a detailed assessment of the UK's primary power generation technologies and grid capabilities to better understand issues of resilience, emissions, and scalability associated with data centre expansion. This also presents an opportunity to decrease carbon emissions and pair data centres with renewable energy technologies, such as wind and solar farms (Department for Science Innovation and Technology, 2025c). Data centre requirements are already driving growth in renewable energy and storage technologies, with projects, such as Northumberland's Artificial Intelligence Zone including wind turbines, solar, and batteries to offset their energy use (Department for Science Innovation & Technology, 2025a).
- The UK's expertise in precision cryogenic engineering related to the research, development, and manufacture of cooling technology (Section 2.4) creates an opportunity in managing the thermal demands of data centres. In particular, the significant heat output generated by data centres presents an opportunity to expand the use of waste heat recovery systems, via technologies such as immersion cooling and heat exchange systems (Data Centre Alliance, 2025). Several UK projects are exploring piping heat generated by data centres to be used in building temperature control (Groucott et al., 2025).
- Although the UK has a strong knowledge base in isotopic purification, there is currently no domestic commercial production of isotopically pure materials (Section 5.2). This position presents an opportunity to explore the expansion of isotope enrichment capabilities within the UK, including through leveraging existing international partnerships and UK equity stakes in leading companies.
- Opportunities exist to develop domestic supplies of high-purity materials, to reduce reliance on foreign imports and for global trade. For example, the UK has upstream capability for methane production and engineering companies, such as ReiCat, that are able to develop methane purification units (ReiCat, 2025). The UK could also strengthen agreements relating to obtaining high purity materials from Europe, following the current development of related infrastructure by companies such as RESilicon (RESiLICON, 2025).
- Whilst the UK has established supply chains relating to semiconductor manufacturing and some cooling systems (Figure 2), opportunity exists to build on this base and expand into adjacent sectors, including servers, hardware assembly, advanced packaging and photonics. This could be further supported by developing capabilities in rare earth element processing and enhancing those in precision metal fabrication.
- The use of secondary feedstock presents an opportunity to develop alternative sources of critical raw materials, especially in the absence of significant domestic primary extraction. For example, semiconductors represent a source of germanium (Tolcin, 2025), whilst photovoltaic cells can provide a source of silicon (International Energy Agency, 2025b). The development of recycling and processing infrastructure for these

electronic waste components would reduce reliance on imports and mitigate supply chain risks. Although recycling can limit the functions of some recovered materials, a secondary supply would still ease competition and supply risks associated with importing primary material.

- The technical challenges associated with recovering materials from complex components (Section 6.4) creates an opportunity to promote design approaches that facilitate recycling and material recovery. This includes designing products and systems in ways that enable recovery of critical and precious metals.
- Opportunity exists to recover valuable materials, such as gallium and indium, from component manufacturing waste and scrap streams, supporting the development of alternative domestic supply sources that are less exposed to global supply chain risk.
- Alongside domestic capability development, there are opportunities to expand strategic international partnerships to access parts of the supply and value chain which is not available in the UK. Existing bilateral agreements between the UK and six other countries in relation to quantum computing (Willis oral communication, 12/01/2026) provide a foundation that could be extended across a broader range of critical technology sectors.

7 Conclusions and recommendations

The digital revolution is driving the growth of data centres to meet the processing requirements of artificial intelligence and the development of quantum computing technologies to address increasingly complex challenges within a range of sectors. Growing UK and global demand for these technologies is putting pressure on the supply chains of raw materials needed for their manufacture.

Whilst these technological developments have progressed at an exponential pace in a short period of time, many of the raw materials required are trace elements, high purity, or isotopically separated elements that have had limited past industrial applications. As a result, their supply chains are juvenile and immature. Many of the elements required are recovered as by-products of primary commodities and are therefore less responsive to market demands. Furthermore, much of their production is concentrated in a small number of countries, including China, Australia, South Africa, and Chile. In contrast, the refining of high purity materials and isotopic purification are conducted by a wider array of suppliers, albeit dominated by the USA, China, and Russia, with some key European participation. Therefore, many of the elements necessary for development of both data centres and quantum computing, such as lithium, niobium, silicon, rare earth elements, and helium, have been identified as critical raw materials by the UK government.

Supply chains are currently limited in the UK for digital technologies, both in terms of the extraction and refining of raw materials and manufacture of components. Growth in demand from other sectors, such as defence, aerospace, and clean energy technologies, is also resulting in competition for these elements. Opportunities exist for the UK to meet this growing demand by developing domestic capacity across raw material and component supply chains, whilst also strengthening a distinctive portfolio of skills that could support international collaboration and trade. As demand for these materials increases, supply chains will need to diversify, creating supply-demand gaps in the market resulting in opportunities for the UK. Potential areas of opportunity include the domestic extraction of selected critical minerals, such as lithium; greater utilisation of full-value mining approaches to recover valuable by-product elements, such as caesium and rubidium; and utilising the UK’s strong knowledge base in isotopic purification to support the development of domestic supplies of high purity and isotopically pure materials required for the digital revolution. In addition, designing components with improved end-of-life recovery in mind presents an opportunity to support development of secondary domestic supply through recycling. Building on these opportunities whilst utilising existing UK expertise and component supply chains enhances the potential for the UK to become a global leader in the supply chain for data centres and quantum computing technologies.

Within this landscape, investments have already been made by the UK government to develop a skilled domestic workforce and create artificial intelligence and data centre growth zones to meet infrastructure challenges. Quantum computing research is being supported by creating communities and partnerships, such as the UK National Quantum Technologies Programme and National Quantum Computing Centre, to facilitate the progression and adoption of technologies suitable for a range of applications and security requirements. As global investment in both data centres and quantum technologies grows, it is important that the UK maintains the ability to identify potential challenges, implement effective mitigation measures, and harness opportunities within the global supply chain to ensure that the UK becomes a centre of excellence within the digital revolution.

7.1 RECOMMENDATIONS

The UK Government aims to strengthen its sovereignty in the development and manufacture of digital technologies, including data centres, AI, and quantum computing. The following recommendations outline areas through which the UK could capitalise on opportunities to address supply and demand gaps in global supply chains and further develop a distinctive skills portfolio to support engagement with international partners:

7.1.1 Isotopic purification and high-purity materials

The UK has a strong knowledge base in isotopic purification but lacks domestic commercial production. Development of a high-purity material and isotopically pure material supply chain would contribute to diversifying global supply chains, reducing supply risks and supporting growing UK and international demand for these materials. Areas of focus for the UK could include methane purification and silicon isotopic purification.

Exploration of the potential for helium-3 recovery from UK nuclear reactors offers a pathway towards establishing a more secure domestic supply of a gas that has experienced recurring global shortages since 2006. Global demand for helium-3 is high and suppliers are limited, indicating an opportunity for the UK to play a prominent role in the helium-3 supply chain.

7.1.2 Expansion of downstream manufacturing capabilities

The UK has established expertise and existing supply chains for industries such as cryogenics, photonics, and semiconductor design. Expanding these industries from a focus on design toward manufacturing could reduce UK reliance on component imports and create added value within downstream domestic digital industry. Other manufacturing areas into which the UK could also expand include servers, hardware assembly, and advanced packing.

7.1.3 Critical minerals and processing capacity

Whilst the UK is unlikely to specialise in all aspects of the digital technology supply chain and will remain reliant on international trade partnerships, assessment of viable opportunities in the domestic critical mineral supply chain should continue. These could include the extraction of critical minerals and encouraging full value mining where potential exists to ensure that valuable by-products, such as caesium and rubidium, are recovered. In addition, expanding domestic refining and processing capabilities, such as rare earth element processing and specialist metal fabrication facilities, could reduce import reliance whilst also strengthening the UK's role within global supply chains.

7.1.4 Quantum-enabling materials

Non-linear materials and crystals are required for many quantum modalities and quantum networks. However, these materials are a major bottleneck within the quantum technology supply chains, with production dominated by China and trade interventions already threatened. Developing domestic capabilities in these materials, such as lithium niobate, offers an opportunity to enhance supply resilience. The UK also has the potential to expand domestic capacity in the production of high purity synthetic diamonds.

7.1.5 Recycling and secondary supply

The development of recycling and processing hubs for electronic waste components would aid in establishing a secondary domestic supply of materials for which the UK has limited or no current or future primary extraction potential. Increased supply would help reduce competition for materials between sectors and mitigate global supply chain bottlenecks. To this end, consideration should also be given to the design of components that facilitate recovery and reuse at end of life.

7.1.6 Industrial support and enabling environment

There may be a role for targeted support mechanisms to encourage the development or expansion of domestic facilities involved in primary production, materials refining, isotopic purification, and secondary material recovery. Such measures could contribute to reducing risks across critical technology supply chains.

7.1.7 Data, demand visibility, and supply chain mapping

Encouraging UK companies to report quantified material requirements for key technologies, such as data centres and batteries, would support improved modelling of future demand under different technology adoption and growth trajectories. This, in turn, would help to identify material flow constraints and supply chain vulnerabilities, enabling more informed consideration of potential mitigation strategies.

7.1.8 Workforce and skills development

Consideration of further support for the development of the skilled workforce required for emerging sectors, such as quantum computing, would be beneficial, particularly in addressing shortages across both specialist and technical roles spanning engineering, computer science and physics. Approaches include targeted incentives, training programmes, and support for apprenticeships within relevant industries. In addition, greater engagement with further and higher education institutions could facilitate delivery of vocational courses helping to ensure vacancies in both mid-skilled and highly skilled job roles are filled.

Appendix 1 Data centre material requirements

Table 23. Raw and compound material requirements for data centres, based primarily on enterprise data centre type. TRL: technology readiness level.

Element	Compound	Component	Quantity	Reason for material choice	TRL	Citation
Aluminium (Al)		Server printed circuit board	Mainboard: 51430 ppm Expansion card: 51430 ppm Memory: 39320 ppm HDD board: 25720 ppm CPU: 308590 ppm Network board: 128580 ppm			Peñaherrera Vaca (2024)
		Cooling units and heat sinks		High thermal conductivity; effective heat dissipation	Widely utilised	Peñaherrera Vaca (2024); SFA (2025)
		Uninterruptible power supply			Widely utilised	Peñaherrera Vaca (2024)
		Air conditioning radiators, fans, pumps				Peñaherrera Vaca (2024)
		Random access memory	0.016 to 0.31 kg/kg			Peñaherrera Vaca (2024)
		Structural chassis		Light weight; good strength to weight ratio	Widely utilised	SFA (2025)
Antimony (Sb)		Random access memory	1.6 g/kg			Peñaherrera Vaca (2024)
		Semiconductors				SFA (2025)
		Flame retardants		Enhances fire resistance in electronic components and enhances thermal stability in circuit boards		SFA (2025)
Barium (Ba)		Server printed circuit board	7.9 g/kg			Peñaherrera Vaca (2024)
		Random access memory magnets	7.1 g/kg	Barium shields against electromagnetic interference by reducing signal disruptions, helping improve stability and reliability of data transmission	Widely utilised	Peñaherrera Vaca (2024); SFA (2025)
Beryllium (Be)		Server printed circuit board	Mainboard: 0.24 ppm Expansion card: 0.24 ppm Memory: 0.18 ppm			Peñaherrera Vaca (2024)

			HDD board: 0.26 ppm CPU: 0.14 ppm Network board: 0.10 ppm			
		Thermal management solutions		Thermal conductivity and mechanical strength help dissipate heat in processors and semiconductor devices		Peñaherrera Vaca (2024)
Bismuth (Bi)		Memory		Used in low melting alloys and soldering materials as a non-toxic and lead-free alternative	Widely utilised	SFA (2025)
		Circuit boards		Used in low melting alloys and soldering materials as a non-toxic and lead-free alternative	Widely utilised	SFA (2025)
Boron (B)	B_2O_3	Hard disk drive NdFeB magnets	1 % of magnet		Widely utilised	Peñaherrera Vaca (2024)
Chromium (Cr)		Structural server enclosures, heat sinks, infrastructure		Stainless steel and protective coatings provide corrosion resistance	Widely utilised	SFA (2025)
Cobalt (Co)		Hard disk drive NdFeB magnets	2 % of magnet		Widely utilised	Peñaherrera Vaca (2024)
		Server printed circuit board	Mainboard: 24.77 ppm Expansion card: 24.77 ppm Memory: 18.94 ppm HDD board: 26.53 ppm CPU: 14.18 ppm Network board: 10.5 ppm			Peñaherrera Vaca (2024)
		Uninterruptible power supply lithium-ion batteries	15 to 20 wt.%		Widely utilised	Peñaherrera Vaca (2024)
Copper (Cu)		Capacitors				Peñaherrera Vaca (2024)
		Server printed circuit board				Peñaherrera Vaca (2024)
		Power and network cables				Peñaherrera Vaca (2024)
		Uninterruptible power supply lead-acid batteries and generators			Widely utilised	Peñaherrera Vaca (2024)
		Air conditioning radiators, fans, hydraulic components, heat exchangers				Peñaherrera Vaca (2024)
		Water cooling device chiller				Peñaherrera Vaca (2024)
		Random access memory	310 to 490 g/kg			Peñaherrera Vaca (2024)

Dysprosium (Dy)		Hard disk drive NdFeB magnets	1 % of magnet		Widely utilised	Peñaherrera Vaca (2024)
		Server printed circuit board	25 g/kg			Peñaherrera Vaca (2024)
		Random access memory NdFeB magnets	23 g/kg	Enhances heat resistance and magnetic stability, ensuring strong magnetic properties are maintained even under high temperatures	Widely utilised	Peñaherrera Vaca (2024); SFA (2025)
Gallium (Ga)		Server printed circuit board	Mainboard: 4.21 ppm Expansion card: 4.21 ppm Memory: 3.22 ppm HDD board: 4.51 ppm CPU: 2.41 ppm Network board: 1.79 ppm			Peñaherrera Vaca (2024)
		Random access memory	0.0024 to 2.6 g/kg			Peñaherrera Vaca (2024)
	GaN	Processor semiconductors		High electron mobility and efficiency	Widely utilised	SFA (2025)
	GaAs	Processor semiconductors		High electron mobility and efficiency	Widely utilised	SFA (2025)
Germanium (Ge)		Semiconductors				SFA (2025)
	GeO_2	Network optic fibre cables				Peñaherrera Vaca (2024); SFA (2025)
Gold (Au)		Lead-free printed wiring board		Used in electrical connectors and circuit board contacts due to excellent conductivity and resistance to oxidation		Peñaherrera Vaca (2024); SFA (2025)
		Server printed circuit board	Mainboard: 49.38 ppm Expansion card: 60.96 ppm Memory: 198.38 ppm HDD board: 132.31 ppm CPU: 99.89 ppm Network board: 3.62 ppm			
		Server data cable pins	<100 ppm			Peñaherrera Vaca (2024)
		Random access memory	0.1 to 0.86 g/kg			Peñaherrera Vaca (2024)
Hafnium (Hf)		Processors and memory semiconductor chips		Forms high-k dielectric materials, which allow for greater transistor density and lower power consumption		SFA (2025)
Indium (In)		Server printed circuit board	Mainboard: 0.24 ppm Expansion card: 0.24 ppm			Peñaherrera Vaca (2024)

			Memory: 0.18 ppm HDD board: 0.26 ppm CPU: 0.14 ppm Network board: 0.1 ppm			
		Random access memory	0.00014 – 0.043 g/kg			Peñaherrera Vaca (2024)
Iron (Fe)		Capacitors				Peñaherrera Vaca (2024)
		Printed wiring board				Peñaherrera Vaca (2024)
		Hard disk drive NdFeB magnets	65 % of magnet		Widely utilised	Peñaherrera Vaca (2024)
		Server printed circuit board	Mainboard: 73030 ppm Expansion card: 73030 ppm Memory: 7300 ppm HDD board: 36520 ppm CPU: 7300 ppm Network board: 175280 ppm			Peñaherrera Vaca (2024)
		Cooling units				Peñaherrera Vaca (2024)
		Structural racking, chassis reinforcements, electromagnetic shielding		Steel provides strength, durability, and helps shield electronic components from electromagnetic interference, reducing signal disruptions	Widely utilised	Peñaherrera Vaca (2024); SFA (2025)
		Uninterruptable power supply and generator			Widely utilised	Peñaherrera Vaca (2024)
		Random access memory	7.3 to 13 g/kg			Peñaherrera Vaca (2024)
		Air condition unit pumps, fans, hydraulic components, encasement				Peñaherrera Vaca (2024)
		Water cooling device chillers				Peñaherrera Vaca (2024)
Lead (Pb)		Printed wiring board				Peñaherrera Vaca (2024)
		Server printed circuit board	Mainboard: 15430 ppm Expansion card: 15430 ppm Memory: 0 ppm HDD board: 16530 ppm CPU: 0 ppm Network board: 6540 ppm			Peñaherrera Vaca (2024)
		Uninterruptable power supply lead-acid batteries			Widely utilised	Peñaherrera Vaca (2024)

Lithium (Li)		Uninterruptable power supply lithium-ion batteries	2 to 3 wt. %		Widely utilised	Peñaherrera Vaca (2024)
Manganese (Mn)		Batteries		Improves energy storage capabilities	Widely utilised	SFA (2025)
		Structure		Improves mechanical strength of alloys	Widely utilised	SFA (2025)
Neodymium (Nd)		Server printed circuit board	1.7 g/kg			Peñaherrera Vaca (2024)
		Random access memory NdFeB magnets	0.2 g/kg			Peñaherrera Vaca (2024); SFA (2025)
		Spindle motor NdFeB magnets				Peñaherrera Vaca (2024); SFA (2025)
	Nd_2O_3	Hard disk drive magnets	Should be 28 to 35 % of magnet, but typically 24.8 % average		Widely utilised	Peñaherrera Vaca (2024)
Nickel (Ni)		Lead free printed wiring board				Peñaherrera Vaca (2024)
		Server printed circuit board	Mainboard: 13370 ppm Expansion card: 13370 ppm Memory: 10220 ppm HDD board: 14320 ppm CPU: 7660 ppm Network board: 5670 ppm			Peñaherrera Vaca (2024)
		Server cooling systems		Superalloys used for high performance heat exchangers and thermal management; corrosion resistant means long term reliability in harsh operating conditions	Widely utilised	SFA (2025)
		Server electroplating of connectors and high-frequency transmission systems		Enhances durability and prevents oxidation	Widely utilised	SFA (2025)
Niobium (Nb)		Server printed circuit board	1.7 g/kg			Peñaherrera Vaca (2024)
		Random access memory	1.3 g/kg			Peñaherrera Vaca (2024)
Palladium (Pd)		Server printed circuit board	Mainboard: 40.72 ppm Expansion card: 40.72 ppm Memory: 61.08 ppm HDD board: 43.62 ppm CPU: 50.9 ppm Network board: 4.07 ppm	Used in multilayer ceramic capacitors (MLCCs) which are essential for regulating power and ensuring signal stability in electronics and server motherboards		Peñaherrera Vaca (2024); SFA (2025)
		Random access memory	0.01 to 0.051 g/kg			Peñaherrera Vaca (2024)

Platinum (Pt)		Hard drive		Used as coating due to high resistance to wear and chemical degradation		SFA (2025)
		Semiconductors		High resistance to wear and chemical degradation		SFA (2025)
		Power supply unit catalytic convertors		high resistance to wear and chemical degradation		SFA (2025)
Promethium (Pr)		Hard disk drive NdFeB magnets	6.2 % of magnet	Produces high performance read-write mechanisms allowing for faster and more accurate data access	Widely utilised	Peñaherrera Vaca (2024); SFA (2025)
Ruthenium (Ru)		Hard disk drives magnetic storage coatings		Enhances durability, wear resistance, and drive performance		SFA (2025)
Samarium (Sm)	SmCo	Hard disk drive magnets		Alternative for Nd in magnets		Peñaherrera Vaca (2024)
Silicon (Si)		Silicon wafers and semiconductor chips in central processing units, graphics processing units, and memory storage	180 cm^2 of wafer per kg of CPU	Enhances fire resistance in electronic components	Widely utilised	Peñaherrera Vaca (2024); SFA (2025)
		Silicon chips			Widely utilised	IEA (2025)
		Server printed circuit board	Mainboard: 436140 ppm Expansion card: 436130 ppm Memory: 333430 ppm HDD board: 467150 ppm CPU: 249740 ppm Network board: 184950 ppm			Peñaherrera Vaca (2024)
Silver (Ag)		Lead-free printed wiring board connectors and soldering		Exceptional electrical conductivity which enhances signal integrity and power efficiency		Peñaherrera Vaca (2024); SFA (2025)
		Server printed circuit board connectors and soldering	Mainboard: 232.35 ppm Expansion card: 232.35 ppm Memory: 348.53 ppm HDD board: 248.87 ppm CPU: 290.44 ppm Network board: 23.24 ppm	Exceptional electrical conductivity which enhances signal integrity and power efficiency		Peñaherrera Vaca (2024); SFA (2025)
		Random access memory connectors and soldering	0.29 to 1.2 g/kg	Exceptional electrical conductivity which enhances signal integrity and power efficiency		Peñaherrera Vaca (2024); SFA (2025)
Tantalum (Ta)		Server printed circuit board capacitors	Mainboard: 1440 ppm Expansion card: 1440 ppm Memory: 1100 ppm HDD board: 1540 ppm	Used in high reliability capacitors on circuit boards due to stability under high temperature and resistance to corrosion		Peñaherrera Vaca (2024); SFA (2025)

			CPU: 820 ppm Network board: 610 ppm			
		Random access memory	0.077 to 2.4 g/kg			Peñaherrera Vaca (2024)
Tin (Sn)		Capacitors				Peñaherrera Vaca (2024)
		Server printed wiring board solder		Provides reliable, strong connections in circuit boards due to low melting point and excellent conductivity		Peñaherrera Vaca (2024); SFA (2025)
		Uninterruptable power supply lead-acid batteries			Widely utilised	Peñaherrera Vaca (2024)
Titanium (Ti)		Server printed circuit board	14 g /kg			Peñaherrera Vaca (2024)
		Random access memory	17 g/kg			Peñaherrera Vaca (2024)
Tungsten (W)		Server printed circuit board	6.5 g /kg			Peñaherrera Vaca (2024)
		Random access memory	0.51 g/kg			Peñaherrera Vaca (2024)
Yttrium (Y)		Server printed circuit board	Mainboard: 135 ppm Expansion card: 135 ppm Memory: 103.21 ppm HDD board: 144.6 ppm CPU: 77.3 ppm Network board: 57.25 ppm			Peñaherrera Vaca (2024)
		Random access memory	0.21 g/kg			Peñaherrera Vaca (2024)
Zinc (Zn)		Server printed circuit board	Mainboard: 11.01 ppm Expansion card: 11.01 ppm Memory: 0 ppm HDD board: 11.79 ppm CPU: 0 ppm Network board: 4.67 ppm			Peñaherrera Vaca (2024)
		Structural server racks and enclosures		Galvanisation of steel components prevents rust and corrosion to extend lifespan of infrastructure in high humidity environments		SFA (2025)

Appendix 2 Quantum computer material requirements

Table 24. Raw, compound, purity, and isotopic material requirements for quantum computing technologies. TRL: technology readiness level.

Element	Compound	Isotope/ property	Purity	Technology	Component	Reason for material choice	Issue with material	TRL	Citation
Aluminium (Al)				Superconducting qubits	Josephson junction boxes	Low melting point, therefore, devices using Al-based insulating thermal barriers have increased coherence times			de Leon et al. (2021); Trento (2025)
				Trapped ion	Trap electrodes			Demonstrated	de Leon et al. (2021)
				Topological	Superconductors	Simple to work with; predictable properties	Low critical temperature and magnetic field, limiting practical applications	Experimental	de Leon et al. (2021); Trento (2025)
					Quantum cores	Al breadboard assists easy trap alignment		In production	Infleqtion (2025b)
					Quantum processor chips	Superconducting material		In production	Rigetti Computing (2025)
				Superconducting qubits	Memory				Lee (2024)
				Superconducting qubits	Microwave kinetic inductance detectors, transition edge sensors				Lee (2024)
				Superconducting qubits	Signal traces				Burnett oral communication (15/01/2026)
		Granular		Superconducting qubits	Nanojunctions, Josephson junctions, qubit substrates				Lee (2024)

		Epitaxial crystalline		Topological	Al shells grown on nanowires	Grown in situ to reduce density of sub-gap states		Experimental	de Leon et al. (2021)
	AlO	Kinetically limited	High quality	Superconducting qubits	Josephson junction boxes	Forms thin, insulating barrier a few nm thick causing low current leakage			de Leon et al. (2021); Lee (2024)
		Amorphous		Superconducting qubits	Tunnel barrier				de Leon et al. (2021)
	Al_2O_3			Trapped ion	Substrate material	High thermal conductivity to manage dissipation of current and prevent heating of chip			de Leon et al. (2021)
	AlGaAs	^{69}Ga, ^{71}Ga, ^{75}As		Quantum dots	Semiconductor heterostructures	Isotopes reduce magnetic field fluctuations arising from nuclear spins in isotopes; has exceptional structural quality leading to large electron mobility and low percolation density, creating disorder-free quantum dots			de Leon et al. (2021); Scappucci et al. (2021)
	Sapphire			Superconducting qubits	Substrate material	Low dielectric loss so substrate has long coherence time as superconducting qubits can store fraction of electric field in substrate			de Leon et al. (2021)
				Trapped ion	Substrate material	High thermal conductivity to manage dissipation of current and prevent heating of chip			de Leon et al. (2021)
				Topological	Substrate material	Substrate for growing topological insulator films due to low cost and inert growth surface			Scappucci et al. (2021)
				Trapped ion	Quantum core cryogenic trap window	Low birefringence and high UV transparency to allow good view through window of ion trapping experiments		In production	Infleqtion (2025c)
Antimony (Sb)	$SbTe_3$			Topological	Topological insulator film	Van der Waals material		Most studied topological insulator film	Scappucci et al. (2021)
Argon (Ar)				Trapped ion	Trap electrodes	In situ argon milling of electrodes causes heating rates to reduce by a factor of 100 at room temperature		Demonstrated	de Leon et al. (2021)

Barium (Ba)		^{137}Ba		Trapped ion	Ion trap target	Atoms have 2 electrons in valence shell so singly ionised state has one valence electron			de Leon et al. (2021); Infleqtion (2025c); Willis oral communication (13/01/2026)
	$BaGa_2GeSe_6$			Photonics	Non-linear laser crystals	Efficient for interactions in the infrared spectral range			Clark oral communication (15/01/2026)
	$BaTiO_3$			Topological	Substrate				Burnett oral communication (15/01/2026)
Beryllium (Be)				Trapped ion	Ion trap	Atoms have 2 electrons in valence shell so singly ionised state has one valence electron			de Leon et al. (2021)
Bismuth (Bi)	$(BiSb)_2Te_3$			Topological	Semiconductor - vortices at topological insulator or superconductor heterointerfaces			Experimental	de Leon et al. (2021); Lee (2024)
	Bi2Se3			Topological	Topological insulator film	Van der Waals material		Most studied topological insulator	Scappucci et al. (2021)
	Bi2Te3			Topological	Topological insulator film	Van der Waals material		Most studied topological insulator	Scappucci et al. (2021)
	BiSrCaCuO			Superconducting qubits	Qubits	Superconductive at temperatures significantly higher than conventional superconductors (above 30 K) allowing them to operate at liquid N temps (77K), which is more cost-effective than liquid He			Trento (2025)
Cadmium (Cd)	Cd_3As_2			Topological	Topological insulator film	Able to be grown by conventional epitaxy	Lattice-matched substrate required for film growth	Demonstrated	Scappucci et al. (2021)
	CdTe				Tunnel barrier	Fine tunes coupling at interface between		Prospective	(Jardine et al., 2023)

						semiconductor nanowire and superconductor			
Calcium (Ca)				Trapped ion	Ion trap	Atoms have 2 electrons in valence shell so singly ionised state has one valence electron			de Leon et al. (2021)
				Topological	Topological insulator film	Used as a non-magnetic dopant in topological insulator film to tune Fermi energy			Scappucci et al. (2021)
Carbon (C)	Allotropes	^{12}C		Quantum dots	Host material e.g. nanotubes, bandgap-engineered few-layer graphene	Possibility of isotopic purification of nuclear spin-free ^{12}C			de Leon et al. (2021)
	Diamond			Trapped ion	Substrate	High thermal conductivity to manage dissipation of current and prevent heating of chip			de Leon et al. (2021)
				Quantum dots	Semiconductor				Lee (2024)
			Synthesised with impurity concentration on <ppb level	Colour/vacancy centres	Solid-state host crystal	N and Si vacancy centres have long coherence times; ultra-high purity causes very low magnetic noise	N vacancy centre has poor optical properties; etching and polishing of diamond is difficult so susceptible to process contamination.	Commercially available bulk substrate.	de Leon et al. (2021)
Caesium (Cs)					Quantum core: magneto-optical trap	Atom vacuum system allowing creation and control of quantum matter		In production	Infleqtion (2025b)
		^{133}Cs		Neutral atom	Qubit atoms	Well suited for cooling and trapping due to electronic structure		Experimental	Wintersperger et al. (2023)
Cerium (Ce)	$CeCu_2Si_2$				Superconducting material	Unconventional superconductor material - electrons behave as if they have extremely high mass			Trento (2025)
Chromium (Cr)				Topological	Topological insulator film	Magnetic dopant in film to break the time reversal		Studied	Scappucci et al. (2021)

						symmetry of the surface states to allow for easier study of quantum anomalous Hall effect in film			
	Cr-doped $(Bi,Sb)_2Te_3$			Topological	Magnetic topological insulator, superconductor devices			Experimental	de Leon et al. (2021)
Cobalt (Co)	$Co_3Sn_2S_2$			Topological	Topological insulator film	Able to be grown by conventional epitaxy	Lattice-matched substrate required for film growth	Demonstrated	Scappucci et al. (2021)
Copper (Cu)				Trapped ion	Al-Cu trap electrodes			Demonstrated	de Leon et al. (2021)
				Superconducting, topological, quantum dots	Cryogenic cooling e.g. dilution fridges	High thermal conductivity at low temperatures so is used for transferring heat		In production	Burnett oral communication (15/01/2026)
				Trapped ions, photons	Cryogenic detectors				Burnett oral communication (15/01/2026)
	CuO				Superconductors				Trento (2025)
Europium (Eu)	EuS			Topological	Semiconductor, Josephson Junction				Lee (2024)
Fluorine (F)				Colour/vacancy centres	Surface terminations	Termination after polishing and etching removes subsurface damage to extend coherence time of shallow NV centres by more than an order of magnitude		Exploration	de Leon et al. (2021)
Gallium (Ga)	GaAs			Topological	Heterostructures	High electron mobility			de Leon et al. (2021)
		^{69}Ga, ^{71}Ga, ^{75}As		Quantum dots	Heterostructures	These isotopes limit dephasing by magnetic field fluctuations arising from nuclear spins; has exceptional structural quality leading to large electron mobility & low percolation density, creating disorder-free quantum dots	Dephasing in GaAs limits coherence time of spin qubits leading to noise generation; hyperfine coupling to		de Leon et al. (2021); Scappucci et al. (2021)

							nuclear spin bath causes severe qubit decoherence; challenging integration of GaAs on a Si wafer limits integration of large numbers of qubits into a practical quantum processor.		
		As(111)		Topological	Substrate	Substrate for growing topological insulator films			Scappucci et al. (2021)
		As(001)		Topological	Substrate	Substrate for growing topological insulator films			Scappucci et al. (2021)
	(Ga,Al)As			Topological	Heterostructures	High electron mobility			de Leon et al. (2021)
	AlGaN			Quantum dots	Semiconductor				Lee (2024)
	GaSb			Topological	Semiconductor	If electric field is applied across the InAs/GaSb interface, band crossing can be achieved between the InAs conduction band and GaSb valence band. When electrical field is increased, inverted gap can be opened		Experimental	Yang et al. (2021)
Germanium (Ge)					Nanowires	Hole spin orbit qubits		Experimentally demonstrated	de Leon et al. (2021)
		Removal of Ge-73		Quantum dots	Heterostructures	Four qubit system can be obtained with controllable coupling along both directions in 2x2 array; have high electron mobility, low effective mass, and sizable spin orbit coupling allowing large energy spacing for easy fabrication of quantum dots with full electrical qubit control		Experimental	de Leon et al. (2021); Scappucci et al. (2021)

	GeH_4			Quantum dots	Heterostructures	Used as growth precursor gas in reduced pressure chemical vapour decomposition tools to grow heterostructures		Experimentally demonstrated	Scappucci et al. (2021)
Gold (Au)				Trapped ion	Trap electrodes				de Leon et al. (2021)
				Topological	Hybrid Au/superconductor nanowires				de Leon et al. (2021)
				Topological	Catalyst	Growth of InAs and InSb nanowires capable using Au-catalysed vapour-liquid-solid method			de Leon et al. (2021)
Hafnium (Hf)	$HfTe_2$			Topological	Topological insulator film	Film grown by van der Waals epitaxy		Demonstrated	Scappucci et al. (2021)
Helium (He)		^3He, ^4He		Superconducting, topological, quantum dots	Cryogenic cooling e.g. dilution fridges			In production	Burnett oral communication (15/01/2026)
				Trapped ions, photons	Cryogenic detectors				Burnett oral communication (15/01/2026)
Indium (In)					Quantum processor chips	Superconducting material		In production	Rigetti Computing (2025)
				Superconducting qubits	Signal traces				Burnett oral communication (15/01/2026)
	InAs			Quantum dots	Spin orbit controlled qubits	Electrons in compound used for fast electric control of spin states			de Leon et al. (2021)
				Topological	Semiconductor and semiconductor nanowires			Experimental	de Leon et al. (2021); Yang et al. (2021)
	InSb			Quantum dots	Spin orbit controlled qubits	Electrons in compound used for fast electric control of spin states			de Leon et al. (2021)
				Quantum dots	Semiconductors				Lee (2024)
				Topological	Semiconductor nanowires				de Leon et al. (2021)
	[InAs(InSb)/Al(Nb)(NbTiN)]			Topological	Semiconductor and superconductor nanowires			Experimental	de Leon et al. (2021)

	InP			Superconducting qubits	Superconducting nanowire single-photon detector				Lee (2024)
		P(III)		Topological	Substrate for growing topological insulator films and nanowires			Demonstrated	de Leon et al. (2021); Scappucci et al. (2021)
	In_2Se_3			Topological	Topological insulator film	Used as insulating lattice-matched buffer layer to bury disordered layers and isolate topological insulator, reducing doping and increasing electron mobility			Scappucci et al. (2021)
	$(In,Bi)_2Se_3$			Topological	Topological insulator film	Used as insulating lattice-matched buffer layer to bury disordered layers and isolate topological insulator, reducing doping and increasing electron mobility			Scappucci et al. (2021)
	InGaAs			Superconducting qubits	Superconducting nanowire single-photon detector				Lee (2024)
				Quantum dots	Semiconductor				Lee (2024)
	InO			Superconducting qubits	Qubit substrate, Josephson Junction				Lee (2024)
Iron (Fe)				Topological	Fe-chalcogenide superconductors				de Leon et al. (2021)
	FeAsOF				Superconductor	Superconductive at temperatures significantly higher than conventional superconductors (above 30 K) allowing them to operate at liquid N temps (77K), which is more cost-effective than liquid He			Trento (2025)
	Stainless steel			Superconducting, topological, quantum dots	Cryogenic cooling e.g. dilution fridges			In production	Burnett oral communication (15/01/2026)
				Neutral atoms, trapped ions	Vacuum chambers			In production	Burnett oral communication (15/01/2026)
Lanthanum (La)	LaAlGe			Topological	Topological insulator film	Film able to be grown by conventional epitaxy	Lattice-matched	Demonstrated	Scappucci et al. (2021)

							substrate required for film growth; careful flux matching of volatile element is required		
Lead (Pb)				Topological	Topological insulator film	Nonmagnetic dopant in film to tine Fermi energy			Scappucci et al. (2021)
					Superconductor	Superconducting material	Limited practical application due to low critical temperature and magnetic field		Trento (2025)
				Superconducting qubits	Signal traces				Burnett oral communication (15/01/2026)
	PbSnTe			Superconducting qubits	Josephson junction boxes	Cubic alloy system with large spin-orbit coupling whose energy gap is widely tuneable	Minimises the experimental signatures of Majorana bound states		Scappucci et al. (2021)
Lithium (Li)	$LiNbO_3$			Photonics	Non-linear laser crystals	Fast switching ability and ideal for mass manufacture			Paul oral communication (16/01/2026)
Magnesium (Mg)				Trapped ion	Ion trap	Atoms have 2 electrons in valence shell so singly ionised state has one valence electron			de Leon et al. (2021)
	MgB_2			Superconducting qubits	Superconducting nanowire single-photon detector	98% efficiency reported, critical temperature of 39 K			Lee (2024); Trento (2025)
Manganese (Mn)				Topological	Topological insulator film	Magnetic dopant in film to break the time reversal symmetry of the surface states to allow for easier study of quantum anomalous Hall effect in film		Studied	Scappucci et al. (2021)

Mercury (Hg)					Superconductor	Superconducting material	Limited practical application due to low critical temperature and magnetic field		Trento (2025)
	HgCdTe			Quantum dots	Semiconductors				Lee (2024)
	HgTe			Topological	Topological insulator film		Needs critical thickness of 16 layers of HgTe band to cause crossing and open an inverted gap		Yang et al. (2021)
Molybdenum (Mo)	$MoTe_2$			Topological	Topological insulator film	Film can be grown by van der Waals epitaxy		Demonstrated	Scappucci et al. (2021)
	MoAu			Superconducting qubits	Microwave kinetic inductance detectors, transition edge senors				Lee (2024)
	MoSi			Superconducting qubits	Superconducting nanowire single-photon detector	98 % efficiency reported			Lee (2024)
	MoGe			Superconducting qubits	Superconducting nanowire single-photon detector				Lee (2024)
	MoRe			Superconducting qubits	Superconducting nanowire single-photon detector				Lee (2024)
Nickel (Ni)	Ni_2MnIn				Magnetic interface	Magnetic Heusler compound		Experimental	(Heischmidt et al., 2023)
Niobium (Nb)				Superconducting qubits	Josephson junction boxes, memory, microwave kinetic inductance detectors, transition edge sensors				de Leon et al. (2021); Lee (2024)

				Quantum processor chips	Superconducting material		In production	Rigetti Computing (2025)
			Topological	Magnetic topological insulator, superconductor devices	High critical temperature		Experimental	de Leon et al. (2021); Trento (2025)
			Superconducting qubits	Signal traces				Burnett oral communication (15/01/2026)
NbTiN			Superconducting qubits	Josephson junction boxes	Increased coherence times; type II superconductor can withstand higher magnetic fields and have higher critical temperatures.			de Leon et al. (2021); Lee (2024); Trento (2025)
			Superconducting qubits	Microwave kinetic inductance detectors, transition edge sensors, superconducting nanowire single-photon detector				Lee (2024)
			Superconducting qubits	Signal traces				Burnett oral communication (15/01/2026)
			Topological	Superconductor insulator			Experimental	de Leon et al. (2021); Lee (2024)
NbSe$_2$			Topological				Experimental	de Leon et al. (2021)
NbP			Topological	Topological insulator film	Film can be grown by conventional epitaxy	Lattice-matched substrate required for film growth	Demonstrated	Scappucci et al. (2021)
NbN			Superconducting	Microwave kinetic inductance detectors, transition edge sensors, superconducting nanowire single, qubit substrate, Josephson junction				Lee (2024)

				Superconducting qubits	Signal traces				Burnett oral communication (15/01/2026)
	NbRe			Superconducting	Superconducting nanowire single-photon detector				Lee (2024)
	NbSi			Superconducting	Superconducting nanowire single-photon detector				Lee (2024)
	Nb_3Sn				High field magnets	Can withstand higher magnetic fields and have higher critical temperatures			Trento (2025)
Oxygen		High quality		Colour/vacancy centres	Surface terminations	Termination after polishing and etching removes subsurface damage to extend coherence time of shallow nitrogen vacancy centres by more than an order of magnitude		Exploration	de Leon et al. (2021)
Phosphorous (P)				Quantum dots, colour/vacancy centres	Electron donors	Can be made into atomically precise arrays of P donors in silicon		Demonstrated	de Leon et al. (2021)
Platinum (Pt)	$PtSe_2$			Topological	Topological insulator film	Film can be grown by van der Waals epitaxy		Demonstrated	Scappucci et al. (2021)
	$PtTe_2$			Topological	Topological insulator film	Film can be grown by van der Waals epitaxy		Demonstrated	Scappucci et al. (2021)
Rare earth elements (REE)				Colour/vacancy centres	Host material		Currently suffer fast dephasing from nuclear spins	Exploration	de Leon et al. (2021)
Rubidium (Rb)					Quantum cores			In production	Infleqtion (2025b)
		^{87}Rb		Neutral atom	Entangling gates	Creation of long-lived hyperfine qubits		Experimental	Evered (2023)
				Neutral atom	Logical processor	Arrays of individual ^{87}Rb atoms trapped in optical tweezers can be dynamically reconfigured in the middle of computation whilst preserving qubit coherence		Experimental	Bluvstein et al. (2024)
Ruthenium (Ru)	RuO_2			Superconducting, topological, quantum dots	Cryogenic cooling e.g. dilution fridges			In production	Burnett oral communication (15/01/2026)

Silicon (Si)				Quantum dots	Semiconductors, heterostructures	Si qubits can operate at hot temperatures, up to 1K, demonstrate two-qubit logic		In production	de Leon et al. (2021); Scappucci et al. (2021); Lee (2024); Rigetti Computing (2025)
				Colour/vacancy centres	Host material			Exploration	de Leon et al. (2021)
				Trapped ion	Substrate	High thermal conductivity to manage dissipation of current and prevent heating of chip			de Leon et al. (2021)
				Photon	Photons				Lee (2024)
		High resistivity		Superconducting qubits	Substrate	Low dielectric loss so substrate has long coherence time as superconducting qubits can store fraction of electric field in substrate			de Leon et al. (2021)
			Isotopically pure	Quantum dots	Implementation of quantum dots	Si quantum-dot spin qubits have extremely long coherence times, enabling high fidelity single and two qubit gates	Need to be grown with isotopically pure sources to minimise noise from residual nuclear spins		de Leon et al. (2021); Lodri and Nichol (2021)
		^{28}Si enriched	>99.92 %	Quantum dots	CVD epilayers	Provide more than order of magnitude improvement in coherence compared to natural silicon by minimising noise from residual nuclear spins	Large effective mass of Si requires quantum dots in Si to be smaller than in GaAs	Implementation of industry level production	de Leon et al. (2021); Lodri and Nichol (2021); Scappucci et al. (2021)
		Crystal quartz		Trapped ion	Substrate	High thermal conductivity to manage dissipation of current and prevent heating of chip			de Leon et al. (2021)
		Fused silica		Trapped ion	Substrate	High thermal conductivity to manage dissipation of			de Leon et al. (2021)

					current and prevent heating of chip			
	Si(111)		Topological	Substrate for growing topological insulator films				Scappucci et al. (2021)
SiGe			Quantum dots	Heterostructures	Possible to define and control large linear arrays of quantum dots	Lattice mismatch between Si and Ge, causing more Ge to be required		de Leon et al. (2021); Scappucci et al. (2021)
			Quantum dot	Host material		Coupling processes can cause decoherence		Lodri and Nichol (2021)
			Topological	Semiconductor insulator				Lee (2024)
SiO			Quantum dots	Semiconductor structures, complementary MOS structures				de Leon et al. (2021)
			Topological	Substrate for nanowire growth			Demonstrated	de Leon et al. (2021)
SiO_2			Quantum dots	Semiconductors				Lee (2024)
			Trapped ion	Trapped ion substrate				Burnett oral communication (15/01/2026)
SiC			Colour/vacancy centres	Host material	Long coherence time at room temp as material has high Debye temp and low spin-orbit coupling leading to low electron-phonon coupling and long spin lifetimes		Exploration	de Leon et al. (2021)
SiH_4			Quantum dots	Heterostructures			Experimentally demonstrated	Scappucci et al. (2021)
Si_3N_4			Photon	Photons				Lee (2024)
			Photon	Silicon detectors				Burnett oral communication (15/01/2026)
			Topological	Substrate				Burnett oral communication (15/01/2026)

				Trapped ion	Trapped ion substrate				Burnett oral communication (15/01/2026)
Silver (Ag)	AgGaS$_2$			Photonics	Non-linear laser crystals	Efficient for interactions in the infrared spectral range			Clark oral communication (15/01/2026)
Strontium (Sr)				Trapped ion	Ion trap	Atoms have 2 electrons in valence shell so singly ionised state has one valence electron			de Leon et al. (2021)
		Sr-87		Neutral atom	Qubit atoms	Energy level structure allowing nuclear spin states to be employed as qubits with longer decoherence times	Control of nuclear spin qubits is technically more challenging, involving additional magnetic fields and lasers to isolate the qubit transition	Experimental	Wintersperger et al. (2023)
	Sr$_3$PbO			Topological	Topological insulator film	Film can be grown by conventional epitaxy	Lattice-matched substrate required for film growth	Demonstrated	Scappucci et al. (2021)
Tantalum (Ta)				Superconducting	Shunting capacitors, qubit substrate, Josephson junction	Ta forms thin, kinetically limited, chemically robust oxides			de Leon et al. (2021); Lee (2024)
				Superconducting qubits	Signal traces				Burnett oral communication (15/01/2026)
	TaP			Topological	Topological insulator film	Film can be grown by conventional epitaxy	Lattice-matched substrate required for film growth	Demonstrated	Scappucci et al. (2021)
	TaIrTe$_4$			Topological	Topological insulator film	Film can be grown by conventional epitaxy	Lattice-matched substrate	Demonstrated	Scappucci et al. (2021)

							required for film growth		
	TaN			Superconducting	Superconducting nanowire single-photon detector				Lee (2024)
Tin (Sn)				Topological	Superconductor			Experimental	de Leon et al. (2021)
	SnSe			Topological	Topological crystalline insulator	Bulk insulation but conducting state at the surface		Experimental	Yang et al. (2020)
Titanium (Ti)				Superconducting	Microwave kinetic inductance detectors, transition edge sensors				Lee (2024)
				Superconducting qubits	Signal traces				Burnett oral communication (15/01/2026)
	TiN			Superconducting	Josephson junction boxes				de Leon et al. (2021)
	Ti_2MnIn				Magnetic interface	Magnetic Heusler compound, produces a more significant spin polarisation due to the position of the Heusler's transition metal d states with respect to the Fermi level		Experimental	Heischmidt et al. (2023)
Tungsten (W)				Superconducting	Superconducting nanowire single-photon detector, microwave kinetic inductance detector, transition edge sensor				Lee (2024)
	WSi			Superconducting	Superconducting nanowire single-photon detector				Lee (2024)
Vanadium (V)				Topological	Topological insulator film	Magnetic dopant in film to allow for easier study of quantum anomalous Hall effect in film		Studied	Scappucci et al. (2021)
Ytterbium (Yb)				Trapped ion	Target within ion trap	Atoms have 2 electrons in valence shell so singly ionised state has one valence electron			de Leon et al. (2021); Infleqtion (2025c)

		Yb^{3+}		Trapped ion	Semiconductor				Lee (2024)
Yttrium (Y)				Trapped ion	Ion trap	Atoms have 2 electrons in valence shell so singly ionised state has one valence electron			Burnett oral communication (15/01/2026)
	YBaCuO			Superconducting	Qubits	High temperature superconductor allowing them to operate at liquid N temps (77K), which is more cost-effective than liquid He			Lee (2024), Trento (2025)
Zirconium (Zr)	$ZrTe_2$			Topological	Topological insulator film	Film can be grown by van der Waals epitaxy		Demonstrated	Scappucci et al. (2021)

Appendix 3 List of data centre players in the UK

Table 25. List of data centre players in the UK.

Company name	Region	Sector	Source
ABB	West Midlands	Power infrastructure	ABB (2025)
Ark Data Centres	Hayes	Data centre operator	Craske (2025b)
Arm Holdings	Cambridge (HQ)	Semiconductors	Arm (2025)
Cambridge GaN Devices HQ	Cambridge	Semiconductors	CGD (2025)
Colt Data Centre Services (DCS)	Hayes	Data centre operator	Craske (2025b)
Digital Realty	London	Data centre operator	Digital Realty (2025)
E+I Engineering (E&I) (now part of Vertiv group for many	Ireland	Power infrastructure	Data Center Dynamics (2025)
Eaton	Loughborough	Power infrastructure	Eaton (2025)
EcoCooling	Suffolk	Cooling system	EcoCooling (2025)
Equinix	London, Manchester, Slough	Data centre operator	EQUINIX (2025)
Faradion Ltd.	Sheffield	Battery / energy storage	Faradion (2025)
FTDI	Glasgow	Semiconductors	FTDI Chip (2025)
Global Switch	London	Data centre operator	Global Switch (2025)
Graphcore	Bristol (HQ), Cambridge, London	Semiconductors	Graphcore (2025)
Iceotope	Sheffield (HQ)	Cooling system	Swinhoe (2025)
Imagination Technologies	Kings Langley (HQ)	Semiconductors	Imagination Technologies (2025)
IQE plc	Cardiff and South Wales	Semiconductors	IQE (2022)
Kao Data	Harlow, Hertfordshire	Data centre operator	Kao Data (2025)
Lion Volt (formerly AMTE Power)	Thurso	Battery / energy storage	Osborne (2022)
NTT Global Data Centre	Hemel Hempstead	Data centre operator	Craske (2025b)
Paragraf	Cambridgeshire	Semiconductors	Paragraf (2025)
Pragmatic Semiconductors	Cambridge, Durham	Semiconductors	Pragmatic Semiconductors (2025)
Prysmian Group	Southampton (HQ), & 3 additional sites in UK	Power infrastructure	Prysmian (2025)

Pulsant	Various (e.g., Maidenhead & Reading)	Data centre operator	Pulsant (2025)
Rittal	Plymouth	Cooling system	Rittal (2025)
Salience Labs (Oxford)	Oxford (HQ)	Semiconductor	Salience Labs (2025)
Schneider Electric (UK / EcoStruxure)	Telford	Power infrastructure	Schneider Electric (2025)
Semefab	Glenrothes	Semiconductor	Semefab (2025)
Submer	Newcastle	Cooling system	Swinhoe (2024)
Telehouse	London	Data centre operator	Craske (2025b)
Vantage Data Centers	Newport	Data centre operator	Craske (2025b)
Vertiv	Northern Ireland	Power infrastructure	Vertiv (2025)
VIRTUS Data Centres	London	Data centre operator	Craske (2025b)
Vishay Newport	Newport	Semiconductors	Vishay Newport (2025)
XMOS	Bristol	Semiconductors	XMOS (2025)

Appendix 4 List of selected players in quantum computing

Table 26. Selected players in quantum computing.

Company	Country	Notes	Source
Aegiq	UK	Photonic quantum systems & deployment	Aegiq (2025)
Alpine Quantum Technologies (AQT)	Austra	Trapped ion quantum computers	AQT (2025)
Fujitsu (and RIKEN)	Japan	Superconducting qubit modality	(Fujitsu, 2025)
Google (Quantum AI)	USA	Superconducting qubit platform	Acharya et al. (2025)
IBM (IBM Quantum)	USA	Superconducting qubit platform	Mandelbaum (2025)
IQM	Finland	Superconducting quantum processors	IQM (2025)
Infleqtion	USA	Neutral atom, sensing & cold-atom systems	Infleqtion (2025a)
IonQ	USA	Trapped ion quantum computers	IonQ (2025)
Microsoft (Azure Quantum)	USA	Topological qubits	Nayak (2025)
ORCA Computing	UK	Photonic quantum computing	ORCA Computing (2025)
Origin Quantum (OriginQ)	China	Superconducting qubits, electronics, quantum processing unit (QPU) manufacture	Origin Quantum (2025)
Oxford Ionics	UK	Trapped ion systems	Oxford Ionics (2025)
Oxford Quantum Circuits (OQC)	UK	Superconducting qubits (Coaxmon)	OQC (2025)
PsiQuantum	USA	Silicon photonics (photonic quantum chips)	PsiQuantum (2025)
Q-CTRL	Australia	Quantum control software	Q-CTRL (2025)
QunaSys	Japan	Quantum software / algorithms	QunaSys (2025)
Quantinuum	UK & USA	Trapped ion hardware & software	Quantinuum (2025)
Quantum Brilliance	Australia & Germany	Diamond-based (NV centre) quantum accelerators	Quantum Brilliance (2025)
QuantumCTek	China	Quantum communication & computing	QuantumCTek (2025)
QuantInnov	Germany	QC components / calibration	Quantum Innovation (2025)
Quantum Machines	Israel	Quantum control & orchestration	Quantum Machines (2025)
Quantum Motion	UK	Silicon spin qubits / CMOS quantum	Quantum Motion (2025b)
QuEra Computing	USA	Neutral atom quantum computers	QuEra (2025)

Rigetti Computing	USA	Superconducting QPUs	Rigetti Computing (2025)
Riverlane	UK	Quantum software / error-correction	Riverlane (2025)
SeeQC	USA	Digital quantum control/SoC	SEEQC (2025)
SpinQ	China	Compact superconducting / NMR systems	SpinQ (2025)
Xanadu	Canada	Photonic quantum computing & software	Xanadu (2025)

8 Acronyms and abbreviations

AI	Artificial intelligence
ALD	Atomic layer deposition
ASIC	Application specific integrated circuit
ASU	Air separation units
BGS	British Geological Survey
BOC	British Oxygen Company
CBMM	Companhia Brasileira de Metalurgia e Mineração
CCTV	Closed circuit television
CMIC	Critical Mineral Intelligence Centre
CPU	Central processing unit
CRAC	Computer room air conditioning
CRAH	Computer room air handler unit
CRM	Custom relationship management
CVD	Chemical vapour deposition
DBT	Department of Business and Trade
DL	Deep learning
DRAM	Dynamic random access memory
DRC	The Democratic Republic of the Congo
DTC	Direct to chip
ERP	Enterprise resource planning
FinFET	Fin field-effect transistor
GPU	Graphics processing unit
HKMG	High-k metal gate
HPC	High performance computing
IT	Information technology
KW	Kilowatts
LLM	Large language model

LNG	Liquified natural gas
ML	Machine learning
MTDC	Multi-tenant data centres
MTIA	Meta training and inference accelerator
MW	Megawatts
NQCC	National Quantum Computing Centre
PDU	Power distribution unit
PEM	Proton exchange membranes
PGE	Platinum group elements
ppb	Parts per billion
ppm	Parts per million
PV	Photovoltaic
QC	Quantum computers
QPU	Quantum processing units
REE	Rare earth elements
RF	Radio frequency
SMEs	Small and medium sized enterprises
SoC	System on chip
SOFC	Solid oxide fuel cell
TPU	Tenor processing units
TWh	Terrawatts per hour
UK	United Kingdom
UPS	Uninterruptible power supply

9 Glossary

Betterton–Kroll process: a pyrometallurgical method used to remove impurities such as bismuth and lead from molten metals by adding reagents that form a separable slag.

Betts process: an electrolytic refining method for producing high-purity copper by dissolving impure copper at the anode and plating purified copper onto the cathode.

Chemical vapour deposition: a process where gases enter a vacuum chamber and react on a heated surface to form a thin solid layer.

Cryogenic distillation: separation of gases at very low temperatures; heavier components condense at the bottom as liquids while lighter ones stay gaseous and rise.

Czochralski method: a technique for growing large, high-purity single crystals by pulling a seed crystal upward from molten material as it cools and solidifies.

Decoherence: loss of quantum information when a quantum system interacts with its environment.

Electron beam melting: a refining process that melts material using a focused high-energy electron beam in a vacuum, producing very pure metals.

Electrowinning: extraction of dissolved metals by applying an electric current so metal ions plate onto a cathode as solid metal.

Entanglement: correlation or sharing of quantum states between qubits, even when separated by vast distance.

Epitaxy/epitaxial growth: growth of a thin film on a crystalline substrate so the new layer adopts the substrate's crystal orientation.

Floating-zone refining: a high-purity refining technique where a molten zone is passed along a solid rod, carrying impurities with it.

Fractional crystallisation: purification by cooling or evaporating a solution so different components crystallise at different times and can be separated.

Graphics processing units: electronic circuit or processor specifically designed for the processing of digital images and the acceleration of graphics rendering.

Heterostructure: a layered structure of different materials, often semiconductors, engineered to control electronic or quantum behaviour.

Interference: the wave-like nature of quantum particles that cause either constructive or deconstructive interference that can be manipulated to enhance the probability of a correct solution and suppress the probability of an incorrect solution, respectively.

Ion exchange: a separation process where ions in solution are exchanged with ions bound to a solid resin.

Latency: the delay between initiating a request and receiving a response.

Membrane separation: a process where compressed gas passes through selective membranes that remove specific components while allowing others to pass.

Molecular sieve beds: beds filled with porous crystalline materials (e.g., zeolites) that trap molecules based on size or polarity.

Parallel processing: a computing method that divides tasks into smaller units processed simultaneously across multiple processors.

Plasma/arc melting: melting and refining materials using extremely high temperatures generated by a plasma torch or electric arc.

Polysilicon: high-purity silicon made of many small, fused crystals, used as feedstock for semiconductors and solar panels.

Pressure swing adsorption: a gas separation method where adsorbent material captures target gases at high pressure and releases them at low pressure.

Quantum coherence: the time a qubit maintains its quantum state, similar to how long a bell rings after being struck.

Quantum dots: nanoscale structures that confine electrons like artificial atoms, enabling qubit storage and manipulation.

Qubits: the basic units of quantum information that can exist as 0, 1, or a superposition of both.

Qudits: *quantum digits are generalised quantum units of information (qubits) that can have three or more simultaneous states*

Reductive pyrolysis: thermal decomposition in a reducing environment that breaks materials into simpler compounds or metals.

Rydberg states: highly excited atomic states where an electron is far from the nucleus, creating strong interactions useful in quantum technologies.

Solvent extraction: a separation method where a solute moves from one liquid phase into another immiscible liquid phase, often used to extract metals.

Superconductor: a material that carries electric current with zero resistance below a critical temperature.

Superposition: a concept describing how a quantum system can exist in multiple states at the same time until observed.

Thermal decomposition: breaking down a substance by heating it, often with little or no oxygen, to produce new materials or deposits.

Vacuum arc remelting: a process where metal is remelted in a vacuum using an electric arc to remove gases and impurities and improve homogeneity.

Vacuum distillation: distillation carried out under reduced pressure, so substances boil at lower temperatures, useful for heat-sensitive or high-boiling materials.

Zone crystallisation: a purification technique where a molten zone travels along a material and carries impurities to one end.

Zone-refining: another name for zone crystallisation, used to produce extremely high-purity crystals.

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