Royal Academy of Engineering

Quantum Infrastructure Review

An independent review of the UK's quantum sector's infrastructure requirements for the next decade

6 June 2024

Foreword

The Royal Academy of Engineering is delighted to present its Quantum Infrastructure Review. This study was commissioned through the National Quantum Strategy by the UK government's Department for Science Innovation and Technology (DSIT).

This is an important time for the UK quantum community with the first two phases of the National Quantum Programme's (NQTP) Hubs coming to fruition; all of which have established a range of quantum enabled capabilities ripe for further exploitation.

This report represents the culmination of an extensive journey of engagement with the UK's quantum community to identify opportunities for infrastructure investments that can unlock transformative advances for the UK's quantum sector. This has been no small task. Quantum technology is a 'broad church' encompassing a wide range of technologies at different stages of development, with distinct infrastructure requirements and various potential impacts and uncertainties. This means there is not a simple or straightforward answer to the question of which infrastructure should be prioritised. Instead, there is a set of options with different implications and trade-offs. The important point to note, however, is that the UK does have some very attractive options it can pursue to maintain the momentum that its success in research and development (R&D) has established.

The potential of quantum technology is being quickly propelled forward by international players placing their bets through major investments on infrastructure for quantum applications. Against this fast-moving international landscape, the main risk the UK faces is losing on its hard-won quantum capability and expertise. Therefore, the UK needs to take a bold stance for championing quantum areas where it has real potential for leadership, as well as areas where it cannot afford to miss out on due to major implications on the economy and national security.

We put the question out to the quantum community: what infrastructure investments should be prioritised for the UK quantum sector to take the next step in commercialising its strong quantum R&D foundation?

We received an abundance of evidence and insights from a wide range of stakeholders, from small-scale entrepreneurs to industry giants, and everything in between. We are very grateful for all the input provided. It is clear that the quantum community is strongly engaged and passionate to succeed in the UK. Nevertheless, the views on how success can be best delivered are diverse and at times divergent.

Our approach focused on identifying overlaps in infrastructure requirements that cut across different types of technologies and that have emerged as key priorities for quantum. Alongside physical infrastructure requirements, we also make recommendations on enablers required for successful operation of infrastructure, cross-sectoral dependencies, and the international context.

We hope the insights provided here enable the UK to make strategic decisions to support the ambition for quantum in the UK.

Dr Dame Frances Saunders DBE CB FREng
Chair of Working Group

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Executive summary

The Review

The Royal Academy of Engineering was commissioned by the UK government's Department for Science Innovation and Technology (DSIT) to conduct an independent review of the UK's quantum sector's infrastructure requirements for the next decade, including for fabrication facilities; to help identify opportunities where there is a rationale for government to invest in infrastructure for the future.

The UK government recognises the need to take the next step in moving from its very successful programme of quantum research and development (R&D) towards to commercialisation, accelerating the transition from laboratory settings to deployment in real-world applications. This Review considers what infrastructure the UK will require to make this transition, with a focus on the needs of industry. The quantum sector is broad and complex, and the Review adopts a systems approach to consider a wide range of quantum technologies, cross-sectoral dependencies, and the international context.

Following evidence collection activities, including extensive engagement with industry stakeholders, the Review sets out six recommendations for how government should intervene to strengthen the UK's emerging quantum sector and increase its potential for future success. These recommendations address the opportunities for investment in physical infrastructure and the system enablers required for its successful operation. Additionally, they capitalise on synergies among areas with shared resources and overlapping needs. The recommendations are summarised in Table 1.

Infrastructure

While the UK has been a frontrunner in quantum technology development to date, it sits in a dynamic global landscape with other nations rapidly advancing in this field by investing heavily in their own quantum national strategies and infrastructure. The UK faces a choice now about its level of ambition for being at the forefront of quantum technology exploitation and commercialisation.

Infrastructure is critical to building on and securing the UK's quantum future. The right infrastructure can accelerate companies' abilities to progress commercial R&D by creating fully engineered prototypes, and enabling testing, piloting, and demonstration. Accessing low-volume manufacturing for serving small or niche markets can also speed-up development towards volume production. Infrastructure can also be crucial to achieving national security objectives where sovereign capabilities are required.

This type of infrastructure is often beyond that which current academic facilities can provide, and is also beyond what commercial entities, especially Small and Medium Size Enterprises (SMEs), can afford in terms of resource and risk. Consequently, government support for infrastructure is crucial to de-risk the technology development process and to facilitate its adoption and commercialisation, as well as to attract investment from the private sector. Without government intervention as this stage, there is a high risk of losing ground to countries making significant investments in quantum.

Given the current relative lack of maturity of many quantum technologies, there remains a wide range of options for infrastructure investment. The Review has identified several options for providing industry accessible infrastructure to facilitate commercial R&D and support the growth of the UK's quantum sector. To prioritise these options effectively, further strategic decisions will be needed, and this Review includes discussion of some approaches to taking that work forward.

Findings

One of the strongest and most often repeated concerns raised by UK quantum companies in this Review was that the UK's existing open-access infrastructure is not adequate for meeting industry needs. Therefore, at a minimum, the Review recommends that the UK upgrades and improves access for industry to existing infrastructure. This requirement is particularly relevant across a range of technology development stages that underpin most quantum technologies: design; nanofabrication prototyping; packaging, advanced packaging, and heterogeneous integration.

Additionally, the Review recommends:
- Better coordination and support to industry in navigating the UK's fast-moving quantum landscape, including infrastructure.
- Improving the UK's advanced manufacturing capabilities, which would have benefits beyond the quantum sector.
- Collaboration between industry, academia, and government to set a clearer direction for quantum technologies, and thereby shore-up strategic decision-making in public and private sectors.
- Progress on enablers such as skills provision and the standards and regulation needed for responsible, ethical, and sustainable innovation.

The UK should also be clear about its level of ambition. Enabling the UK to stay on its current trajectory and retain agility without major investments is the minimum the UK should do (Scenario A). But it can do so much more, with sufficient investment and ambition. The catalytic opportunity lies in the UK adopting a proactive stance by investing in critical capabilities, positioning itself at the forefront of particular domains (Scenario B).

The Review sets out several different options for investment in new infrastructure. This type of investment done well should have significant impacts in terms of accelerating the UK's quantum sector by stimulating and speeding up R&D translation and scale-up, as well as attracting further investment and talent. Industry is clear that it is advantageous to have in-country capabilities, as development times can be accelerated, costs can be lowered, value is more likely to be secured in the UK, customers can be engaged, and risks around intellectual property (IP) and national security can be mitigated.

Considering the likely costs involved for new infrastructure, strategic decisions will need to be made to prioritise the options for investment effectively. The Review provides a systems approach to aid the decision-making process by assessing a range of decision factors alongside the opportunity they present and their feasibility. This approach revealed various opportunities that can be realised with government intervention:

- **Design**: there is an untapped opportunity for developing further capability in quantum-specific design tools. This presents the possibility for the UK to carve out leadership in new markets. By developing this capability domestically, the UK not only addresses concerns around sovereignty, national security, and supply chain resilience but also positions itself at the forefront of designing quantum-specific applications. The opportunity here will be greater if new nanofabrication facilities are developed in parallel.

- **Nanofabrication prototyping**: quantum technologies rely on a variety of foundational materials, each offering distinct properties and capabilities. The Review identified compound semiconductors, silicon photonics, diamond, and superconductors as key priorities for the UK to invest in. Specifically, there is significant demand for open-access nanofabrication prototyping facilities in the UK that can bridge the gap between academic and mid-volume industrial manufacture. However, each material presents a distinct set of opportunities, which are shaped by the varying levels of strength in the UK for each, as well as the current international landscape. The Review is not suggesting investing in new capability for all materials at once, however it is unlikely that only one option would be sufficiently strategic or catalytic.

  - ***Compound semiconductors*** emerged as an area of significant opportunity relative to the other materials considered. The UK has key strengths in developing compound semiconductors across academia and industry, especially material deposition, through several organisations working in this space. However, its focus has been on a subset of specific applications and materials. There is an opportunity to harness novel opportunities within new markets, particularly for next generation applications such as those emerging from quantum. Seizing this opportunity will require investment in open-access commercial capability to move from low to high-volume epitaxy and nanofabrication across a range of materials, including phosphides, arsenides, and nitrides.

- ***Silicon photonics*** is another key area ripe for investment in a new UK facility. With well-established research activity, the UK is well-positioned to take leadership in silicon photonics for quantum with comparatively modest investments. The compatibility of silicon photonics with legacy Complementary Metal-Oxide-Semiconductor (CMOS) lithography tools and supply chains underscores this cost-effectiveness. However, time is of the essence for the UK to capitalise on this opportunity, given the considerable international momentum being driven by major industry players.

- ***Diamond*** is a promising candidate for the development of quantum sensors, quantum communication systems, and components of quantum computers. The UK possesses key expertise in synthesising diamonds equipped with the necessary vacancy centres for applications in magnetic sensing and quantum computing, with good academic facilities and commercial entities. Building on existing UK strengths, there is an opportunity to increase the likelihood of the UK carving out a niche speciality, which has the potential for growth, in diamond for quantum applications. Creating a UK facility dedicated to nanofabrication of synthetic diamonds for quantum devices could be an investment to consider in the longer-term as more R&D is conducted in this space. For the shorter term, by expanding low volume manufacturing capabilities, the UK can meet the growing demand for synthetic diamonds, ensuring a steady supply for research and commercial applications.

- ***Superconductors*** have important potential applications for quantum computing, communications, and sensing. The UK has developed a research base in this space; however, the commercial capability to translate R&D into practical applications is currently limited. By upgrading existing facilities with advanced nanofabrication tools and testing equipment (cryogenics and Radio Frequency (RF)) that support wafer scale would make superconductor platforms industrially relevant and leverage the existing infrastructure. Establishing a purpose-built, open-access superconducting foundry would align with industry needs, allowing for the exploration of different superconducting materials and the development of quantum-specific Process Design Kits (PDKs). The scale of opportunity depends in part on the role of superconductors in quantum computing.

- **Packaging, advanced packaging and heterogeneous integration** is a critical stage for the scalability of quantum technologies. There remains a relatively unexplored market for quantum-specific applications and photonics applications beyond quantum which could be leveraged by the UK. Heterogeneous integration technologies for quantum are in the early stages of development; with efforts focused on R&D, alongside piloting and testing. The UK has significant expertise in some heterogeneous integration technologies with relevance to quantum within several of its research institutions. Establishing a centre for advanced packaging for quantum with a dedicated pilot line for heterogeneous integration technologies would leverage the current UK strengths, increase capability, and signal the UK's intention to lead in the development and scaling-up of heterogeneous integration technologies for quantum. To gain market advantage in this space, the UK will need to invest in scaling its research efforts into commercially deployable devices at pace.

Quantum technologies interact with a wider technology landscape, including semiconductors, photonics, cryogenics, and sectors including Artificial Intelligence (AI); Position, Navigation, and Timing (PNT); telecommunications; and space. Cross-sectoral collaboration and coordination is key to unlock synergies between these fields of innovation and capitalise on technological convergence, including through the infrastructure investments options set out in the Review. In addition, investments such as those recommended by the 'UK Semiconductor Infrastructure Initiative' led by the Institute for Manufacturing Engage (IfM Engage) need to consider quantum technology as a means to augment capability and provide a distinctive competitive edge in manufacturing capability.

As the UK moves towards quantum commercialisation and industrialisation, it must address the inherent challenges in transitioning from the early stages of conceptualisation to commercial scale-up. While the current relative lack of maturity of many quantum technologies makes prioritisation of the infrastructure options challenging, it does also mean that there is still ample opportunity for the UK to strengthen its advantage in numerous areas. The UK was an early mover in quantum technologies, action is needed now to capitalise on that early advantage. The most significant risk would be the opportunity cost of inaction which may lead key players in the UK's quantum ecosystem to relocate outside the UK.

Recommendations at a glance

The priorities related to upgrading or establishing physical infrastructure are outlined within Recommendation 1, whereas Recommendations 2–6 relate to the requirements for infrastructure to operate successfully.

Within this framework, there are several options for intervention under Recommendation 1. To articulate ambition for each of these options, these have been grouped in two scenarios:

Scenario A: UK upgrades and improves access to existing infrastructure to stay on current trajectory.

Scenario B: UK adopts a proactive stance by investing in novel capabilities to position itself at the forefront of particular domains.

Recommendations	Options	
Recommendation 1 Upgrade and improve access for industry to existing open-access infrastructure and prioritise investment in at least one new flagship facility to support quantum technology development across design, nanofabrication prototyping, packaging, advanced packaging and heterogeneous integration.	**Scenario A**: UK upgrades and improves access to existing infrastructure to stay on current trajectory.	**Scenario B**: UK adopts a proactive stance by investing in critical capabilities to position itself at the forefront of particular domains.
	Design	
	Improved access to Electronic Design Automation (EDA) tools and PDK through i) leveraging and tailoring accelerator schemes such as the ChipStart UK programme to meet the design requirements of quantum technologies for industry; ii) providing reduced rates to UK companies through an expanded Europractice, which currently only supports academic discounts; and iii) nationally negotiated access with EDA vendors.	Innovate UK or National Quantum Technology Programme (NQTP) to establish a programme to support the development of quantum-specific PDKs with industry for use with UK prototyping infrastructure.
	Nanofabrication prototyping	
	Compound semiconductors	
	Upgrade existing open-access facilities for higher volume of epitaxy and advanced nanofabrication tooling on condition of improving industry access and standards.	Establish an open-access compound semiconductor facility focused on materials that are useful for quantum such as phosphides, arsenides, and nitrides.
	Silicon photonics	
	Upgrade industry relevant equipment in existing open-access facilities on condition of improving industry access and standards.	Develop an open-access silicon photonics facility that can address the requirements of quantum applications and accelerate industry adoption.
	Diamond	
	Expand and coordinate existing facilities to enable an open-access prototype/pilot line capability, spread across multiple industrial and academic entities.	Create an open-access facility dedicated to nanofabrication of synthetic diamonds for quantum devices.

Recommendations	Options	
Recommendation 1 *continued*	**Superconductors**	
	Invest in more advanced nanofabrication tools and test equipment (e.g. for both cryogenics and with RF) for industry use within existing open-access facilities.	Establish a purpose-built, open-access superconducting foundry for industry use.
	Packaging, advanced packaging, and heterogeneous integration	
	Develop collaborative R&D programmes to solve packaging challenges and advance heterogeneous integration technologies specific to quantum. Upgrade industry relevant equipment in existing open-access facilities on condition of improving industry access and standards.	Establish an open-access centre for advanced packaging for quantum technologies with a dedicated pilot line for heterogeneous integration technologies for quantum applications.

Recommendation 2
Infrastructure where quantum industry is a user must meet industry requirements; for existing infrastructure, upgrade programmes should be focused on meeting industry needs.

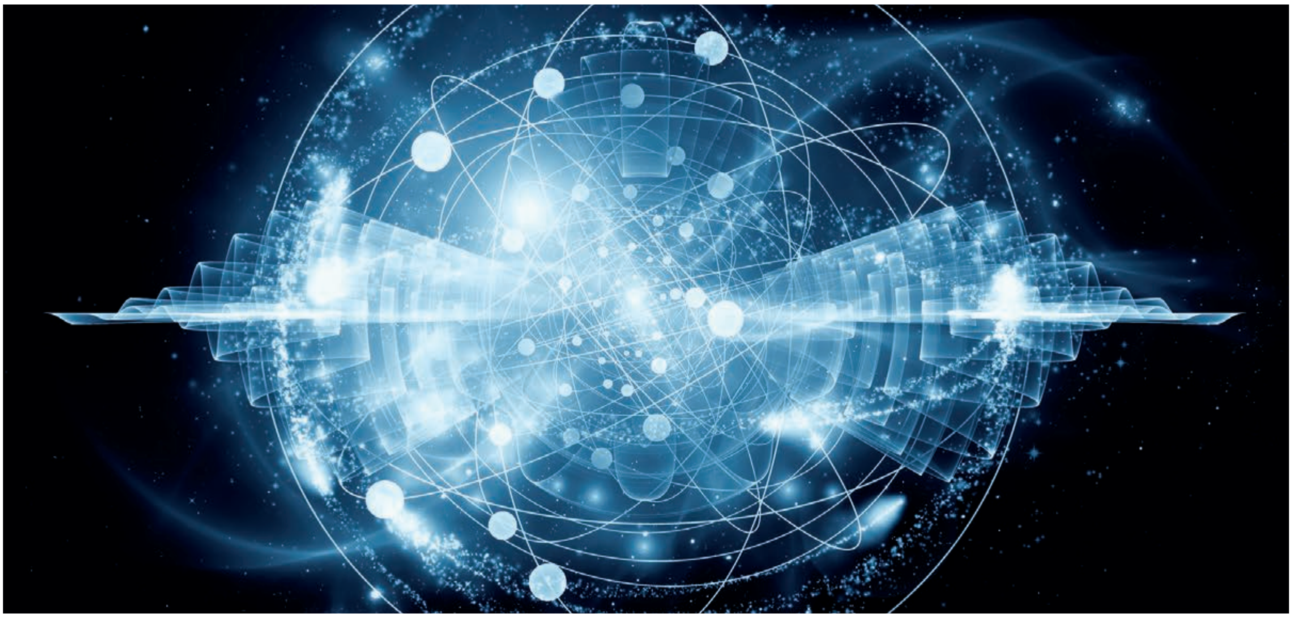
Recommendation 3
Establish a quantum technology coordination function that provides guidance to industry on navigating the UK's quantum technology landscape, and coordinates and facilitates access for industry to infrastructure.

Recommendation 4
Incentivise industry to invest in advanced manufacturing capabilities needed for quantum and other technologies.

Recommendation 5
Government to provide clear strategic direction for quantum technologies including through roadmaps developed in partnership between academia and industry.

Recommendation 6
For successful operation of infrastructure, government needs to consider key enablers such as sufficient provision of skills, appropriate development of standards and adequate regulation to ensure responsible and ethical innovation, including environmental impacts.

Table 1 | Recommendations at a glance.



Introduction

Quantum technologies

Quantum technologies exploit the principles of quantum mechanics to develop novel applications and technologies. The first wave of quantum technologies, also referred to as quantum 1.0, used effects such as quantised energy and tunnelling to develop applications which included lasers, atomic clocks, and superconductors that are now taken for granted. Quantum 2.0 followed, leveraging superposition and entanglement for quantum computing; quantum networks; quantum sensing and imaging; and Position, Navigation, and Timing (PNT). These advances deliver capabilities and efficiencies for a range of applications that go beyond what can be achieved using classical physics.

Quantum technologies have a wide spectrum of current and potential applications across sectors including finance, health, space, telecommunications, and defence (Figure 1). Quantum computing has garnered considerable attention given its potential to reshape the computational landscape through faster and more powerful problem solving. However, the technical challenges to making it widely applicable are considerable and is uncertain when and to what extent those will be resolved. Other quantum technologies also have major potential and have applications already in use today. The points below describe some of these technologies in more detail.

- **Quantum computing** has the potential to offer significant speed advantage over classical computers for tasks such as simulation, optimisation, and database searches. These capabilities may unlock advances in fields such as transport planning, logistics, prediction of chemical processes, analysis and management of complex datasets, and other activities requiring advanced problem solving and optimisation. However, such enhanced capabilities also create security risks for current computational systems, particularly as quantum computers could have the ability of breaking current encryption systems, compromising data privacy and security.

- **Quantum networks** rely on the exchange of single photons through fibre optic networks to ensure secure data transmission. The quantum properties of photons such as superposition, entanglement, distributed entanglement, and no-cloning are used in a way that can determine whether there has been unauthorised access to data or 'wiretapping'. Quantum networks have the potential to transform the way data is transmitted and computed and are particularly relevant for applications which require high levels of data security.

- **Quantum sensing and imaging** exploits the sensitivity of quantum states to physical factors such as vibration, temperature fluctuations, electric, magnetic, and gravitational fields. This enables the exploring of physical systems with higher precision, with applications in environmental monitoring, exploration of subsurface resources, and other applications requiring high-precision sensors. It also allows for advancements in imaging providing more precise measurements in medical settings.

- **PNT** relies on a set of applications including quantum atomic clocks, sensors, accelerometers, gyros and methodologies such as map matching with gravity or magnetometry to correct drifts in classical systems and provide precise time measurements. This provides critical capability for synchronising worldwide data and communication networks with applications in personal and vehicle navigation, telecommunications, electricity networks, finance systems, emergency services, and transportation.

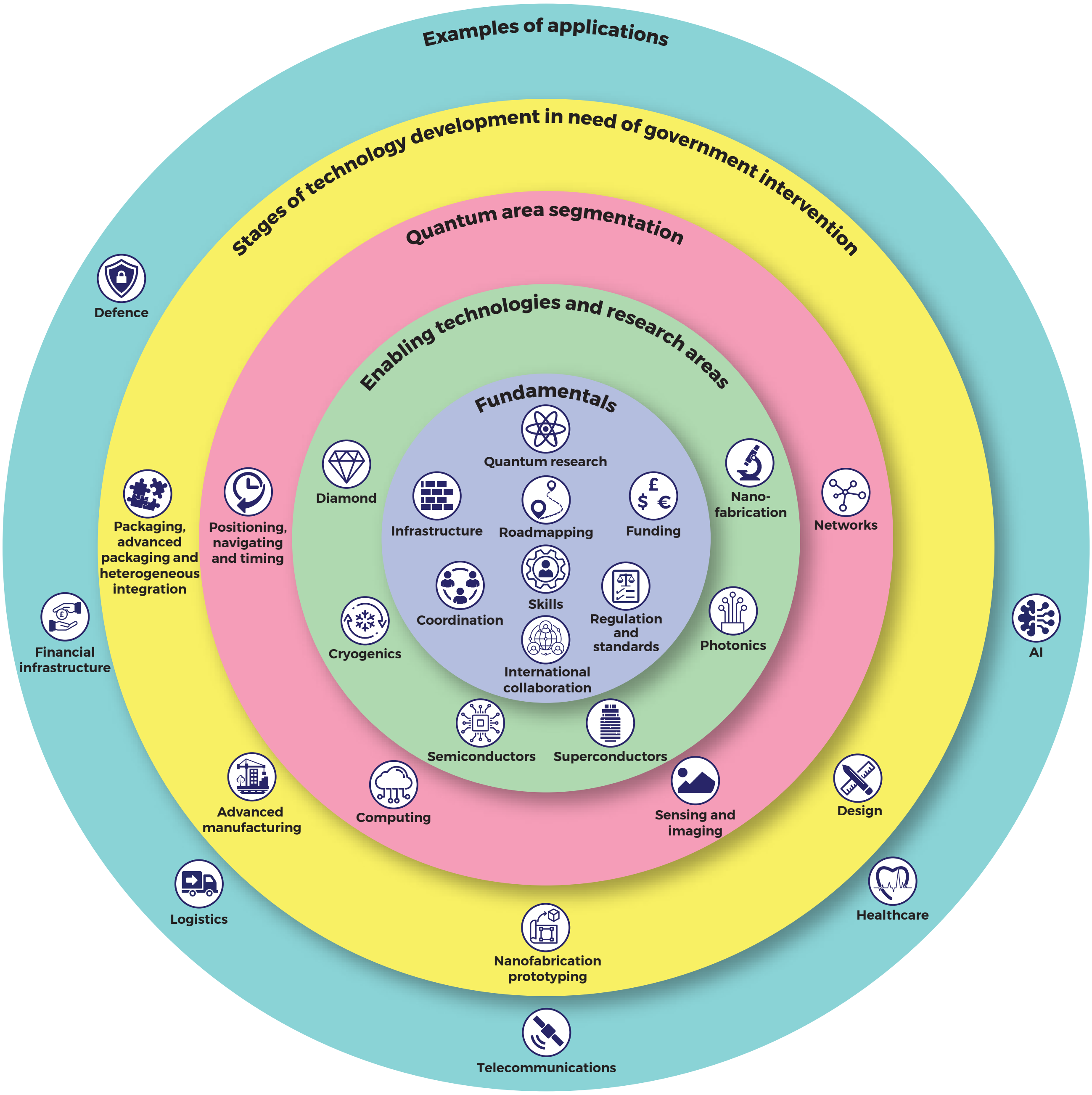


Figure 1 | Simplified depiction of the key components of the quantum technology ecosystem and some of the main application areas.

State of quantum technologies in the UK

The UK was an early mover in quantum technologies. The establishment of the National Quantum Technologies Programme (NQTP) in 2014 laid a strong foundation for taking the first steps in building a commercial path for quantum research and development (R&D). Among its various initiatives, the creation of six national centres for developing quantum technologies, including the four Quantum Research Hubs[1], National Quantum Computing Centre (NQCC) and the Quantum Metrology Institute (QMI) at the National Physical Laboratory (NPL), have added key landmarks to the quantum sector landscape in the UK. The Defence Science and Technology Laboratory (Dstl), Ministry of Defence (MoD), Department for Science Innovation and Technology (DSIT), Government Communications Headquarters (GCHQ), and UK Research and Innovation (UKRI) are important partners of NQTP.

Box 1 | Cluster approach to innovation

STFC is a key UK science organisation for a range of technology areas including astronomy, physics, and space science. Its infrastructure includes large-scale facilities, many of which are part of National Science and Innovation Campuses in Harwell and Daresbury. These campuses have become important innovation hotspots for the development of technologies such as quantum.

The recent establishment of the NQCC at Harwell adds another key piece of infrastructure to an already vibrant ecosystem with facilities such as the Quantum Space Laboratory (QSL) at STFC Rutherford Appleton Laboratory (RAL) Space, STFC Cryogenics, Element Six, STFC's large science facilities, including Diamond Light Source and Central Laser Facility, RedWave Labs, NQCC industry test beds and the recently launched Quantum Business Incubation Centre for start-up support.

The success of STFC is attributed to collaboration supported by the co-location of essential infrastructure and intentional clustering in areas such as space, energy, health. The overarching vision is to create an environment conducive to collaboration and engagement between industry and academia. The clustering has been instrumental in fostering cross-disciplinary approaches, enabling early connectivity and innovation within organisations, and embedding this approach into their operational framework. Harwell's forthcoming quantum cluster will also aim to leverage this collaborative model to address the challenge of scaling quantum technology across several use cases.

Funding streams such as the Industrial Strategy Challenge Fund (ISCF) and its Commercialising Quantum Technologies Challenge have fostered industry-led projects aimed at translating quantum science breakthroughs into tangible products and technologies. Through dedicated Centres for Doctoral Training (CDTs), the NQTP has developed a pipeline of highly skilled quantum researchers, though more needs to be done to address the current skills shortage.[2]

Beyond the NQTP, the UK quantum sector has benefited from existing strengths in enabling areas such as photonics, cryogenics, and compound semiconductors with infrastructure in the photonics cluster in Scotland, the cryogenics facilities in the Science and Technology Facilities Council (STFC) at Daresbury Laboratory and Harwell, and the compound semiconductor cluster in South Wales. The STFC campuses in Harwell and Daresbury provide hotspots for collaboration and research translation, housing numerous companies and essential facilities for quantum R&D (Box 1). NPL's Measurement for Quantum (M4Q) supports companies with access to specialist quantum measurement expertise to facilitate the transition from prototype to real-world applications.[3]

Other connectors in the UK's quantum landscape include Research and Technology Organisations (RTOs) such as the Fraunhofer Centre for Applied Photonics (CAP), NPL and the Catapult Network that collaborate with innovators, government, and industry to support innovation and accelerate the transition from research to commercialisation. UKQuantum[4] provides a defined and centralised voice to the UK quantum industry and the Knowledge Transfer Network's (KTN) Quantum Technology Innovation Network aims to connect innovators with partners and opportunities.

The UK government has recognised the need to take the next step in moving from its very successful programme of quantum R&D towards commercialisation and announced quantum as a critical technology in its Science and Technology Framework.[5] To provide strategic direction to this next stage, the government unveiled its first National Quantum Strategy in March 2023[6], setting out its vision for the UK to cement its position in the quantum landscape, and committing £2.5 billion to a set of priority actions to be delivered by 2033. Complementing this strategy are long-term, time-bound missions announced in the Autumn Statement 2023[7], strategically targeting ambitious outcomes for a concerted effort to lead the UK towards quantum leadership (Box 2). Driving these efforts is the newly formed Office for Quantum, a focal point for steering these initiatives.

Since the publication of the National Quantum Strategy the Regulatory Horizons Council[8] have looked at the regulation of quantum technology application and the Quantum Skills Taskforce[9] has been established to provide expert advice on skills. The Quantum Business Incubation Centre (QuBIC)[10] aims

Box 2 | Quantum Missions

Mission 1: By 2035, there will be accessible, UK-based quantum computers capable of running 1 trillion operations and supporting applications that provide benefits well in excess of classical supercomputers across key sectors of the economy.

Mission 2: By 2035, the UK will have deployed the world's most advanced quantum network at scale, pioneering the future quantum internet.

Mission 3: By 2030, every NHS Trust will benefit from quantum sensing-enabled solutions, helping those with chronic illness live healthier, longer lives through early diagnosis and treatment.

Mission 4: By 2030, quantum navigation systems, including clocks, will be deployed on aircraft, providing next-generation accuracy for resilience that is independent of satellite signals.

Mission 5: By 2030, mobile, networked quantum sensors will have unlocked new situational awareness capabilities, exploited across critical infrastructure in the transport, telecoms, energy, and defence sectors.

to further strengthen the ecosystem, nurturing startups and fostering innovation. The Small Business Research Initiative (SBRI) Quantum Catalyst Fund aims to make the public sector an early customer for the procurement of quantum solutions.[11]

All these efforts combined have created an ecosystem of companies, partnerships, and investments across the full range of existing quantum technologies.

Quantum technologies interact with a wider technology landscape, including semiconductors, photonics, and cryogenics. These are all technology areas in their own right, with photonics and cryogenics showcasing key strengths in the UK; however, they are also components of quantum technologies. Quantum technologies stand both as beneficiaries and catalysts within this broader technological landscape, and, as such, cross-sectoral collaboration and coordination is key to unlock synergies between these fields of innovation. Therefore, investments such as those recommended by the 'UK Semiconductor Infrastructure Initiative' led by the IfM Engage need to consider quantum technology as a means to augment capability and provide a distinctive competitive edge in manufacturing capability. Similar opportunities for alignment and convergence can also be found for sectors such as artificial intelligence (AI), PNT, telecommunications, and space, for which strategic initiatives have also been developed.[12]

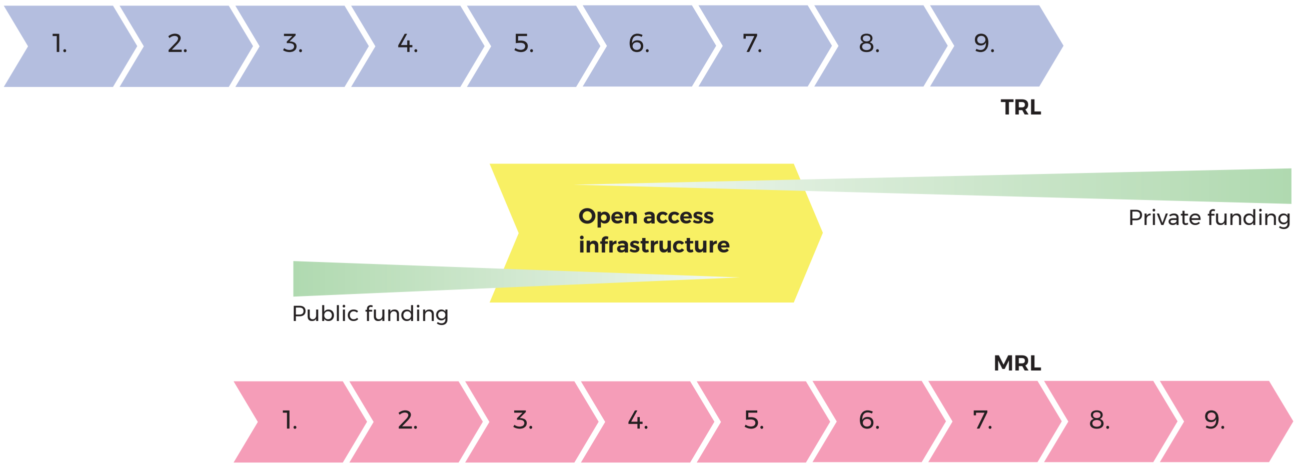
Commercialisation

As the UK moves towards quantum commercialisation and industrialisation, it must address the inherent challenges in transitioning from the early stages of conceptualisation to commercial scale-up. This process can be delineated using frameworks such as Technology Readiness Levels (TRL), Manufacturing Readiness Levels (MRL), and Systems Readiness Levels (SRL) (Figure 2). While these frameworks do not capture every nuance of technology development, they offer valuable guidance in assessing potential risks at different stages of maturity. Aligning technical progression (TRL, MRL, and SRL) with market readiness is required for strategic decision-making and roadmapping, especially given the substantial investments and long timeframes required for the development of quantum technologies. Such an informed approach is important for regulatory planning and risk management, thereby increasing confidence among investors and end users, and facilitating technology adoption.

Quantum technologies currently sit across a wide range of TRLs, MRLs, and SRLs, ranging from proof-of-concept noisy intermediate-scale quantum (NISQ) computing to more mature applications such as quantum networks and sensors (e.g. quantum key distribution (QKD) networks and brain imaging, respectively). From a technical perspective, several technologies are not yet at a pre-production stage and

Technology Readiness Levels

1. Research and basic principles observed
2. Technology concept formulated
3. Experimental proof-of-concept
4. Technology validated in laboratory environment
5. Technology validated in relevant environment
6. Technology demonstrated in relevant environment
7. System prototype demonstration in operational environment
8. System complete and qualified
9. Actual system proven in operational environment



Manufacturing Readiness Levels

1. Basic manufacturing implications identified
2. Manufacturing concepts identified
3. Manufacturing proof-of-concept in laboratory environment
4. Prototype components in relevant environment
5. Prototype systems in relevant environment
6. Prototype components and system in representative environment
7. Pilot line capability demonstrated
8. Low rate production demonstrated
9. Full rate production demonstrated

Figure 2 | **Representation outlining the concepts of TRLs and MRLs in relation to infrastructure investment and public and private funding. For simplicity of depiction, SRLs were not included in this image. The diagram is a visual representation and does not aim to be empirically accurate.**

are still based on heroic one-off prototypes and components that require further testing to prove their full capability. Figure 3 shows a simplified representation of the technological development of a quantum technology to working prototype and then to working product.

From a market perspective, there is considerable uncertainty in predicting the transformational potential of quantum technologies and their adoption by end users because of the relative lack of technological maturity. This level of technical and market uncertainty can discourage investors from investing early in the transition of quantum technologies from lab to market.

Before being deployed at scale quantum technologies will require extensive prototyping, testing, and demonstrating. The resource and infrastructure required for evaluating the performance, reliability, and scalability of quantum solutions in real-world scenarios are often beyond that which current academic facilities can provide, and are also beyond what commercial entities, especially SMEs, can afford in terms of resource and risk.

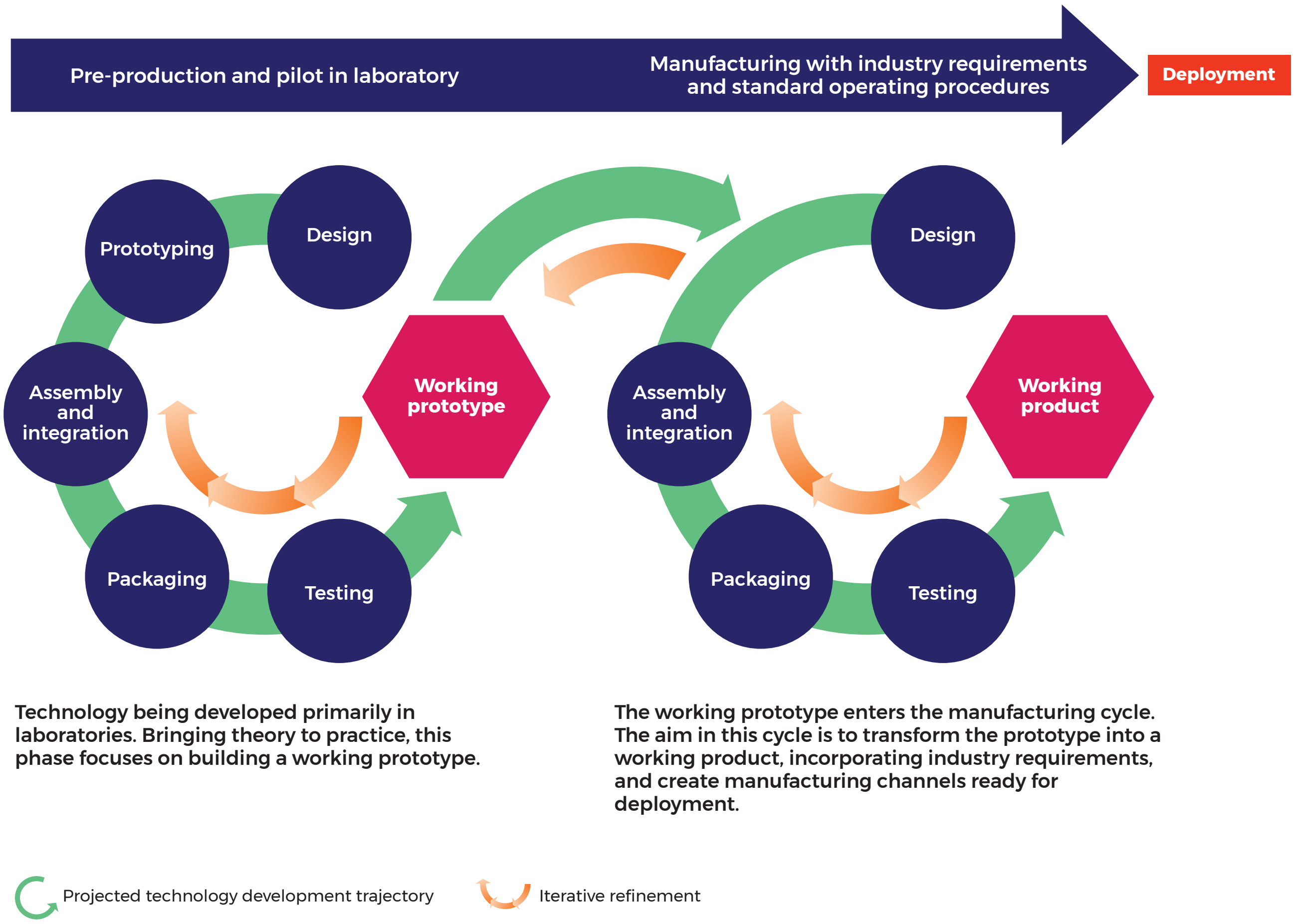


Figure 3 | **Simplified representation of the iterative journey of quantum technology development. It demonstrates how a technology transitions from pre-production in laboratory settings through to manufacturing and deployment.**

Government intervention at this stage is critical to secure a leadership position and strategic advantage in fields of high national interest, bridging the gap between academia and the private sector. This support is crucial to de-risk the technology development process and to facilitate its adoption and commercialisation, as well as to attract investment from the private sector. Without government intervention at this stage, there is a high risk of losing ground to countries making major investments in quantum. This could result in the UK having to rely on technologies developed elsewhere, potentially compromising its security and strategic interests.

Global landscape

While the UK has been a frontrunner in quantum technology development to date, it sits in a dynamic global landscape with other nations rapidly advancing in this field by investing heavily in their own quantum national strategies and infrastructure.

Numerous countries have publicly committed to the development and commercialisation of quantum technologies, as well as increasing international collaboration. The international scale of quantum investment and development is vast, and globally there has been approximately £30 billion committed public funding.[13] The UK's planned investment is dwarfed by nations like the US with its National Quantum Initiative (NQI) and China making large investments in scaling-up R&D, but this is to be expected in the face of much larger economies.

Several comparator countries are developing and funding national quantum strategies built around their strengths. The EU has its Quantum Flagship Programme and Canada and Australia have also stepped up their efforts in scaling-up quantum technologies through their national strategies. Country profiles can be found in Annex 3.

Agreements such as those established between the UK and Australia, Canada, and the US showcase the importance of leveraging global resources and expertise. Such partnerships will become increasingly relevant for accessing the infrastructure and talent required for bringing quantum technologies into a global market. It is crucial that the UK bolsters and leverages its strengths to attract further international collaboration and investment. The UK needs to ensure that it has strengths to offer to engage internationally and currently, its offer could be stronger. While there is a need to protect and improve its sovereign capability, the UK needs to enhance its own capability to open the door to collaboration. In doing so, it may also allow the UK access to infrastructure in quantum areas where it does not necessarily have strength.

The UK needs to continue to engage in international programmes and continue dialogue with government agencies where there is alignment, especially with regards to national security. This will ensure that international collaborations will be mutually beneficial.[14]

The Review

The Royal Academy of Engineering was commissioned to undertake an independent review of the UK's quantum sector's infrastructure requirements for the next decade, including for fabrication facilities; to help identify opportunities where there is a rationale for government to invest in infrastructure for the future.

The right infrastructure can accelerate companies' abilities to progress commercial R&D by creating fully engineered prototypes, and enabling testing, piloting, and demonstration. Accessing low-volume manufacturing for serving small or niche markets can also speed-up development towards volume production. Infrastructure often plays a crucial role in bridging the gap, between the development of a prototype and a product or service that is commercially viable.

Government action is crucial to ensuring the UK has the infrastructure it needs and that it operates successfully. Infrastructure, where the benefits will be shared and no single company is able to take on the risk alone, can require significant investment from government, including through models such as public-private partnerships. Government also has a role in ensuring the UK has access to capabilities that have an important part in the economy and for national security.

The Review takes a systems view of the infrastructure requirements for scaling-up the UK quantum sector over the coming decade. As detailed in the Methodology (Annex 2), the approach focused on industry needs, and considered the full breadth of quantum technologies, cross-sectoral dependencies, and the international context. Alongside options for infrastructure investment, the Review has also considered the underpinning-systems enablers required for successful prioritisation and operation of infrastructure for the quantum sector.

As the development of quantum technologies and their applications progress, infrastructure to support the industrial demonstration and testing of use-cases in the real world with users and integrators will be needed. This type of infrastructure, while essential, was largely out of scope of the Review, as it prioritised infrastructure of greatest need to industry now and that would benefit multiple quantum technologies. In line with this approach, the Review focused on identifying overlaps in infrastructure requirements that cut across different types of technologies, rather than a siloed approach with a focus on specific quantum sectors (e.g. quantum networks). In addition, infrastructure requirements solely to support public research by academia or public sector research establishments (PSREs), unless they overlap with industry requirements, were out of scope of the Review. While the Review mentions key system enablers such as skills and standards, they were out of scope of the Review and many are currently being covered by other initiatives such as the Quantum Skills Taskforce and therefore, do not feature prominently here.

Findings and recommendations

The UK has established a robust foundation for developing quantum technologies, owing to substantial investments over the past decade. However, to advance towards commercialisation, it is necessary to ensure that the infrastructure prerequisites for commercialising quantum technologies are in place. These requirements are delineated across the following sections:

- **Opportunities for infrastructure investment (Section 1).**
- **Meeting industry requirements (Section 2).**
- **Coordination (Section 3).**
- **Integration with wider manufacturing capabilities (Section 4).**
- **Strategic direction (Section 5).**
- **Infrastructure enablers (Section 6).**

Section 1: Opportunities for infrastructure investment

Recommendation 1: Upgrade and improve access for industry to existing open-access infrastructure and prioritise investment in at least one new flagship facility to support quantum technology development across design, nanofabrication prototyping, packaging, advanced packaging, and heterogeneous integration.

Through engagement with a wide range of industry stakeholders, key infrastructure gaps within the UK's quantum landscape have been identified across design, nanofabrication prototyping, packaging, advanced packaging, and heterogeneous integration.

The Review has identified several options for investments to provide accessible infrastructure that facilitates commercial R&D and supports the growth of the UK's quantum sector. These options are outlined in Table 2.

Prioritising infrastructure investments

Given much remains uncertain in the development of quantum technologies, including which technical approach will prove most effective (particularly for quantum computing), what size the future markets will be and thus what future volumes will be, the options for infrastructure investment are broad. While this uncertainty makes prioritisation of the options challenging, it does also mean that there is still ample opportunity for the UK to strengthen its advantage in numerous areas.

Strategic decisions about where to focus efforts to realise the benefits of quantum technologies will be needed over time, with decisions on infrastructure acting as both an input and output of that process. This Review implements a systems approach in the methodology to obtain a comprehensive view of the quantum ecosystem. The outcomes of this approach are presented as a series of options for infrastructure investments. To support the decision-making process, the infrastructure investment options are grouped into two scenarios:

Scenario A: UK upgrades and improves access to existing infrastructure to stay on current trajectory.

Scenario A seeks to maintain the UK's current trajectory by capitalising on existing infrastructure strengths by upgrading them and ensuring that they are fit for purpose for industry use. This approach keeps options open for most quantum technologies and will benefit several other sectors. Industry will benefit from being able to access upgraded facilities which are incentivised to work in a more industry-friendly way.

The Review recommends that Scenario A is implemented in its totality.

While keeping options open and providing much needed capabilities, Scenario A lacks any flagship infrastructure and is unlikely to catalyse significant new private investment. By upgrading and improving what already exists, Scenario A is unlikely to make the step change in the problem-solving and industry required way of working which the Review has identified as a particular UK weakness.

Scenario B: UK adopts a proactive stance by investing in critical capabilities to position itself at the forefront of particular domains.

Scenario B assumes Scenario A has been implemented.

Scenario B sets out a range of options where investment in infrastructure would demonstrate that the UK is seeking to position itself at the forefront of particular domains. For most options a new facility is proposed, allowing the UK to design the facility specified for commercial R&D, both via its capabilities and its mode of operation. This type of investment done well should have catalytic impacts in terms of accelerating the UK's quantum sector by speeding up the R&D process, stimulating further R&D, engaging customers, and attracting further investment and talent.

There are several options presented here demonstrating that there is a wealth of opportunity. Considering the likely costs involved, the Review is not proposing that everything in Scenario B is implemented at once, however it is unlikely that only one option from Scenario B would be sufficiently strategic or catalytic. Strategic decisions between these options will still need to made.

To further support decision-makers in assessing the options in Scenario B, a set of decision factors have been characterised for each option. These are:

- **Quantum technologies' impact** – the infrastructure's relevance to the range of quantum technologies (where breadth is beneficial). These range from benefiting niche quantum technologies to most quantum sectors.
- **UK's current position** – the strength and nature of the UK's foundation which the infrastructure will build on. These range from the UK having niche and emerging strengths, mostly in academia, to the UK as a frontrunner with capability spanning academia and industry.
- **Opportunity for the UK** – the realistic ambition for what the infrastructure will enable for the UK quantum sector. This ranges from being high risk and low certainty to being integral for the commercial scale-up of quantum technologies.
- **Cross-sectoral relevance** – the infrastructure's alignment with other key sectors and their strategies. These range from infrastructure only relevant to quantum technologies to that relevant across several sectors beyond quantum-specific.
- **Risk of inaction** – the likely impact if the infrastructure is not pursued.

These decisions factors are characterised in a summary table for each infrastructure investment option. The following factors should also be considered in the strategic decision-making process; however, they were out of the scope of this Review:

- **National security** – relevance of infrastructure to UK national security objectives.
- **Cost** – cost of building and operating the infrastructure.
- **Timelines** – timescales for implementation.

The assessment of the infrastructure options presented in Scenario B, along with the consideration of the decision factors must be flexible and ongoing, it will require maintenance, review, and updates overtime as new evidence emerges and interventions are made.

Consideration must also be given to how the infrastructure options relate to each other as extra impact will be gained by ensuring compatibility where possible. Such decisions should be framed by a systems approach which maps the interdependencies, causal loops, patterns, and interactions between factors likely to impact outcomes. For example, a new nanofabrication prototyping facility should be combined with a programme to develop PDKs for that infrastructure.

The exact detail and cost of resources and the specifics of responsibilities will need to be assessed once options have been reviewed and as business cases are developed.

Recommendations	Options	
Recommendation 1 Upgrade and improve access for industry to existing open-access infrastructure and prioritise investment in at least one new flagship facility to support quantum technology development across design, nanofabrication prototyping, packaging, advanced packaging, and heterogeneous integration.	**Scenario A**: UK upgrades and improves access to existing infrastructure to stay on current trajectory.	**Scenario B**: UK adopts a proactive stance by investing in critical capabilities to position itself at the forefront of particular domains.
	Design	
	Improved access to EDA tools and PDKs through: i) leveraging and tailoring accelerator schemes such as the ChipStart UK programme to meet the design requirements of quantum technologies for industry; ii) providing reduced rates to UK companies through an expanded Europractice, which currently only supports academic discounts; and iii) nationally negotiated access with EDA vendors.	Innovate UK or NQTP to establish a programme to support the development of quantum-specific PDKs with industry for use with UK prototyping infrastructure.
	Nanofabrication prototyping	
	Compound semiconductors	
	Upgrade existing open-access facilities for higher volume of epitaxy and advanced nanofabrication tooling on condition of improving industry access and standards.	Establish an open-access compound semiconductor facility focused on materials that are useful for quantum such as phosphides, arsenides, and nitrides.
	Silicon photonics	
	Upgrade industry relevant equipment in existing open-access facilities on condition of improving industry access and standards.	Develop an open-access silicon photonics facility that can address the requirements of quantum applications and accelerate industry adoption.
	Diamond	
	Expand and coordinate existing facilities to enable an open-access prototype/pilot line capability, spread across multiple industrial and academic entities.	Create an open-access facility dedicated to nanofabrication of synthetic diamonds for quantum devices.
	Superconductors	
	Invest in more advanced nanofabrication tools and test equipment (e.g. for both cryogenics and with RF) for industry use within existing open-access facilities.	Establish a purpose-built, open-access superconducting foundry for industry use.
	Packaging, advanced packaging, and heterogeneous integration	
	Develop collaborative R&D programmes to solve packaging challenges and advance heterogeneous integration technologies specific to quantum. Upgrade industry relevant equipment in existing open-access facilities on condition of improving industry access and standards.	Establish an open-access centre for advanced packaging for quantum technologies with a dedicated pilot line for heterogeneous integration technologies for quantum applications.

Recommendation 2
Infrastructure where quantum industry is a user must meet industry requirements; for existing infrastructure, upgrade programmes should be focused on meeting industry needs.

Recommendation 3
Establish a quantum technology coordination function that provides guidance to industry on navigating the UK's quantum technology landscape, and coordinates and facilitates access for industry to infrastructure.

Recommendation 4
Incentivise industry to invest in advanced manufacturing capabilities needed for quantum and other technologies.

Recommendation 5
Government to provide clear strategic direction for quantum technologies including through roadmaps developed in partnership between academia and industry.

Recommendation 6
For successful operation of infrastructure, government needs to consider key enablers such as sufficient provision of skills, appropriate development of standards and adequate regulation to ensure responsible and ethical innovation, including environmental impacts.

Table 2 | Summary of recommendations and options for investment.

Design

Design represents one of the foundational stages in the development of quantum technology, encompassing the conceptualisation and specification of quantum systems and components. For complex devices such as those required for several quantum applications, EDA facilitates faster and more efficient prototyping. EDA corresponds to a category of tools that streamline and automate the design process for electronic systems such as printed circuit boards (PCBs) and integrated circuits (ICs). EDA uses PDKs that are collections of data files and libraries tailored to specific manufacturing processes. It is closely linked to prototyping, as designs are translated into physical prototypes. The EDA workflow encompasses everything from initial design to final packaging, including schematic capture, layout, simulation, verification, and the generation of data for manufacturing. This integrated approach allows for the efficient creation of electronic devices ensuring they meet required specifications and standards for use in various applications.

Access to full-stack EDA and PDKs, particularly for those seeking to exploit classical semiconductors for quantum technologies, is often restricted and costly. Companies typically need to negotiate directly with vendors for access and depending on the use case, licence agreements for EDA access can cost more than £100k. The high cost of EDA licences and the dominance of major EDA vendors, primarily based in the US, have posed barriers to entry for UK companies, particularly for startups and SMEs lacking the financial resources. Barriers to entry are further exacerbated by PDKs being linked to specific physical prototyping and manufacturing sites, primarily outside the UK, which are costly to access. UK companies are at a disadvantage compared to international competitors who can take advantage of national subsidised programmes for rapid prototyping. Further details on international programmes can be found in Annex 3.

While EDA for classical semiconductors is currently being utilised to create solutions for quantum (e.g. Riverlane developing application specific ICs for quantum computing error correction), the creation of EDA tools that incorporate quantum is still very much in its infancy. There are limited commercial offerings such as those provided by US-based Keysight's Quantum Pro for superconductors. Therefore, there is an opportunity for UK companies to develop quantum-specific EDA/PDKs for directly exploiting quantum effects across applications.

Overall, addressing issues with EDA and PDK access for the design of quantum technologies would help with progression through both TRL and MRL. A set of options is outlined below for improving design capability in the UK for the quantum sector.

Scenario A: UK upgrades and improves access to existing infrastructure to stay on current trajectory.

This scenario addresses the pressing need to secure support for UK-based companies, particularly SMEs, in accessing EDA tools, enabling several startups and SMEs to sustain their operations. This objective can be achieved through various approaches that leverage and customise the resources and expertise currently provided by non-UK entities. While facilitating access is key, outsourcing this capability still poses risks, particularly concerning the resilience of supply chains in the face of geopolitical challenges.

Leverage and tailor accelerator schemes such as the ChipStart UK programme to meet the design requirements of quantum technologies for industry.

ChipStart UK[15] is a pilot programme delivered by SiliconCatalyst and funded by the UK government to provide early-stage semiconductor design startups with the tools, expertise and networks to design chips. This includes access to design tools, IP, and prototyping capability.

This approach would provide UK companies with access to classical design tools that can be used to solve quantum problems. Utilising an existing programme could offer important advantages in resource efficiency and timeliness, minimising duplication of efforts. Additionally, since semiconductors are integral to many quantum technologies, integrating a ‘quantum add-on’ to the programme could extend its reach and capitalise on synergies.

While classical electronics can be used for quantum applications, incorporating a quantum component into ChipStart UK would require customisation of design tools, expertise, and regulatory guidance (including IP). It would also require having access to the physical prototyping that could support these quantum add-ons. It would be important to define specific priorities in terms of use cases. Given the programme’s limited two-year duration, ensuring long-term support and funding from the UK government would also be crucial for continued success.

Provide reduced rates to UK companies through an expanded Europractice, which currently only supports academic discounts.

Europractice currently provides access to EDA tools to 600 academic organisations through an education licence. In contrast, Europractice provides industry with access to physical manufacturing, but not the EDA tools. Providing industry access to state-of-the-art EDA tools at discounted rates would lower the financial barriers of access, particularly for startups and SMEs.

Design tools need to align with the requirements of prototyping and manufacturing facilities. For these stages to be conducted in the UK, there would need to be EDA/PDKs specific for UK prototyping and manufacturing infrastructure. At present, Cornerstone is the main UK open-access silicon photonics foundry that companies can access through Europractice for prototyping and manufacturing with a focus mostly on telecommunications. Cornerstone was a recent recipient (24 February 2024) of £11 million to create an innovation and knowledge centre (C-PIC). This centre aims to unite leading UK entrepreneurs and researchers to streamline the route to commercialisation, underpinned by the C-PIC silicon photonics prototyping foundry. The C-PIC will also aim to create an open-access model for its PDKs so that these can be expanded for different applications such as quantum.

The use of the existing framework and ecosystem provided by Europractice could leverage accumulated expertise, streamline resource allocation, and minimise costs and administrative burden. However, it is important to note that extending EDA tool access to SMEs could be a complex process with having to manage both commercial licence agreements and training to use the tools. While EDA tool access and training courses offered via Europractice are in part EU-funded, the services are offered by STFC Didcot UK. This would mean that providing licences to UK-based companies would be via STFC Didcot UK rather than under the main Europractice framework.

Nationally negotiated access with EDA vendors.

Having the government negotiate directly with EDA vendors on behalf of small companies for favourable rates would enhance transparency in licensing agreements and help mitigate issues related to export controls. This would ensure that companies can maintain a steady workflow without the fear of interruptions due to licensing restrictions. This could be done through a coordination function as outlined in Recommendation 3, and/or linked to the UK's Office for Quantum with experts capable of negotiating effectively with EDA vendors, managing the distribution of licences and ensuring compliance with export controls.

This approach would level the playing field, allowing startups and SMEs to compete more effectively with larger companies, since there would be transparency on the cost of accessing EDA, compared to the current situation where each company negotiates individually. However, it is important to consider that EDA vendors might resist a national bargaining approach if they perceive it as less profitable or more restrictive than dealing with customers individually.

Scenario B: UK adopts a proactive stance by investing in critical capabilities to position itself at the forefront of particular domains.

This scenario proposes the development of commercial and open-access capabilities to development of quantum-specific PDKs that align with current EDA tools and the following stages of technology development (e.g. prototyping and manufacturing).

Innovate UK or NQTP to establish a programme to support the development of quantum-specific PDKs with industry for use with UK prototyping infrastructure.

The development of quantum-specific PDKs would enable hybrid integration between quantum components (including atomic vapour cells; single photon detectors and emitters; ion traps) with classical semiconductors (compound semiconductor to create lasers at atomic wavelengths, silicon photonics platform for chip-scale miniaturisation, and silicon microelectronics for control). The UK could also pioneer the development of less mature platforms such as diamond and superconductors, where there are limited EDA offerings. This would enable these platforms to scale in terms of TRL and MRL by following the same design principles that have guided silicon microelectronics.

Aligning PDKs with existing UK facilities would simplify the process for industry to prototype designs and would also allow working directly with physical infrastructure to adapt capability to meet quantum needs. This combined with the right expertise would be needed to exploit the opportunity to develop quantum-specific PDKs. However, as set out in the rest of this nanofabrication prototyping section and in Section 2, there is a need to upgrade existing open-access prototyping provided by academic facilities and innovation centres to ensure that these facilities' infrastructure complies with industry grade processes. PDKs require quality assurance to ensure repeatability, as well as continuous updates as new functionality becomes available. PDKs would also need to be included within EDA (commercial or open-access) to provide the full process stack (including device modelling, layout, fabrication, and packaging).

Alternatively, new, purpose-built, open-access prototyping facilities, like those described in Scenario B, could enable easier development of quantum-specific PDKs. New facilities could be designed to match industry standards without having the challenge of retrofitting existing facilities with the required equipment and processes. For example, new facilities could be developed from the ground up to accommodate the unique requirements of quantum technology fabrication, including advanced cleanroom standards and specialised equipment for quantum component integration. Without the constraints of existing infrastructure, new facilities could also better adapt to the evolving needs of quantum technologies, allowing for quicker transition from research prototypes to commercial-scale production. This would also aid the development of PDKs that could be better aligned to international large scale manufacture foundries allowing for easier translation to mass manufacture.

Design

Scenario A Improved access to EDA tools and PDKs through: i) leveraging and tailoring accelerator schemes such as the ChipStart UK programme to meet the design requirements of quantum technologies for industry; ii) providing reduced rates to UK companies through an expanded Europractice, which currently only supports academic discounts; and iii) nationally negotiated access with EDA vendors.

Scenario B Innovate UK and/or NQTP to establish a programme to support the development of quantum-specific PDKs with industry for use with UK prototyping infrastructure. To support decision-makers in assessing the options in Scenario B, the different decision factors outlined in the table below should be considered.

Quantum technologies impact	Quantum computing, quantum sensing, and quantum communications all make use of electronic systems such as PCBs and ICs.
Current position	EDA tools and PDKs have been developed over several years for the semiconductor sector, offering a solid base that can potentially be repurposed for quantum applications. The UK has strengths in chip design with a range of fabless companies. The EDA market is covered by multinationals such as Synopsys, Cadence, and Siemens all headquartered in the US. The market for quantum-specific PDKs is still nascent. The integration of quantum capabilities into design tools is in its early stages, with limited commercial options such as Keysight's Quantum Pro for superconductors. The UK could pioneer the development of less mature platforms for quantum-specific applications where there are limited EDA offerings.
Opportunity	There is an immediate need to secure affordable access for UK-based companies to the essential tools required for design, a foundational stage for the development of several quantum technologies. This requirement can be fulfilled through government's support in facilitating negotiations with current external vendors and providing financial resources for companies to access EDA tools. Such measures increase the likelihood of safeguarding the operations of UK-based companies, particularly startups and SMEs. Beyond ensuring access, there is an untapped opportunity for developing further capability in quantum-specific design tools. This presents the possibility for the UK to carve out leadership in new markets. By developing this capability domestically, the UK not only addresses concerns around sovereignty, national security, and supply chain resilience but also positions itself at the forefront of designing quantum-specific applications. The opportunity here will be greater if new nanofabrication facilities are developed.
Cross-sectoral	EDA tools have played a key role in the development of semiconductor technologies, benefiting from substantial investment over several decades. Investment in EDA for semiconductors could benefit quantum technologies, and vice versa. Leveraging the established expertise and capability in microelectronics and semiconductors could play a key role in providing foundational platforms for quantum applications.
Risk of inaction	The financial challenges preventing UK-based startups and SMEs from accessing EDA tools is a considerable bottleneck stifling their growth and potential success. These challenges not only negatively impact the UK's startup and SME ecosystem, but also disrupt various stages of technology development, due to the foundational importance of design. Given that EDA vendors are located outside the UK, this raises concerns about national security, sovereignty, and supply chain resilience. Additionally, the influence exerted by non-UK prototyping and manufacturing sites through their PDKs exacerbates the situation. The lack of subsidies for UK companies to access EDA tools creates an uneven playing field compared to countries with supportive schemes. This increases the risk of companies choosing not to engage with the UK ecosystem and/or its current design expertise relocating elsewhere.

Nanofabrication prototyping

In scaling quantum technologies, prototyping facilities focused on low-volume nanofabrication play a critical role in commercial R&D and transitioning from laboratory-bound prototypes to practical, field-deployable devices. Nanofabrication facilities have been used for classical semiconductor technologies and are now also being adapted to process novel materials such as superconductors and diamond with the aim of reducing the size, weight, power, and cost (SwaP-C), enabling their application across a wide range of markets.

The nanofabrication prototyping infrastructure options cover a range of foundational materials for quantum technologies, with each offering distinct properties and capabilities: compound semiconductors, silicon photonics, diamond, and superconductors. A broad categorisation is provided in Box 3.

Nanofabrication of these foundational materials has uses in a wide range of other sectors, with particular alignment with the development of electronic ICs for semiconductors. Therefore, the Review strongly recommends that any investments in semiconductor-related infrastructure in support of the National Semiconductor Strategy includes capabilities to support the development of quantum technologies, as outlined in this Review, to provide a distinctive competitive edge in manufacturing capability.

The Review has identified significant demand for open-access low-volume prototyping facilities in the UK that can bridge the gap between academic and mid-volume industrial manufacture. The current UK provision for open-access, quantum-specific prototyping is primarily met by academic facilities and innovation centres. However, the current capabilities often fall short of meeting industry standards and

Box 3 | Materials that enable quantum technology

Compound semiconductors provide the necessary materials platform for designing and building a variety of quantum technologies, offering the flexibility to control and manipulate quantum states, create miniature lasers, exploit unique optical properties, and enable the development of practical quantum devices.

Silicon photonics is a key enabler for telecommunications by providing a platform that combines the benefits of optical communication with the well-established infrastructure of silicon-based electronics. Silicon photonics is also playing a crucial role in the field of quantum technologies by providing a platform for the integration of quantum devices, enabling the manipulation and transmission of quantum information using photons. This is being explored for all areas of quantum. There is quite a diverse requirement within silicon photonics, with materials including silicon nitride and germanium.

Diamond, particularly with the presence of nitrogen vacancy (NV) centres, is a versatile material for various quantum applications. Its unique combination of quantum properties, such as sensitivity to magnetic fields, long coherence times, and room temperature operation, makes it a promising candidate for the development of quantum sensors, quantum communication systems, and components of quantum computers.

Superconductors provide a foundation for the development of various quantum technologies, including quantum computing, quantum sensing, and quantum communication. Their unique quantum mechanical properties, such as zero electrical resistance and the ability to maintain quantum coherence, make them essential components in the construction of advanced quantum devices and systems.

Advanced silicon is a key foundational element for classical semiconductors. Silicon-based qubits benefit from the well-established semiconductor manufacturing processes, offering a scalable and potentially more stable platform for quantum computing. Moreover, silicon allows for the classical control of qubit states with high precision. This compatibility with classical control electronics simplifies the integration of quantum processors with conventional computing architectures. Infrastructure options for advanced silicon are not proposed as part of this Review.

access is frequently constrained for industry stakeholders. Recommendation 2 provides further detail on how these limitations can be addressed. While there may be other prototyping capabilities within industry in the UK, these are not open-access.

UK companies currently access a range of nanofabrication prototyping facilities abroad. UK startups and SMEs are often at a disadvantage compared to international competitors who can take advantage of national subsidised programmes for rapid prototyping and who are able to work directly with foundries to develop quantum-specific PDKs for EDA tools. More details on international programmes are provided in Annex 3.

While the UK does not have the infrastructure to compete with large manufacturing regions like those found in Asia, there are several opportunities for the UK to provide manufacturing capability at medium and low range volume production for commercial R&D to capitalise on R&D and quantum startups' strengths. Industry is clear that it is advantageous to have in-country capabilities, as development times can be accelerated, costs can be lowered, value is more likely to be secured in the UK, customers can be engaged, and risks around IP and national security can be mitigated.

Compound semiconductors

Compound semiconductors consist of two or more elements from the periodic table, for example gallium nitride (GaN). They provide the materials platform for designing and building a variety of quantum technologies, offering the flexibility to control and manipulate quantum states, create miniature lasers, exploit unique optical properties, and enable the development of practical quantum devices. These have potential for quantum applications in communications, QKD, sensing, imaging, lasers, atomic clocks, and quantum computing.

Compound semiconductors use and market goes far beyond quantum. They currently account for about 20% of the chips used[16], with growth of this market being driven by electrification and net zero technologies, telecommunications, self-driving vehicles, and more.

As identified in the UK's National Semiconductor Strategy, the UK has enormous strengths in compound semiconductors. The UK has a significant share of the global compound semiconductor market.[17] Key capabilities are spread across universities, research and innovation (R&I) technology organisations, and companies, and include the Engineering and Physical Science Research Council (EPSRC) National Epitaxy Facility, Compound Semiconductor Applications Catapult, Compound Semiconductor Centre, III-V Epi, IQE, Plessey, Sivers Semiconductors, Kelvin NanoTechnology (KNT), and Henry Royce Institute. Internationally, open-access compound semiconductor foundries are beginning to emerge. For example, WIN Semiconductors was the first pure-play 6-inch gallium arsenide (GaAs) foundry for microwave and RF devices. Global Foundries (GF) has recently announced the development of a $11 billion GaN plant supported through $1.5 billion subsidies.[18] Samsung has announced a new 8-inch GaN foundry to be started in 2025.[19] Smart photonics in the Netherlands provides an indium phosphide (InP) foundry.

There is an opportunity to build on the UK's considerable expertise and capabilities in the development of compound semiconductors to explore, innovate, and exploit early advances in the use of novel materials for quantum applications. There is also a need to upgrade the existing capability for both epitaxy and nanofabrication to turn epitaxial wafers into devices and establish mid-volume wafer production. Any upgrades or new capability would need to align with the tools and processes used by volume foundries to scale both TRL and MRL. It would also be important to assess whether there is sufficient market demand to ensure cost efficiency in producing compound semiconductor chips. Additionally, considering that there are several facilities already in this space, coordination would be a key requirement (see further details in Section 3).

Scenario A: UK upgrades and improves access to existing infrastructure to stay on current trajectory.

This scenario addresses some of the missed opportunities on compound semiconductor innovation and paves the way for the exploration of new applications and materials, leveraging the robust research foundation the UK has in this domain.

Upgrade existing open-access facilities for higher volume of epitaxy and advanced nanofabrication tooling on condition of improving industry access and standards.

The National Epitaxy Facility with its primary mission to support academic research works with industry either directly or through Innovate UK funding calls. This is primarily on a low-volume basis, whereas higher volume can be supported commercially by companies such as IQE. Building upon existing capabilities with higher volume epitaxy and advanced nanofabrication tools would benefit industry by helping bridge the gap between low and high-volume manufacture. This type of investment would allow also academic and national facilities to match their tools and processes to those used by companies such as IQE and Sivers Semiconductors, which in turn would further enhance existing industrial capability.

This option would require upgrading compound semiconductor epitaxial deposition and nanofabrication capability. It would also require formalising partnerships between academia, industry, and government to pool resources, share expertise, and align on strategic goals for the quantum sector. Careful planning and coordination are necessary to avoid duplicating facilities and equipment already available in the industry. Allocating resources efficiently between upgrading epitaxial growth capabilities and investing in nanofabrication tools would be critical to avoid overemphasis on one aspect at the expense of another.

Scenario B: UK adopts a proactive stance by investing in critical capabilities to position itself at the forefront of particular domains.

Implementing Scenario A does not fully address the gap in translating and scaling-up compound semiconductor research into commercial applications. Scenario B outlines further investments that would need to be made to ensure that the UK builds a more resilient supply chain to capitalise further on this sector.

Establish an open-access compound semiconductor facility focused on materials that are useful for quantum such as phosphides, arsenides, and nitrides.

Specialised facilities can maintain optimal conditions tailored to each material, ensuring repeatability in meeting the precise and stringent performance standards of quantum. This is especially important to produce lasers, which demand far higher material quality and fabrication compared to electronic devices. Creating facilities targeting materials such as phosphides, arsenides, and nitrides would allow faster optimising cycles, enabling translation from prototype to manufacture for, for example:

- InP is utilised for emitters and detectors in telecommunications applications particularly at the optimum wavelengths around 1550nm. Lasers for single photons and single photon detectors can be used for photonics-based quantum process including QKD, computing and sensing.
- GaAs is useful for making lasers directly for wavelengths in atom-based quantum devices as well as single and entangled photon emitters from quantum dots.
- GaN is used for making blue lasers that are of interest for strontium clocks. It is also an important material for its potential use in microfabrication of optical components at visible wavelengths, including lenses, waveguides, and highly nonlinear components for optical circuits.

Compound semiconductor requires wafer handling which is typically ≤ 100 mm and does not need the most advanced lithography tools. This could be a brand new, standalone facility or composed of existing upgraded infrastructure. The advantage of a distributed model is that it negates the challenge of processing different compound semiconductor materials such as phosphides, arsenides, and nitrides within the same facility as each material system would need specific processing conditions, such as gas flows, temperature profiles, and chemical reactions. Additionally, equipment used for one material system may not be optimal for another without major reconfiguration or cleaning, leading to potential throughput and efficiency issues. There is also a high risk of cross-contamination if multiple types of compound semiconductors were to be processed in a single foundry. Considerable funding would be required to establish such a facility range or a single foundry that can efficiently handle the risk of cross-contamination.

Compound semiconductors

Scenario A Upgrade existing open-access facilities for higher volume of epitaxy and advanced nanofabrication tooling on condition of improving industry access and standards.

Scenario B Establish an open-access compound semiconductor facility focused on materials that are useful for quantum such as phosphides, arsenides, and nitrides. To support decision-makers in assessing the options in Scenario B, the different decision factors outlined in the table below should be considered.

Quantum technologies impact	Various quantum technologies, including communications, QKD, sensing, imaging, lasers, atomic clocks, quantum computing, PNT.
UK's current position	The UK has key strengths in developing compound semiconductors, especially material deposition, through several organisations working in this space. These include universities, startups, RTOs, highly specialised commercial and small-scale academic fabs. Companies include IQE, Plessey and Sivers Semiconductors. There is a gap in terms of open-access commercial capability to move from low- to high-volume epitaxy and nanofabrication. Therefore, most value from this sector ends up being captured outside the UK.
Opportunity for UK	There is an opportunity to harness novel opportunities within new markets, particularly for next generation applications like those emerging from quantum. To maintain relevance and capitalise on the expanding compound semiconductor markets, the UK must take proactive steps to address the untapped potential for further growth and innovation in this field.
Cross-sectoral relevance	Compound semiconductor is a key capability for the semiconductor sector in the UK. Applications include power electronics (GaN and silicon carbide (SiC)), high-speed data and telecommunications (GaAs and InP), solid-state lighting and displays (GaN), and sensing and imaging (GaAs, InP, InAs).
Risk of inaction	Given the UK's strong capabilities in the initial stages of compound semiconductor development, the failure to advance this expertise domestically and translate it into applications risks its value being directed and captured overseas.

Silicon photonics

Silicon photonics combines silicon chip technology with photonics to create photonic integrated circuits (PICs). Silicon photonics is relatively lower-cost high-volume manufacture compared with other PIC platforms, due to its ability to leverage the significant investments made within CMOS infrastructure over the last half-century. Silicon photonics can support a diverse array of PIC platforms such as silicon, silica, silicon nitride, and germanium due to these materials all being CMOS foundry compatible. PICs play a crucial role in the field of quantum technologies by providing a platform for the integration of quantum devices, enabling the manipulation and transmission of quantum information using photons. This capability is being explored for all areas of quantum, with silicon photonics driving the reduction in SwaP-C for field-deployable quantum devices. This will enable chip-scale atomic devices for PNT, quantum-enabled sensing (including healthcare, and light detection and ranging (LiDAR), and communications, however there is potential for many more applications including quantum computing.

Silicon photonics is experiencing rapid growth primarily driven by investments from large companies such as Intel, IBM, Cisco, and other key players, alongside support from organisations such as the Defense Advanced Research Projects Agency (DARPA) in the US. Major electronics foundries such as Taiwan Semiconductor Manufacturing Company (TSMC) are increasingly engaging in silicon photonics. Their primary interest is in telecommunications, where large volume and low cost are they key advantages. Despite its growth, the technology faces challenges, notably the difficulty of heterogeneously integrating compound semiconductor laser sources.

The UK has a robust global standing in silicon photonics R&D, with well-established expertise and capability. Cornerstone at the University of Southampton is an open-source, licence-free silicon photonics rapid prototyping foundry. Its PDKs have been developed for telecommunication applications. The James Watt Nanofabrication Centre (JWNC) at the University of Glasgow is a partner with Cornerstone and can also be accessed industrially through KNT, who have developed a quantum portfolio.

With strengths in silicon photonics R&D, and emerging in quantum applications, the UK is well-positioned to take leadership in this domain with comparatively modest investments. The compatibility of silicon photonics with legacy CMOS lithography tools and supply chains underscores this cost-effectiveness.

Scenario A: UK upgrades and improves access to existing infrastructure to stay on current trajectory.

This scenario leverages the leadership that the UK already has in silicon photonics, particularly for R&D and low-volume manufacturing. Improving existing capability with an increased focus on delivering quantum applications and meeting industry's needs could benefit several quantum technologies.

Upgrade industry relevant equipment in existing open-access facilities on condition of improving industry access and standards.

The evidence collected throughout the Review shows that current facilities for silicon photonics require upgrades, so they are fit for purpose for quantum industry's needs.

This option would require providing more industrially relevant equipment, thus necessitating funding for purchasing lithography tools, automation technology, and other necessary equipment. Currently, the JWNC has electron beam lithography capability (Raith EBPG 5200), capable of writing up to 200 mm wafers with minimum feature sizes down to 10 nm. Cornerstone has the UK's only krypton fluoride photolithography stepper (248 nm) and it was the recipient of £11 million to create a C-PIC to build on the university's expertise in silicon photonics, enhancing the advancement and commercialisation of related technologies. These facilities could handle more throughput, reducing wait times, and increasing efficiency.

Integrating industrial processes into academic settings may present logistical and management challenges, requiring clear guidelines and coordination. Recommendation 2 outlines further details on compliance with industry requirements.

Scenario B: UK adopts a proactive stance by investing in critical capabilities to position itself at the forefront of particular domains.

This scenario leverages the fact that silicon photonics is a relatively mature sector and there is industry interest across a wide range of applications. With its current capability, the UK is in a good position to advance silicon photonics further for quantum technologies and an industry-facing facility should enable that.

Develop an open-access silicon photonics facility that can address the requirements of quantum applications and accelerate industry adoption.

An industry-facing UK facility would make it easier for UK-based companies to work directly with the facility to develop processes for new devices. This in turn would enable the development of quantum-specific PDKs. This infrastructure fills a critical gap for the UK, supporting the development of prototyping to manufacturing.

For quantum, capabilities needed include reduction in line-edge roughness for lower propagation losses, providing easer integration with CMOS and better reproducibility. This could be achieved by targeting a technology node size of 130–65 nm.

This would enable advanced photonic structures such as sub-wavelength gratings and critically coupled high quality factor micro-ring resonators. In addition, as this technology node range is over twenty years old it does not require the latest and most expensive fabrication technologies. The 130 nm node, for example, is still used by TSMC for its commercial silicon photonics offerings, demonstrating its viability for high-quality, complex device production. This type of capability could support a wide range of silicon photonics applications alongside quantum.

Such a facility could be either established as a fully owned national UK facility, a public-private partnership, or be set up through an external partnership with an industry partner, such as GF.

- For a fully owned national UK facility, depending upon its capacity (wafers/month) and the level of automation. This would reduce dependency on foreign fabrication facilities, strengthening the UK's technological independence and resilience.
- Having the facility set up by an established semiconductor manufacturer could significantly accelerate the time frame for deployment of a standalone silicon photonics foundry by leveraging the partner's extensive experience in building and operating these facilities. Partnership with a leading semiconductor manufacturer would ensure access to the latest manufacturing technologies and processes. There would also be existing PDKs that could be immediately exploited by UK companies. This approach would require major subsidies and/or tax incentives from government. It may be challenging to attract a commercial entity to set up a foundry exclusively for silicon photonics (130–65 nm) as normally these facilities are converted from depreciated CMOS infrastructure.

Any new facility would need to have the adequate expertise to establish, operate, and maintain it. There would also be a requirement for roadmapping, management, and marketing to attract business. These facilities would benefit from being operated by industry for industry to ensure that access and processes meet industry needs.

Silicon photonics

Scenario A Upgrade industry relevant equipment in existing open-access facilities on condition of improving industry access and standards.

Scenario B Develop an open-access silicon photonics facility that can address the requirements of quantum applications and accelerate industry adoption. To support decision-makers in assessing the options in Scenario B, the different decision factors outlined in the table below should be considered.

Quantum technologies impact	Silicon photonics is relevant to a wide breadth of quantum technologies. It is driving the reduction in SwaP-C for field-deployable quantum devices. This will enable chip-scale atomic devices for PNT, quantum-enabled sensing (including healthcare, and LiDAR) and communications, however there is potential for many more applications including quantum computing.
UK's current position	The UK has key R&D expertise in silicon photonics and photonics more generally (e.g. photonics cluster in Scotland). For example, Cornerstone (Southampton University) and JWNC (University of Glasgow) are key players in this field. Next generation silicon photonics requires on-chip heterogeneous lasers and other components that will be composed of compound semiconductors such as GaAs and InP – the UK also has great strength in this area, for instance at the National Epitaxy Facility. Silicon photonics is experiencing rapid growth internationally with investments from large companies and major electronics foundries such as TSMC. However, this interest is driven by volume manufacturing relevant for AI and telecommunications.
Opportunity for UK	With well-established research activity, the UK is well positioned to take leadership in silicon photonics for quantum with comparatively modest investments (compared to advanced silicon). The compatibility of silicon photonics with legacy CMOS lithography tools and supply chains underscores this cost-effectiveness. However, time is of the essence for the UK to capitalise on this opportunity, given the considerable international momentum driven by industry players in silicon photonics, although that interest is focused on volume manufacture for AI and telecommunications. Heterogeneous integration technologies will be crucial to leveraging the full capabilities of silicon photonics for quantum.
Cross-sectoral relevance	Silicon photonics is being commercially exploited for telecommunications with a market value of several £billion. It is also being investigated for biomedical sensors, LiDAR, neural networks for large language models, artificial intelligence, quantum, and next generation communications.
Risk of inaction	The potential of silicon photonics has been recognised by large semiconductor companies in the international sphere. The UK currently has a lead in terms of photonics and quantum expertise. However, if it does not capitalise on this, the UK is at risk of trailing behind or missing out entirely on a transformative technology, as well as have its current expertise relocate elsewhere. With increasing international momentum in this sector, the UK needs to act promptly, as the window of opportunity may close soon.

Diamond

Diamond, particularly with the presence of nitrogen vacancy (NV) centres, is a versatile emerging material for various quantum applications. Its unique combination of quantum properties, such as sensitivity to magnetic fields, long coherence times, and room temperature operation, makes it a promising candidate for the development of quantum sensors, quantum communication systems, and quantum computing.

The growth in the synthetic diamond market for quantum applications is being propelled by advancements in Chemical Vapour Deposition (CVD) which offers the potential with wafer scale (>100mm) diamond with part per million or better control of purity, increasing use in semiconductors, lasers, acoustics and as alternatives to traditional gemstones. The UK possesses important expertise in synthesising diamonds equipped with the necessary vacancy centres for applications in magnetic sensing and quantum computing. Leading commercial entities such as Element Six excel in CVD techniques and defect engineering. OPSYDIA has pioneered laser technologies for generating subsurface vacancy centres. On the academic front, facilities such as the Cardiff Diamond Foundry and the University of Bristol are recognised for their capabilities in synthetic chemical vapor deposition. Meanwhile, the University of Oxford and Warwick University are noted for their fundamental materials characterisation as well as engineering of NV centres, including laser writing. Additionally, University College London (UCL) specialises in diamond nanofabrication, and the University of Cambridge is utilising NV-diamond for single molecule sensing. This collective expertise and collaborative R&D underscores the UK's position as a frontrunner in the development and application of advanced synthetic diamonds for quantum.

Diamond for quantum has not been extensively commercialised yet. Open-access foundries for synthetic diamond for quantum applications have only started to emerge (e.g. Qnami in Switzerland). There remains a capability gap for capturing more value in diamond for specific target applications, leveraging the flexibility and agility a foundry might offer.

Building on existing UK strengths and capabilities in academia and existing industry players, there is an opportunity to increase the likelihood of the UK carving out a speciality, which has the potential for growth in diamond for quantum applications, by developing an open-access prototype/pilot line capability.

Scenario A: UK upgrades and improves access to existing infrastructure to stay on current trajectory.

As diamond is an emerging material for quantum with the potential for use across a wide range of quantum applications, Scenario A will keep options open, allowing UK partners to better explore its potential and maintain the UK's leading edge.

Expand and coordinate existing facilities to enable an open-access prototype/pilot line capability, spread across multiple industrial and academic entities.

By expanding its existing capabilities, the UK can meet the growing demand for synthetic diamonds, ensuring a steady supply for research and commercial applications. This approach also leverages existing expertise and capability developed over many years.

Expanding the capabilities of key facilities such as Element Six, and pulling together foundry type capabilities that for example exist in Cardiff, and the University of Bristol would be essential for enhancing the UK's synthetic diamond production capacity. This expansion would involve acquiring CVD systems designed to facilitate the transition from prototyping to full-scale production, as well as foundry integration technologies.

Additionally, there is a need to improve the precision and scale at which vacancy centres can be created. Emulating the laser writing techniques currently used by OPSYDIA and academic institutions such as the Universities of Oxford, Warwick, and the Surrey Ion Beam Centre will be pivotal. Such advancements would allow for the mass production of diamonds tailored for specific quantum technologies.

Finally, enhancing the nanofabrication capabilities at UCL would help to meet the scaling requirements from prototype to production. This upgrade would ensure that the UK's academic and commercial sectors are well-equipped to lead in the development and manufacturing of advanced diamond-based technologies. Overall, this upgrading of existing facilities would collectively enable an open-access prototype/ pilot line capability similar to those being developed in Europe (e.g. Qnami). Significant funding would be needed for purchasing new equipment, upgrading facilities, and training staff. Because of the geographic distribution of facilities, there would need to be coordination to ensure companies can easily access all required stages for prototyping.

Given the location of existing facilities and diamond being an emerging material, this option would still be heavily reliant on academic facilities, therefore issues related to industry access and industry grade processes would need to be addressed (as detailed in Section 2).

Scenario B: UK adopts a proactive stance by investing in critical capabilities to position itself at the forefront of particular domains.

Given its emerging nature, Scenario B would be a riskier investment if made now. To reduce risk, this scenario could be considered in two to five years' time, when more is known about diamond application in commercial quantum technologies. International interest and activity should also be monitored.

Create an open-access facility dedicated to nanofabrication of synthetic diamonds for quantum devices.

Creating a standalone UK facility dedicated to synthetic diamond production and research would be a strategic move to consolidate capabilities. This facility should focus on integrating synthetic diamond production with value-add technologies (etching, patterning, defect engineering). This facility would serve as a hub for both commercial productions streamlining efforts to innovate and manufacture synthetic diamonds tailored for various quantum applications. Concentrating equipment, expertise, and research in a single location can improve efficiency and reduce operational costs. It would also not require retrofitting existing infrastructure, especially academic facilities that would also need to adopt industrial grade processes. A flagship facility can attract talent and investment, boosting the UK's reputation as a leader in vacancy centre diamond.

This option would require significant investment to build the facility, purchase equipment, and hire staff. A clear vision and plan would be needed to ensure the facility meets the current and future needs of the UK's synthetic diamond sector.

Concentrating equipment, expertise, and research in a single location can improve efficiency and reduce operational costs. It would also not require retrofitting existing infrastructure, especially academic facilities that would also need to adopt industrial grade processes.

Diamond

Scenario A Expand and coordinate existing facilities to enable an open-access prototype/pilot line capability, spread across multiple industrial and academic entities.

Scenario B Create an open-access facility dedicated to nanofabrication of synthetic diamonds for quantum devices. To support decision-makers in assessing the options in Scenario B, the different decision factors outlined in the table below should be considered.

Quantum technologies impact	A promising candidate for several quantum technology areas, including sensing, quantum communication systems, and quantum computing.
UK's current position	Diamond is an emerging material and R&D is being conducted in both academia and industry in the UK. Key UK players in this space include Element Six, OPSYDIA, Cardiff Diamond Foundry, University of Bristol, University of Oxford, University of Warwick, UCL, University of Cambridge, among others. Internationally, Qnami based in Switzerland is one of the emerging open-access foundries for synthetic diamond with applications in quantum.
Opportunity for UK	The UK possesses key expertise in synthesising diamonds equipped with the necessary vacancy centres for applications in magnetic sensing, networking, and quantum computing, with good academic facilities and commercial entities. Building on existing UK strengths and capabilities in academia and a key industry player, there is a unique but time-bound opportunity to increase the likelihood of the UK carving out a scalable diamond industry for quantum.
Cross-sectoral relevance	Industrial cutting, semiconductors (ultra-wide bandgap and high thermal conductivity), optics, defence, high fidelity audio, and luxury goods.
Risk of inaction	Potential loss of UK leading edge R&D capability and the subsequent inability to capitalise on strengths if application/market proves fertile.

Superconductors

Superconductors provide a foundation for the development of various quantum technologies, including quantum computing, quantum sensing, and quantum communication. Their unique quantum mechanical properties, such as zero electrical resistance and the ability to maintain quantum coherence across long distances, make them essential components in the construction of advanced quantum devices and systems.

Superconductor qubits are one of the leading candidate technologies for scaling quantum computers from NISQ to general purpose machines. This is mainly due to fabrication utilising the same techniques and equipment that are used for CMOS. The qubits are controlled using RF techniques, making controlling large numbers feasible.

The growth in the global superconductor market is mainly being driven by the increasing demand for magnetic resonance imaging (MRI) machines, high-speed transportation (Maglev), low loss electrical transmission, large magnetic field generation (e.g. Conseil Européen pour la Recherche Nucléaire (CERN) in Switzerland). However, these typically use high-temperature superconducting ceramic materials that are not so relevant for quantum, which typically rely upon thin-film metallic superconductors.

As commercial superconducting foundries are only beginning to emerge there is an opportunity for the UK to take a global lead and build on its existing expertise and infrastructure. This includes the Royal Holloway's UK Centre for Superconducting and Quantum Systems (RHUL UK-CSQS), JWNC at University of Glasgow, Lancaster University, and the Quantum Materials group at the University of Oxford. Outside academia there are national facilities such as the STFC at Harwell and Daresbury and NPL who provide industry access to capabilities for superconductor testing. The UK also has strengths in cryogenic hardware manufacturing with key players such as Oxford Instruments, ICE Oxford, and Chase Cryogenics.

Upgrading existing facilities with advanced nanofabrication tools and testing equipment (cryogenics and RF) that support wafer scale production would make superconductor platforms industrially relevant and leverage the existing infrastructure. Moreover, establishing a purpose-built, open-access superconducting foundry would align with industry needs, allowing for the exploration of different superconducting materials and the development of quantum-specific PDKs.

Scenario A: UK upgrades and improves access to existing infrastructure to stay on current trajectory.

This scenario would make superconductor platforms industrially relevant and leverage the existing infrastructure.

Invest in more advanced nanofabrication tools and test equipment (e.g. for both cryogenics and with RF) for industry use within existing open-access facilities.

Upgrading existing facilities would enable companies to access superconductor platforms within the UK that support wafer scale production, leveraging existing infrastructure and expertise. It would also provide opportunities to coordinate between facilities to provide access to different types of superconductor material/devices. This would need to ensure that industry requirements are met, as outlined in Section 2. Upgrades would require investment in more advanced nanofabrication tools and test equipment (cryogenics and RF). It would be necessary to determine whether the existing academic infrastructure could be retrofitted sufficiently to enable an open-access foundry for industry following the requirements outlined in Recommendation 2. Additionally, there are testing capabilities available at STFC Daresbury and NPL, the latter having supported various companies through their M4Q programme.

Scenario B: UK adopts a proactive stance by investing in critical capabilities to position itself at the forefront of particular domains.

This scenario is more ambitious, especially as global corporations are active in this space and with the scale of opportunity depending in part on the role of superconductors in the future of quantum computing.

Establish a purpose-built, open-access superconducting foundry for industry use.

A purpose-built, open-access superconductor foundry designed for industry could allow access to different superconducting materials in a way that is tailored to industry needs, without having to retrofit existing facilities with industrial tooling. This would support the development of quantum-specific PDKs. This option would require capital investment and longer time frame for the facility and tools to become available. An estimate of the cost of a standalone UK facility can be taken from the $115 million funded Superconducting Quantum Materials and Systems (SQMS) Center in the US.[20]

Superconductors

Scenario A Invest in more advanced nanofabrication tools and test equipment (e.g. for both cryogenics and with RF) for industry use within existing open-access facilities.

Scenario B Establish a purpose-built, open-access superconducting foundry for industry use.
To support decision-makers in assessing the options in Scenario B, the different decision factors outlined in the table below should be considered.

Quantum technologies impact	Superconductors are relevant for quantum computing, communication, and sensing. This is due to their zero electrical resistance that enables long coherence times for qubits, quantum repeaters, quantum transducers, ultra-sensitive magnetic field detection (superconducting quantum interference devices), and extremely high-efficiency single photon detectors.
UK's current position	The UK does not currently have commercial capability for superconductors. In terms of its research base, superconducting R&D is primarily concentrated in RHUL UK-CSQS, JWNC, NSQI at the University of Bristol and the Quantum Materials group at the University of Oxford. Outside academia, STFC Daresbury hosts research within superconductivity with RF testing (an example being PsiQuantum) and NPL has testing capability. The UK has also key expertise and capability in cryogenic hardware manufacturing (e.g. Oxford Instruments, ICE Oxford, and Chase Cryogenics). Internationally, commercial superconducting foundries are beginning to emerge such as Scalable Energy Efficient Quantum Computing (SEEQC) (US) and QuantWare (Netherlands). Large investments are being made in national facilities such as in the US with the $115 million SQMS Center.
Opportunity for UK	The UK has a chance to build on its current superconductor initiatives by developing an open-access platform for industrial use. This platform could provide considerable advantages to startups and SMEs that currently face challenges accessing this technology because of the protective measures taken by large multinational corporations, particularly in the field of quantum computing.
Cross-sectoral relevance	Superconductors are crucial for medical imaging systems such as MRI machines, as well as particle accelerators (e.g. CERN), nuclear fusion reactors, and high-speed magnetic levitation (Maglev) transport. However, these typically use high-temperature superconducting ceramic materials that are not so relevant for quantum. Future high-performance computing with superconducting interconnects and single flux quantum logic devices are being explored.
Risk of inaction	Failing to support superconductors could lead to the UK falling behind other nations that are heavily investing in this area such as the US, China, and EU.

Packaging, advanced packaging, and heterogeneous integration[i]

As quantum technologies advance, it becomes essential to integrate a diverse range of materials, photonic, and electronic functions into scalable systems to deliver the improvements in performance, energy consumption, and cost that will enable their application in a wide range of markets.

Miniaturisation is crucial to reduce the SwaP-C of quantum technologies, for example to move from lab-based demonstrations in quantum sensing and quantum communications systems to deliver the complexity, reliability, and manufacturability required by these applications. Packaging to maintain a controlled environment that preserves the performance of quantum devices is also necessary. By shielding against external sources of noise and interference, packaging ensures the reliability, stability, and optimal performance of quantum systems, providing the foundation for their successful integration into practical applications.

Although packaging solutions are widely available from the market for conventional electronic devices and systems, quantum technologies present unique challenges across the full spectrum of packaging and advanced packaging technologies and new technical advances will be needed to deliver what they require.

Heterogeneous integration technologies are at the leading edge of advanced packaging approaches. They enable the consolidation of multiple chips, chiplets, and chip components featuring different materials, manufacturing processes, and/or suppliers, onto a single substrate at the chip level. They will prove pivotal in quantum technologies for their ability to combine diverse materials and components on a single chip, enhancing and scaling quantum complex systems.

For quantum technologies, heterogeneous integration technologies will enable adding micro-scale components, such as specialist materials for photonic integration (e.g. single photon emitters, low noise detectors, cryogenics switches), onto single material chips. They will support the integration of cryogenic electronics with quantum bits for optimised quantum computing and allow the amalgamation of various optical elements in quantum sensing and communication systems. Also, they will facilitate the creation of hybrid quantum systems and the incorporation of devices such as chip-scale atomic clocks, gravimeters, and optically pumped magnetometers, essential for advancing technology, improving performance, reducing costs, and minimising physical footprint. Heterogeneous integration technologies have so far only peripherally addressed some elements of quantum technologies and there are still significant advances to be made.[21] Therefore, at present heterogeneous integration technologies for quantum are still in the early stages of development; with efforts focused on R&D, alongside piloting and testing.

Major investments in heterogeneous integration for electronic chips are being made in the US, Asia, and Europe, with companies such as Intel, ASE Technology, GF, Cisco, NVIDIA, TSMC and Advanced Micro Devices (AMD) leading on key efforts. Governments are also playing a role. Companies such as Nexus Photonics in the US have joined DARPA's Commercial Solutions Opening programme to expedite the development of their heterogeneous integration and advanced photonic integrated circuit concepts into practical applications. The EU's Chips Joint Undertaking has initiated the first calls to fund chip pilot lines aimed at establishing pre-commercial facilities to provide the industry with testing, and validation capability for semiconductor technologies, including heterogeneous integration. PHIX in the Netherlands has received €20 million through the National Growth Fund and more recently Silicon Box received subsidies from the Italian government to create a €3.5 billion centre for heterogeneous integration.
The UK lacks commercial capability for the most state-of-the-art advanced packaging techniques, including 2.5 and 3D heterogeneous integration. However, with international investments focused on heterogeneous integration for electronic chips, there remains a relatively unexplored market for quantum-specific applications and photonics applications beyond quantum which could be leveraged by the UK.

The UK has key expertise in some heterogeneous integration technologies within several of its research institutions. The University of Strathclyde has developed underpinning technology for nanoscale-accuracy micro-transfer printing with in-situ monitoring for multiple materials and device platforms. The National

i The terminology used for defining these stages can vary, is evolving and is sometimes used interchangeably depending on the context.

Epitaxy Facility at Sheffield University commissioned a commercial-grade micro transfer print tool (ASMPT Amicra) for the heterogeneous integration of compound semiconductor devices on silicon in September 2023. This tool is one of the first industrially compatible systems for heterogeneous integration in the UK. Cornerstone is also currently exploring the heterogeneous integration of compound semiconductor lasers with silicon photonics, utilising a Finetech Sigma pick and place tool with 0.5-micron alignment based at the University of Glasgow. Innovate UK and EPSRC programmes have also catalysed advances. For example, the EPSRC programme grant 'Hetero-print' is a £5.5 million funded collaboration between the universities of Manchester, Strathclyde, Cambridge, Sheffield, Cardiff, and Glasgow, and has resulted in significant advances in transfer printing for heterogeneous integration. Another example is the QT Assemble consortium, led by Fraunhofer CAP, and funded by Innovate UK, is developing highly innovative assembly and integration processes for new markets in quantum technologies.

With sufficient support and concerted effort, there is an opportunity to leverage existing expertise in the UK to advance emerging heterogeneous integration technologies for quantum. Existing strengths and skills in photonics and future telecommunications will also be supportive as heterogeneous integration for quantum will require convergence.

Looking more broadly at packaging for quantum technologies the UK's commercial capability, while of high standard, is relatively limited. Alter Technology and Bay Photonics are key players and have the expertise to solve packaging challenges such as thermal mismatch between materials and the ability to withstand harsh environmental conditions such as space. They also offer low- to mid-volume manufacture for various sectors including quantum. Alter Technology offers packaging for high-reliability electronic components and specialises in PIC packaging, RF, and microwave device assembly, tailored for space and defence applications. Bay Photonics provides bespoke advanced photonics packaging, focusing on precision alignment, die bonding, and wire bonding. The Compound Semiconductor Applications Catapult enhances these capabilities with package design, rapid prototyping, and support for photonics and RF technologies. Fraunhofer CAP also provides high-quality support for resolving a limited range of packaging-specific issues, particularly related to innovative designs of optical sources. The lack of commercial packaging capabilities creates a bottleneck for manufacturing quantum technologies in the UK, as even the most groundbreaking device cannot function without the required packaging.

UK-based quantum companies regularly use packaging infrastructure and services in other countries, such as Tyndall in Ireland, Valtion Teknillinen Tutkimuskeskus (VTT) in Finland, and PHIX in the Netherlands. These international offerings are regarded as reliably having the most up to date capabilities, a broader suite of capabilities that the UK can offer, taking a problem-solving approach and meeting industry requirements (see Recommendation 2).

Packaging is an area that still requires extensive R&D. This is particularly the case for quantum systems, as these tend to require precise and often bespoke packaging solutions that accommodate cryogenics and RF to maintain quantum properties, protect them from environmental interference, and ensure their functional integration into various applications. However, packaging R&D is an area that is typically underappreciated in the UK. The scarcity of funding and strategic focus on packaging R&D creates considerable barriers for addressing the unique packaging needs of quantum systems. Developing further domestic capabilities for packaging would allow UK-based quantum technology companies to prototype and develop their technologies within country, accelerating the development cycle and better protecting IP.

In summary, there is scope for the UK to improve its capabilities across packaging, advanced packaging, and heterogeneous integration to advance quantum technologies. Efforts on packaging are best focused on R&D and improving current capabilities, while developing heterogeneous integration technologies for quantum presents a more transformative opportunity for the UK.

Scenario A: UK upgrades and improves access to existing infrastructure to stay on current trajectory.

This scenario builds on the UK's research strengths and incentivises greater industry involvement to progress commercialisations.

Develop collaborative R&D programmes to solve packaging challenges and advance heterogeneous integration technologies specific to quantum. Upgrade industry relevant equipment in existing open-access facilities on condition of improving industry access and standards.

Collaborative R&D programmes between industry and academia should be established to solve packaging challenges and advance heterogeneous integration technologies specific to quantum. The programmes should focus on the development of new heterogeneous integration solutions that are scalable and adaptable to different quantum technologies and use cases. The involvement of industry partners can ensure that quantum technologies are developed with a clear pathway to commercialisation, focusing on scalability, manufacturability, and market needs from the beginning. A challenge funding approach should be considered. By integrating packaging considerations early on, researchers and developers can anticipate and address potential challenges and limitations, leading to more robust and scalable solutions. This approach also fosters closer collaboration between academia and industry, enhancing the relevance and impact of research initiatives.

The collaborative R&D programmes should be long-term and include mechanisms to support companies' capital investment in specialised equipment. UK companies are currently at a competitive disadvantage to obtain the automated equipment required for submicron heterogeneous integration compared to companies outside of the UK, as demonstrated by recent government investments in PHIX in the Netherlands and Silicon Box from the Italian government to create a €3.5 billion centre for heterogeneous integration, although not focused on quantum applications. (See also Recommendation 4 'Incentivise industry to invest in advanced manufacturing capabilities needed for quantum and other technologies'.)

In addition, relevant equipment in existing facilities located in universities should be upgraded on condition of improving industry access and standards.

Scenario B: UK adopts a proactive stance by investing in critical capabilities to position itself at the forefront of particular domains.

This scenario represents a leap forward that the UK would need to take for the effective scale-up of quantum technologies, leveraging current UK strengths, increasing capability and signalling the UK's intention to lead in the development, and scaling-up of heterogeneous integration technologies for quantum.

Establish an open-access centre for advanced packaging for quantum technologies with a dedicated pilot line for heterogeneous integration technologies for quantum applications.

A new industry-facing centre for advanced packaging for quantum technologies should seek to be a centre of excellence, bringing together UK academic and industry expertise, not only in current heterogeneous integration technologies for quantum, but also bringing together multidisciplinary subject matter experts, especially in photonics and telecoms to address the specific requirements of quantum technologies.

An open-access facility providing a pilot line for heterogeneous integration capability for quantum applications would facilitate chip-level integration and testing for low-volume prototyping. This capability would foster collaboration with industry partners, bridging the gap between research and commercialisation. While there is UK capability to produce single material wafers at a pilot level, a pilot line with multi-material functionality could also address the current global gap in manufacturing devices requiring such features.

A pilot line for heterogeneous integration should be tailored to meet the needs of end users and prioritise industry accessibility. While benefiting from close alignment with academic research to ensure a pipeline for future development, delivery of the pilot line's offering should not be reliant on academic facilities. Importantly, to enable the pilot line to operate seamlessly within the semiconductor supply chain, standardisation of the processes and devices will be crucial. As outlined in the Design section of this report, this would need standard PDKs to be established to enable designers to embed integration technology into the international foundries PDK model and ensure compatibility with advanced packaging solutions. In this way, it would enable building on existing UK capability and relationships with international foundries to ensure a supply of integration-compatible materials and devices.

To align with industry requirements, the pilot line would require optimisation of tools for fast-turnaround, accurate and precise printing of micro-scale devices onto foundry chips and process standardisation and quality assurance monitoring, alongside high throughput. To operate successfully and produce commercially viable applications, the pilot line would also require alignment and coordination with efforts in testing, equipment manufacturing, and advanced packaging. Integration of automation and computer-aided processes, along with the appropriate standards for interoperability would also be crucial requirements. Close collaboration should also be sought early on with companies such as Alter and Bay Photonics given their success in this sector. These efforts would ensure synergy rather than competition with ongoing advanced packaging work in the UK.

Such a pilot line could enable not only quantum technologies but also multiple other high value applications including neuromorphic computing, ultra-high bandwidth communications, and the use of integrated photonics in medical technologies. This facility could adopt a model similar to that of the Fraunhofer or Warwick Manufacturing Group (WMG) at the University of Warwick (see Box 4) with the initial infrastructure investment provided by government and a public-private funding model for the longer term. Co-location with an academic facility would ensure access to cutting-edge developments and specialised knowledge, however maintaining operational autonomy would enable meeting industry demands. There would also be key benefits in exploring collaboration with international partners, such as those in Europe, to ensure that the capability within the UK can align with global supply chains.

The successful implementation of shared facilities hinges on creating a framework that governs access, scheduling, cost sharing, and intellectual property rights (IPR). This framework must be equitable, transparent, and designed to maximise the equipment's utilisation while ensuring its maintenance and operational integrity. Potential logistical challenges in managing access to shared facilities would relate to balancing the needs of diverse users.

To set up this capability, an initial investment from government would be required. Government and industry could also collaborate through matched funding models, where both parties share the cost of new equipment and infrastructure investments. Once the facility is operational, the maintenance costs should be covered by government, whereas running costs would be covered by users. This approach spreads the risk and underscores the shared commitment to advancing the quantum technology sector within the UK. However, it is important to note that the upfront cost for acquiring and setting up a facility with the required advanced packaging equipment is substantial.

The successful implementation of shared facilities hinges on creating a framework that governs access, scheduling, cost sharing, and intellectual property rights (IPR). This framework must be equitable, transparent, and designed to maximise the equipment's utilisation while ensuring its maintenance and operational integrity.

Packaging, advanced packaging, and heterogeneous integration

Scenario A Develop collaborative R&D programmes to solve packaging challenges and advance heterogeneous integration technologies specific to quantum. Upgrade industry relevant equipment in existing open-access facilities on condition of improving industry access and standards.

Scenario B Establish an open-access centre for advanced packaging for quantum technologies with a dedicated pilot line for heterogeneous integration technologies for quantum applications. To support decision-makers in assessing the options in Scenario B, the different decision factors outlined in the table below should be considered.

Quantum technologies impact	Heterogeneous integration enables the scaling of a wide range of quantum technologies using different materials such as silicon photonics, compound semiconductor, superconductors, and diamond. Most notably, it will be critical for quantum computing, sensing, and quantum communications.
UK's current position	The UK has key expertise in some heterogeneous integration technologies with relevance to quantum within several of its research institutions, most notably with recent investments in the National Epitaxy Facility and Cornerstone, and expertise in transfer printing. While significant investments are being made by major industry players outside the UK these are focused on electronic chip integration. While the UK lacks commercial capability for the most current advanced packaging techniques and broader packaging needs, Alter Technology, Bay Photonics, Fraunhofer CAP, and the Compound Semiconductor Applications Catapult are high-quality players. For broader packaging needs international providers provide excellent capabilities and quality of service.
Opportunity for UK	Developing heterogeneous integration technologies for quantum stands as at a critical stage for the scalability of quantum technologies. While large investments are being made internationally into heterogeneous integration technologies, these are focused on developing electronic chip integration. There remains a relatively unexplored market for quantum-specific applications and photonics applications beyond quantum which could be leveraged by the UK.
Cross-sectoral relevance	Heterogeneous integration will be a critical technology for next generation semiconductor systems. By working within the global foundry paradigm there is a key opportunity to define the standards and manufacturing routes with tractable levels of UK investment. This capability will be crucial for several technologies beyond quantum, including telecoms, AI, autonomous vehicles, semiconductor technologies.
Risk of inaction	If the current heterogeneous integration technologies capabilities are not expanded, there is a significant risk of the UK not being able to develop several types of quantum technologies such as quantum computing and quantum communications. Furthermore, the UK would lessen the likelihood that it can leverage its existing strengths to be well positioned in an early emerging market for heterogeneous integration technologies for quantum and exacerbate the risk that existing capability will relocate abroad to countries that provide a clearer path to commercialisation.

Section 2: Meeting industry requirements

Recommendation 2: Infrastructure where quantum industry is a user must meet industry requirements; for existing infrastructure, upgrade programmes should be focused on meeting industry needs.

Much of the open-access quantum infrastructure capabilities across the UK are provided by universities or consortiums of universities reflecting the focus of the past decade on early-stage technology development. However, as the quantum sector scales up towards commercialisation, relying on infrastructure in universities becomes a bottleneck for companies. Issues include high access costs, challenging terms of contracts (including licensing arrangements), lack of industry grade processes to ensure reliability, outdated equipment, concerns around confidentiality, inadequate staffing, timelines that don't keep pace with industry, and limited production volumes.

This leaves UK companies either having to use facilities that are not as good as those in comparator countries thus risking the UK not progressing as fast as other nations, or using infrastructure located in other countries, which comes with its own challenges, including cost and confidentiality concerns. There is also a risk of UK companies relocating their business outside the UK to take advantage of internationally subsidised programmes. The impact is most acutely felt by UK quantum startups and SMEs, as smaller companies often do not have the financial means to build or access infrastructure to meet their needs and are less able to take risks on this front.

There is a consensus across industry, and to an extent across academia, about what best practice looks like for an open-access facility which has industry as a user. The standout UK examples used by the quantum industry are the Fraunhofer CAP and NPL, while Tyndall in the Republic of Ireland, PHIX in the Netherlands, VTT in Finland, and Fraunhofer IZM are all standout examples outside the UK. Notably the 'problem-solving' approach, which facilitates the transition from R&D into practical applications, of all these organisations was highlighted as a key advantage. This is often missing from the UK's approach. Also crucial is a long-term plan for the facility that 'includes batteries' to fund maintenance, upgrades, and appropriate staffing.

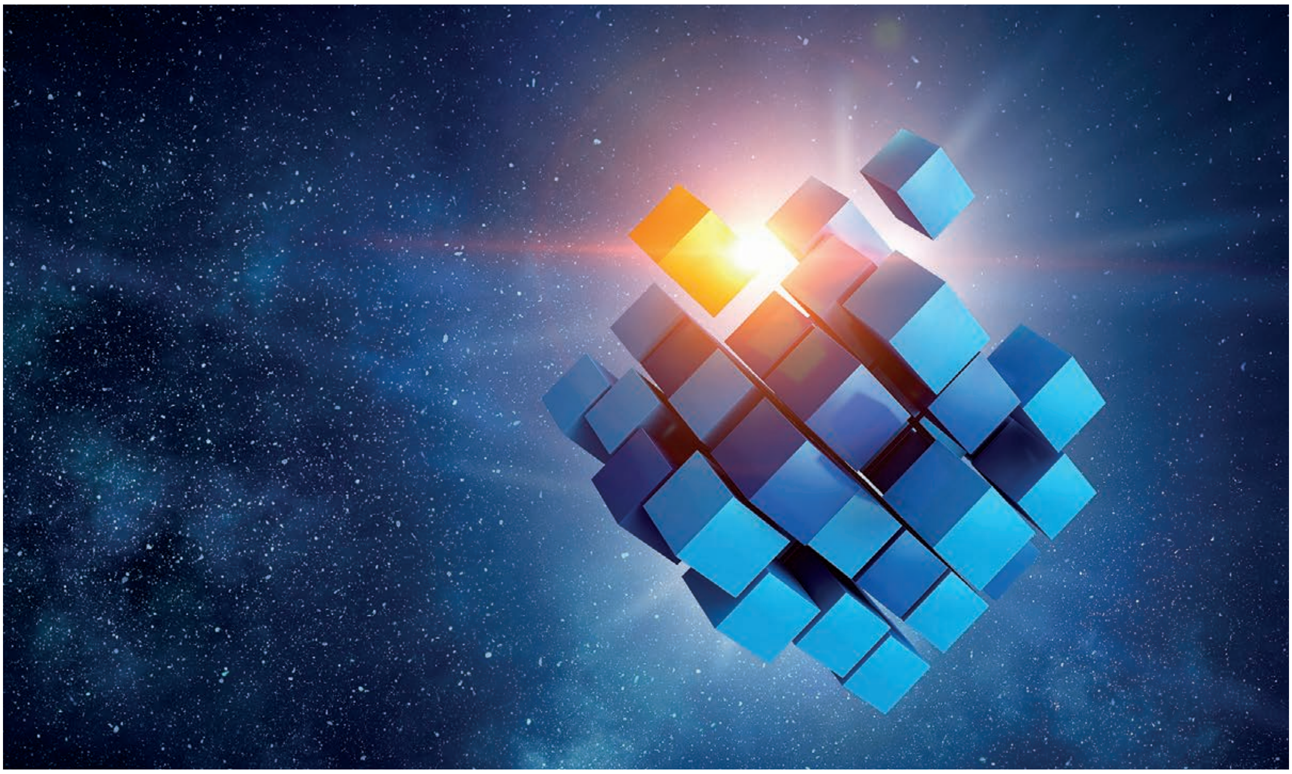
For the UK to scale-up its quantum technology industry and to leverage maximum impact from its infrastructure investments it is essential that all current and prospective infrastructure, where the quantum industry acts as a user or customer, adopts best practice to meet industry needs effectively. The criteria that need to be met for industry use are set out in Table 3, while Box 4 sets out requirements for operation of open-access infrastructure.

As part of Recommendation 1, Scenario A, the Review recommends that the UK upgrades and improves access for industry to existing infrastructure. For university facilities where industry is confirmed to be a main user (or desired user), an infrastructure upgrade programme should only be considered on condition of improving access to industry. This might not be desired for all university facilities, particularly where there is a clear remit for academic research use of the facility, which is a valuable part of the quantum landscape. University infrastructure for academic/research purposes might also warrant upgrading, however this is outside the scope of this Review.

For all new infrastructure investments proposed in Recommendation 1, Scenario B, they should be designed to meet industry criteria outlined in Table 3, as well as the requirements for operation of open-access infrastructure outlined in Box 4.

Affordable access rates	Competitive pricing structures tailored to specific needs and production volume. Transparent pricing models, with clear breakdowns of fees and optional services. Flexibility in pricing arrangements with a multi-tier option of access rates for different types of companies. Access support for smaller companies, such as quantum-specific programmes for startups bringing new products to market and government subsidies.
Favourable terms of access for industry to facilities and equipment	Licensing agreements with clear terms and conditions. Streamlined administrative processes with clear requirements and timelines. Frameworks for managing facilities with multiple users, including scheduling, access priorities, and maintenance responsibilities, as well as having areas with dedicated tools/processes for industrial access only.
Infrastructure that follows industry grade processes and that provides ways to test in outside lab environments	Compatibility with commercial standards and regulatory compliance, with the right certifications and auditing where applicable. Secure/confidential services to protect IP and confidential data. Minimum standards of service and standard operating procedures ensuring quality, reliability, and safety that meet industry standards and specifications.
Infrastructure that is staffed by skilled personnel	Support to customers using the infrastructure. Training sessions for utilising infrastructure.
Strategic distribution of infrastructure across the UK	Strategic distribution across different regions in the UK. Co-location with relevant facilities, including universities, for knowledge exchange.

Table 3 | **Criteria for industry access to infrastructure.**



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Box 4 | Requirements for operation of open-access infrastructure

There are good examples of organisations, both in the UK and abroad, that have been successful in delivering problem-solving capability for moving technologies across the TRL spectrum. The requirements below have been informed by interviews with Fraunhofer CAP, STFC National Satellite Facility, WMG at the University of Warwick, KNT, and Tyndall.

Mission

- Clear mission based on existing and future end user needs underpinned by roadmapping identifying key technology focus areas and anticipated scaling paths, bridging early-stage technology, and commercialisation through a problem-solving approach, acting as a connector between different ends of the supply chain to foster collaborations.
- Flexibility and agility to change over time to ensure the facilities are still relevant in 10 to 15 years to justify large investments.
- Separate and neutral entity, which benefits from not having the pressure that universities face for academic success, while being able to take more risks than industry.

Funding

- Take the approach of organisations such as Fraunhofer with income deriving from industry contracts supported by core government funding.
- Requirement of long-term core funding from government to provide stability and support to these types of facilities which usually are not very commercially viable. This funding needs to ensure that there are pathways for capital refurbishment, which are not typically included in grants but are vital for functioning facilities given the focus on repair, refurbish, and refresh. It also needs to account for hidden costs and funding required for reducing carbon footprint.
- Investments need to be made in a way that can expand facilities in complementary ways, without displacing existing economic activities.
- Not royalty-driven, with access being provided as and when is needed.

People

- Highly qualified scientists, engineers, and technicians in sufficient numbers and availability to ensure resilience.
- Leadership needs to have experience in operating in the field for the facility to be successful.
- Permanent staff that can manage and operate the infrastructure not only at the technical level, but also for business development and commercial activities.
- Establishing a governance board is required to guide strategic decisions on the facility's use as a national asset and to determine future investment and long-term needs.
- Addressing recruitment issues may require a proactive approach such as establishing a headhunting team.

Processes

- Have in place adequate business and quality processes, as well as an efficient operational model defined with the appropriate quality assurance and certification.
- IP used in a way that promotes collaboration and research rather than acting as a bottleneck. Keeping ownership of know-how to licence it to others to have the freedom to operate in the different sectors.
- Problem-solving approach to address challenges without pushing a specific agenda, mapping existing capability and roadmapping, leveraging strengths and identifying opportunities for collaboration.

Equipment

- Both a good quality resource, as well as the necessary add-ons and enablers required to make it operate successfully. If it is a long-term facility, it needs to have space to expand in terms of geography and layout.
- Funded roadmap of equipment upgrades.

Collaborative
- Partnerships between different stakeholders are also helpful for developing the skills base as tech transfer provides awareness of upstream and downstream activities.
- Collaboration with small companies looking to benefit from expertise, connections, and facilities, as well as large companies and multinationals that wish to experiment with new developments.
- Co-location with universities allows benefiting from having sight of the latest developments in cutting edge technology, as well as access to top academic experts and can provide an academic pathway which can help attract researchers.

Section 3: Coordination

Recommendation 3: Establish a quantum technology coordination function that provides guidance to industry on navigating the UK's quantum technology landscape, and coordinates and facilitates access for industry to infrastructure.

Quantum companies often find themselves navigating a maze of changing resources, piecemeal support mechanisms, and potential collaborations without clear guidance. There is a lack of awareness of existing infrastructure, misunderstanding of how initiatives relate to each other, difficulties in identifying resources available, as well as unclear and often conditions of access that are not industry-friendly. This fragmentation can result in duplicated efforts, inefficient use of resources, and missed opportunities.

A quantum technologies coordination function would streamline access to physical infrastructure, enable collaborations, and offer a consolidated view of funding and growth opportunities including through funding and infrastructure roadmaps. This would be a one-stop shop for navigating support. It would provide an easier interface, particularly for startups and SMEs, to interact and negotiate with infrastructure providers nationally and internationally. It would optimise resource awareness, foster effective collaboration, potentially aligning different supply chain stages, and reduce costs and time-to-market in a competitive and fast-paced environment. Moreover, coordination enables the UK's various quantum initiatives to act as a united front when engaging with international stakeholders, enhancing the visibility and reputation of the UK which is important for attracting external investment. Overall, these factors are crucial for advancing the UK's quantum industry.

A quantum technologies coordination function should:

- Provide support and advisory services to help companies navigate the various quantum funding opportunities, infrastructure, and facilities, including sharing funding and infrastructure roadmaps.
- Provide support and advisory services to companies on regulatory compliance, IP, market entry strategies, and other critical business considerations.
- Drive coordination, including of infrastructure and industry engagement, across the Quantum Missions and NQTP Hubs.
- Act as a conduit for access to infrastructure in the UK and internationally. Advise on the design and mode of operation of UK infrastructure. To support Recommendation 1 it should:
  - Design: handle negotiations on rates for EDA tools and PDKs and coordinate access to tools, manage licences, ensure compliance with export controls. It would also provide access to experts with quantum-specific design expertise to help utilising these complex tools.
  - Nanofabrication prototyping: facilitate easier and more cost-effective access to UK and international prototyping services, establishing formal partnerships and agreements to ensure preferred access, pricing, and protection of IP and data. Implementing frameworks to monitor the usage and outcomes of subsidised prototyping access, ensuring that the initiative delivers value for the UK's quantum technology sector.
  - Packaging, advanced packaging, and heterogeneous integration: provide access to training programmes and educational resources to help cultivate a skilled workforce adept in the latest packaging technologies and techniques.

- Be a united front for establishing international collaboration: working with international partners on sensitive quantum technologies can raise IP and data security concerns. The coordination function would develop robust agreements and safeguards particularly with regards to national security considerations.
- Build community and networking to enable knowledge exchange and collaborative innovation across the quantum ecosystem, linking academia, industry including end users, and government.
- Drive coordination and engagement with equivalent coordination functions for other key strategic technologies and sectors such as semiconductors and photonics.

To do this effectively, the coordination function would need to be staffed with experts that have the necessary quantum technical knowledge and understand industry requirements to support stakeholders in navigating the quantum ecosystem.

The coordination function would be well placed to oversee the management of the online directory of infrastructure and initiatives, as outlined in the National Quantum Strategy. Box 5 outlines how the directory should be designed to be most effective.

This coordination function should complement and augment existing coordination efforts in the UK's quantum landscape including Innovate UK's KTN Quantum Technology Innovation Network, NQTP, UKQuantum, and the Office for Quantum.

Box 5 | Features that should be incorporated into a directory

This Review advocates for a single central directory that merges the functions of the directories proposed in the UK's National Quantum Strategy (directory of existing infrastructure and business growth directory). Its features should include:

- Centralised and comprehensive directory of infrastructure (including infrastructure that is not quantum specific but may be required by quantum companies), resources, businesses, organisations, expertise, and initiatives relevant for the quantum sector. Such a directory would need to:
  - Build on a comprehensive and regularly updated database.
  - Have user-friendly interface and accessible to non-specialist audiences.
  - Offer easy access to detailed information (including terms of access to infrastructure).
  - Provide appropriate categorisation, and tools facilitating navigation and filtering for specific information.
  - Allow for users to contribute content and provide feedback.
  - Provide users with access to a dedicated team of well-informed personnel that can support, review, and moderate content.
  - Be regularly updated in close collaboration with industry to be reflective of the evolving landscape of the quantum industry.
  - Integrate with existing platforms such as the Quantum Landscape Map[22] provided by Innovate UK KTN and Quantum Insider[23] to leverage existing resources. In designing the directories, the UK could also draw inspiration from the Henry Royce Institute's catalogue of equipment and facilities[24] and the National Nanotechnology Coordinated Infrastructure (NNCI)[25] in the USA.
  - Be advertised pro-actively and ensuring industry buy-in.

Section 4: Integration with wider manufacturing capabilities

Recommendation 4: Incentivise industry to invest in advanced manufacturing capabilities needed for quantum and other technologies.

The UK is one of the largest global manufacturing nations, with a vibrant and diverse manufacturing capability relevant to quantum across materials (including composites, optics, metamaterials, chemicals), integrated photonics and optics (including 1,500 photonics companies making up about 20% of Europe's total), cryogenics systems (e.g. Oxford Instruments), characterisation and metrology (e.g. NPL) and nanofabrication facilities (e.g. KNT and JWNC, IQE, Cornerstone). This manufacturing capability can be supported by advanced technologies such as automation, robotics, and digital manufacturing; and is of relevance to numerous other sectors including semiconductors, AI and telecommunications.

For the UK to grow its quantum industry, it requires more advanced manufacturing capability in the industrial base and for the existing capability to remain cutting edge with up-to-date equipment. Advanced manufacturing capability is crucial to building supply chains, capturing value, and securing resilience. Much of the advanced manufacturing equipment relevant to quantum will also benefit numerous other sectors and technologies, thus improving the advanced manufacturing capabilities in the UK has benefits beyond the quantum sector.

While there is a reasonable argument to be made that industry should be willing to invest in equipment themselves and the market should drive demand, this argument negates the disadvantage companies in the UK find themselves with, compared to countries where there are government initiatives in place to enable increasing the capability of its advanced manufacturing firms.

Industry feedback revealed that while relevant efforts by UKRI, and specifically Innovate UK, are welcome and important, the level of capital expenditure enabled is relatively low. Also, existing schemes can also be focused on novel innovation in such a way that improvements and upgrades to equipment aren't always eligible. The SBRI also has an important role, however, current terms for liability and IP can make it difficult for quantum and advanced manufacturing companies to engage with it in a meaningful way.

The UK's ambitions in advanced manufacturing are to be welcomed, however the Advanced manufacturing plan does not currently address the needs of the quantum sector. Therefore, the Review recommends that some of the £4.5 billion of funding to support strategic manufacturing sectors over five years from 2025 addresses the needs of quantum and related sectors.

Grants for industry, inspired by the Life Sciences Investment Manufacturing Fund, but geared towards the common advanced manufacturing needs of quantum, semiconductors, and photonics should be established. Business models that allow access for academic researchers to industry facilities should also be considered. Close coordination with other strategies and sector leadership groups is recommended to maximise impact of incentives and investments.

In addition, innovation challenges that encourage companies from different sectors to collaborate on projects requiring advanced manufacturing capabilities should be launched, with the aim of developing new manufacturing technologies and solutions with applications across industries.

A set of advanced manufacturing capabilities were flagged during the Review as requiring investment in the UK. These included advanced FC (not in UK currently), advanced bump (not in UK currently), laser dicing (not in UK currently), through silicon via (TSV), interposers, 3D printing technology in precision optics (not in UK currently), and additive manufacturing, for example, vacuum components.

Section 5: Strategic direction

Recommendation 5: Government to provide clear strategic direction for quantum technologies including through roadmaps developed in partnership between academia and industry.

Establishing a resilient quantum ecosystem requires clear strategic direction, cohesive long-term vision, and overall synchronicity. The UK has already taken key steps in establishing strategic direction through initiatives such as the NQTP and its Hubs, and more recently through the National Quantum Strategy and its associated Missions. On a broader level, strategic direction has also been established for adjacent and underpinning sectors such as semiconductors, PNT, telecommunications, and space. Overall, these frameworks create an important foundational basis for the UK to thrive strategically. However, as outlined below, a series of steps are required to materialise strategy objectives into concrete actions.

The quantum sector is a 'broad church' encompassing a diverse array of different types of technologies with distinct use cases. To provide the resourcing required for scaling-up quantum technologies, effective prioritisation needs to take place. This needs to be underpinned by a detailed vision which aligns with areas of interest for government and is endorsed by industry and academia to ensure buy-in and increase confidence for investment. While the UK's National Quantum Strategy, and more recently, the Quantum Missions provide an important degree of focus, considering the various ways in which these ambitions can be achieved and the current unknowns, there needs to be further detail to map out routes (sometimes multiple) to implementation.

Addressing prioritisation through the lens of strategic advantage, while adopting a systems approach that considers industrial capability, national security, and sovereignty issues can provide the required blend of long-term strategic foresight and short-term priorities. A position paper published by the Royal Academy of Engineering (in 2023)[26] outlines six principles for achieving strategic advantage through science and technology, which are summarised in Box 6. Adopting a scenarios approach such as the one implemented in this report can also support decision-making by articulating the UK's ambition in terms of its future positioning in the quantum landscape.

Roadmapping

As more granular priorities are established, roadmapping emerges as the guiding methodology for navigating towards strategic objectives and for defining short-term priorities to execute long-term missions. This is a common approach taken by companies in devising their internal strategy and it can also be an important tool to support government with decision-making, particularly regarding infrastructure investments.

Roadmaps are also useful to investors and end users, signalling the direction of the market and of technology development, which in turn allows for forward planning and engagement with early adopters. Done well, roadmaps can set out plans for industrial demonstration and testing of use cases in the real world, with users and integrators being involved in the roadmap development.

Government has a powerful role as the first customer of quantum solutions, to aid UK companies to demonstrate quantum solutions and secure first-mover advantage, as well as improving the delivery of public services. SBRI Quantum Catalyst Fund is a welcomed initiative. Effective roadmapping would also support government to more clearly identify procurement priorities and accelerate the potential of quantum technologies to improve the delivery of public services.

Roadmaps can also help map supply and demand within supply chains and identify potential issues such as the sourcing of critical materials for quantum technologies, helping unlock opportunities for increasing the resilience in supply chains.

Roadmapping activities should help government to signal its strategy in terms of funding plans, and the timing and mechanisms underpinning their delivery. This is crucial for industry and academia to align their efforts with the government's vision for quantum in the UK.

Box 6 | Strategic advantage through science and technology

In April 2023, the Royal Academy of Engineering published a position paper on Strategic advantage through science and technology: an engineering view. The paper outlined six principles for policymakers to enable science and technology to deliver positive outcomes for the UK's security, prosperity, resilience, international influence, and people and environment. If applied within a clear understanding of current state of play of the R&I landscape, these principles can support the design of strategic decision-making, informed by choices about the outcome and advantages the UK wishes to achieve by harnessing science and technology (Figure 4).

- **Long-term** – long-term strategic direction, longer-term budgets, durable institutions, and stability to enable the R&I system to deliver and provide confidence for businesses to thrive.
- **Agility and pace** – act at pace and modify priorities when needed to make the most of newly emerging opportunities, address new threats, deploy resources well, operate at timescales that work for business, fail fast, and compete globally.
- **Leadership and capability** – trusted and capable leadership, empowered to make decisions at pace, deploy resources and accept and learn from failure to deliver the broad and complex strategic advantage through the Science and Technology (S&T) agenda.
- **Connections and networks** – a 'connect and convene approach' that engenders a sense of ownership and commitment, with improved interfaces between government and business and optimised role for the networks and organisations that aid permeability such as public sector research establishments and catapult centres.
- **Coherence** – coherent and sustained strategies and policies that align actions across regulation, funding, infrastructure, and skills.
- **Action** – interventions that accelerate progress towards outcomes and deliver results from strategies.

These principles provide the blueprint for a systems approach where innovation policy is considered as a whole. This can be integral to all government departments and enables a public sector that is confident and proactive in managing the risk associated with late-stage R&D and market creation when in pursuit of strategic advantage

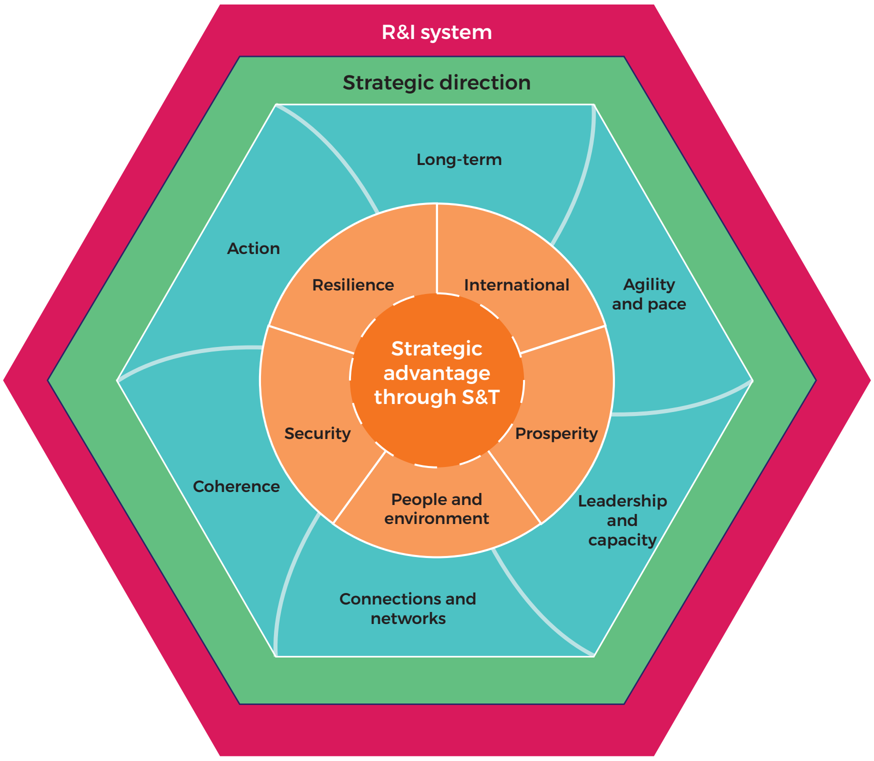

Figure 4 | Strategic advantage through science and technology – types of strategic advantage and principles and pre-requisites underpinning it.

Companies and industry stakeholders operating in the field of quantum and its adjacent sectors (e.g. semiconductors, photonics or PNT) already devise their own roadmaps. There is a great opportunity for government to leverage these efforts by engaging further with industry and ensuring a joined-up approach with academia and the NQTP Hubs to align priorities across government, research, and industry. Such engagement would provide the important technological and business context needed to understand and potentially frame a roadmap according to the quantum-specific missions, while also highlighting areas for strategic intervention and fostering greater coordination and coherence of action. It is important to acknowledge, however, that roadmaps should be tailored to specific areas of quantum as 'one-size-fits-all' will not be appropriate for all use cases. There is also great value in learning from roadmapping activities conducted for other sectors such as semiconductors to embed lessons learnt into current efforts.

Delivery

The roadmapping activities outlined above should be overseen by a coordinating entity such as the Office for Quantum to ensure a joined-up approach with other sectors and strategies. The coordination function outlined in Recommendation 3 could also be a candidate. This integration extends beyond quantum, necessitating a cross-sectoral approach with other relevant sectors such as semiconductors, telecommunications, PNT and space to prevent fragmentation with ongoing strategies. Aligning these workstreams and fostering collaboration across sectors will harness synergies and avoid duplication of effort. While the Office for Quantum serves as a cornerstone for coordination within the quantum field, its success hinges on its ability to bridge the gap between diverse workstreams, promote integration across sectors and provide strategic direction to the field. Our experience conducting this Review suggests that there is significantly more opportunity for join-up between strategies and workstreams, especially quantum, telecommunications, and semiconductors.

Section 6: Infrastructure enablers

Recommendation 6: For successful operation of infrastructure, government needs to consider key enablers such as sufficient provision of skills, appropriate development of standards and adequate regulation to ensure responsible and ethical innovation, including environmental impacts.

Skills

One of the strongest and most often repeated concerns raised by UK quantum companies in this Review was the shortage of skilled staff. There is currently a shortage of the necessary skills needed for developing and commercialising quantum technologies in the UK. Skills are needed to develop and maintain physical infrastructure, for example: skills to operate and maintain fabrication facilities and clean rooms; skills to integrate quantum technologies into existing systems, and skills relating to both hardware and software.

Ensuring a strong skills pipeline should be a UK wide requirement and cross-government initiative. The existing initiatives to improve the skills gap, for example the NQTP, have funded fellowships, PhD projects, and students through quantum centres for doctoral training. Additionally, the priority actions outlined in the National Quantum Strategy such as the Quantum Skills Taskforce, are all important. However, these are unlikely to be sufficient for the scale of need. Fierce international competition means the UK must create the right environment to attract talent. UK universities are struggling to compete with the private sector in attracting teaching and research staff due to salary competition.

There is a wider concern around the need for multidisciplinary skills that will support the scaling-up of the UK quantum sector, however the agenda around skills is extensive and largely out of scope for this Review. Nonetheless, it is imperative to state that for infrastructure to be successfully and sustainably utilised it will need to be fully staffed with a wide range of qualified scientists, engineers, technicians, and professionals, comprising both home-grown and international talent.

Standards

Standards play an important role in the development and overall governance of all quantum technologies and across supply chain stages, being crucial for market uptake and adoption. Any investment in quantum infrastructure needs to be compliant with industry grade processes. This will require the development of specific standards as well as the adaptation of existing standards through a collaborative effort between the relevant stakeholders both in the UK and internationally.

Standards are needed for the benchmarking, verification, validation of quantum technologies, for the evaluation of quantum technologies, and can be used to minimise risk and demonstrate responsible innovation. They will also be required for end users for the application of the technology and are also required to ensure interoperability and integration with classical infrastructure. Standards are needed for both hardware and software. For example, they are required to be aligned and integrated with current data centre infrastructure, and also with algorithm performance. There are standards needed for design tools, and the lack of these slows down production. Furthermore, they are also needed for reliability and frequency which are crucial for quantum technologies. It will also be useful to develop sector- and domain-specific standards, and alignment practices along the supply chain, all of which should be developed at a suitable pace and used appropriately. International standards are needed to enable international collaboration and the UK will need to be involved in the development of this to be globally recognised.[27]

There is a trade-off between setting standards and national security, and the UK may have to work through proprietary standards before it is feasible to adopt international standards. There are challenges faced by SMEs, with limited engagement due to the time and resource demands of developing and adopting standards.[28] At this stage, it is difficult to know where the responsibility lies for both developing and adopting standards. Although the Regulatory Horizons Council recognises the emergent phase of quantum technology development and so state that a voluntary, consensus-based approach to standards is appropriate at this stage.[29]

Despite the various challenges, the UK has an opportunity to become a global leader in this space for quantum as outlined in the National Quantum Strategy, with the potential for enormous economic advantage. It is particularly important that the UK implements the following approaches:

- When developing standards to ensure that investment in quantum infrastructure is compliant with industry grade processes, there should be a joined-up approach between all stakeholders including manufacturers and operators, who should involve end users at an early stage. The Quantum Standards Network Pilot is a good example of encouraging direct involvement from UK stakeholders to enable coordination of strategic priorities.
- Greater international collaboration is needed, and the UK must adopt a proactive approach at shaping standards with international partners, e.g. with the National Institute of Standards and Technology (NIST) and the International Telecommunication Union Standardisation Sector (IUT-T). Collaboration is also needed to ensure access to global markets.
- Establish an independent body to scrutinise products and/or a trusted organisation to offer certification for the technology could boost confidence and encourage adoption. The government needs to establish a detailed strategy to support this.
- Focus and develop technology within sectors where the UK has the most strength and potential for strong impact on the economy and society, fostering 'champions' in this way can encourage standard development to follow.
- Greater encouragement of industry involvement is needed to develop standards.[30]
- Governance of quantum technologies also needs to consider IPR. An innovation-friendly framework should be developed by both government and the Intellectual Property Office (IPO). It needs to support IP protection for developers while also encouraging innovation and allowing for collaborative development, particularly international collaboration.[31]

Responsible and ethical innovation

The UK could be seen as a leader in responsible innovation by strategically developing a robust regulatory environment to ensure that both legal and ethical frameworks support and allow for responsible innovation of quantum technologies in terms of their development, commercialisation, and adoption. There are ethical issues surrounding the potential misuse of technology, including for malicious purposes. This could impact various services that reply on encryption or worsen existing risks, for example around data collection and privacy. There is also a risk of unequal access to the technology in the future and the UK needs to ensure that all parts of society can benefit from it. Furthermore, it should be ensured that individuals are moved along the technology adoption curve in an equitable way.[32] Sustainability needs to be designed throughout the supply chain to help minimise environmental impacts such as those associated with whole lifecycle management; circularity; sourcing of materials; and energy, water, and resource consumption through the development, production, and use of the technology.

The key enablers discussed here are not a comprehensive list of all the enablers that emerged from the Review's evidence gathering. However, they were those mentioned most frequently and supported by substantive discussion. IPR, Venture Capital, and private investment, export control, and international collaboration are examples of other enablers mentioned, but were out of scope of the Review.

Conclusion

The Royal Academy of Engineering was tasked with identifying the UK's quantum infrastructure requirements for the next decade, to accelerate progress towards quantum technology exploitation and commercialisation, and the growth of the quantum sector in the UK. In conducting the Review, it has become apparent that while the UK has been extremely successful to date in developing a quantum research base and burgeoning startup ecosystem, continued success and growth is not guaranteed. Other countries are deploying ambitious strategies matched with investment, including in infrastructure. There is currently a window of opportunity for the UK to take advantage of, but only if it acts soon.

Infrastructure can accelerate companies' abilities to progress commercial R&D by creating fully engineered prototypes, enabling testing, piloting, and demonstration; accessing low-volume manufacturing for serving small or niche markets; and speeding-up development towards volume production. Infrastructure can also act as an anchor around which capabilities, companies, skills, and investment cluster and grow, tying commercial opportunities and growth to the UK. This catalytic potential of infrastructure is only fully realised when it is aligned with the needs of industry, and set up and operated in ways which facilitate the transition from R&D into practical applications, something that the UK is not considered to do as well as comparator countries.

The Review identifies several options for new infrastructure investment in support of the quantum sector. While the current relative lack of maturity of many quantum technologies makes prioritisation of the infrastructure options challenging, it does also mean that there is still ample opportunity for the UK to strengthen its advantage in numerous areas. To prioritise these options effectively, further strategic decisions will be needed. To aid this process, the Review considers the relevance of the infrastructure options to the breadth of quantum technologies and other sectors, the UK's current strengths and international activity, and the opportunities the infrastructure could unlock for the UK, as well as the impact of inaction.

Finally, in taking the findings of this Review forward government should consider issues which lie outside of the Review's scope. These include national security objectives and the requirements for UK sovereign capabilities. In addition, further consideration should be given to the complementarity and strategic advantage that can be achieved from multiple infrastructure investments, both from those proposed here and with infrastructure investments beyond this Review, in related technologies and sectors such as photonics and semiconductors.

The UK was an early mover in quantum technologies, action is needed now to capitalise on that early advantage. The most significant risk would be the opportunity cost of inaction which may lead key players in the UK's quantum ecosystem to relocate outside the UK.

Annexes

Annex 1: Definitions

Cryogenics is branch of physics that deals with the production and effect of low temperatures. This field is a building block for technologies that need to operate in extremely cold environments, like some of the technology being used for quantum computing.

Enablers refers to conditions that facilitate the development and advancement of the quantum ecosystem. These can include access to research funding, skills, and regulatory frameworks. Enablers provide the necessary resources and support for the growth and progress of quantum technologies.

Manufacturing Readiness Levels (MRLs) is a framework for understanding the maturity of developing product for commercialisation, with the caveat of focusing on the manufacturing process. This is often used in tandem with Technology Readiness Levels and System Readiness Levels to describe the necessary steps and requirements to deploy a technology to markets.

Nanofabrication is the manufacture of materials with nanometre dimensions. The purpose of nanofabrication is to produce nanoscale structures that form part of a system, device, or component in large quantities and at a very low cost. The medium- and high-volume production of such nanostructures can represent major financial barriers to the advancement of quantum technologies.

Quantum 1.0 refers to the first wave of quantum technologies, which used effects such as quantised energy and tunnelling to develop applications which included lasers, atomic clocks, and superconductors that are now taken for granted.

Quantum 2.0 leverages superposition and entanglement for quantum computing, quantum networks, quantum sensing and imaging, and Position, Navigation, and Timing (PNT).

Quantum computing is a type of computation that leverages the principles of quantum mechanics to process information in fundamentally different ways from classical computing. It utilises quantum bits, or qubits, which can exist in multiple states simultaneously (superposition) and can be entangled with one another, enabling complex and parallel computations.

Quantum infrastructure refers to capabilities needed to move a broad range of quantum technologies across the full innovation pipeline and TRLs, MRLs, and SRLs. Quantum infrastructure capabilities primarily concern physical infrastructure and access to such infrastructure; however skills and other enabling factors are also be considered in relation to successful operation of physical infrastructure.

Quantum networks refers to quantum technologies focusing on connecting systems and transmitting data using quantum phenomena as opposed to classical networks technology based on photon or electron transmission. Once a quantum transmission link is established, the communication channel is intrinsically secure by allowing the detection of interference or eavesdropping. These secure communications are done via QKD, a set of keys shared only between the receiver and sender.

Quantum sensing and imaging refers to advanced sensor technology that collects data at the atomic level. This improves the accuracy of interactions with real world environments by sensing changes in motion, electric fields, and magnetic fields. Such quantum technology has a vast potential including improved GPS, radars, and LiDAR with applications in transport vehicles, defence, environmental management, healthcare, and space.

Photonics is a field focused on the science and technology of light, including its generation, guidance, manipulation, and detection. The applications of this technology are vast ranging from lasers, optical fibres, and cameras to numerous sectors including life science, health, and defence.

Positioning Navigation and Timing (PNT) services are a critical component of the UK's infrastructure and are essential to the good functioning of telecommunications, transport navigation, and provision of precise timing.

Semiconductors are a class of materials used across a wide range of technologies, most crucially computer chips. Semiconductor devices typically control and manage the flow of electronic current in an electronic equipment or devices. These devices are designed using an array of conducting materials depending on the usage purpose, and the environment in which it operates.

System Readiness Level (SRLs) is a metric defined for assessing progress in the development of systems. It refers to an assessment of the context and use in which a technology is being developed.

Technology Readiness Levels (TRLs) refers to a framework for understanding the technical maturity of a technology. TRLs allow for the understanding, tracking, and assessment of a technology evolution from conception through to research, development, and deployment.

Annex 2: Methodology

Figure 5 provides an overview of the Review's methodology. The Review implemented a systems approach throughout the evidence gathering activities by considering all parts of the quantum ecosystem, from physical infrastructure to the various infrastructure enablers, cross-sectoral dependencies, and the international context. This required a careful consideration of different evidence sources, engagement with a diverse range of stakeholders and triangulation of evidence throughout the different phases of the study, which are outlined below.

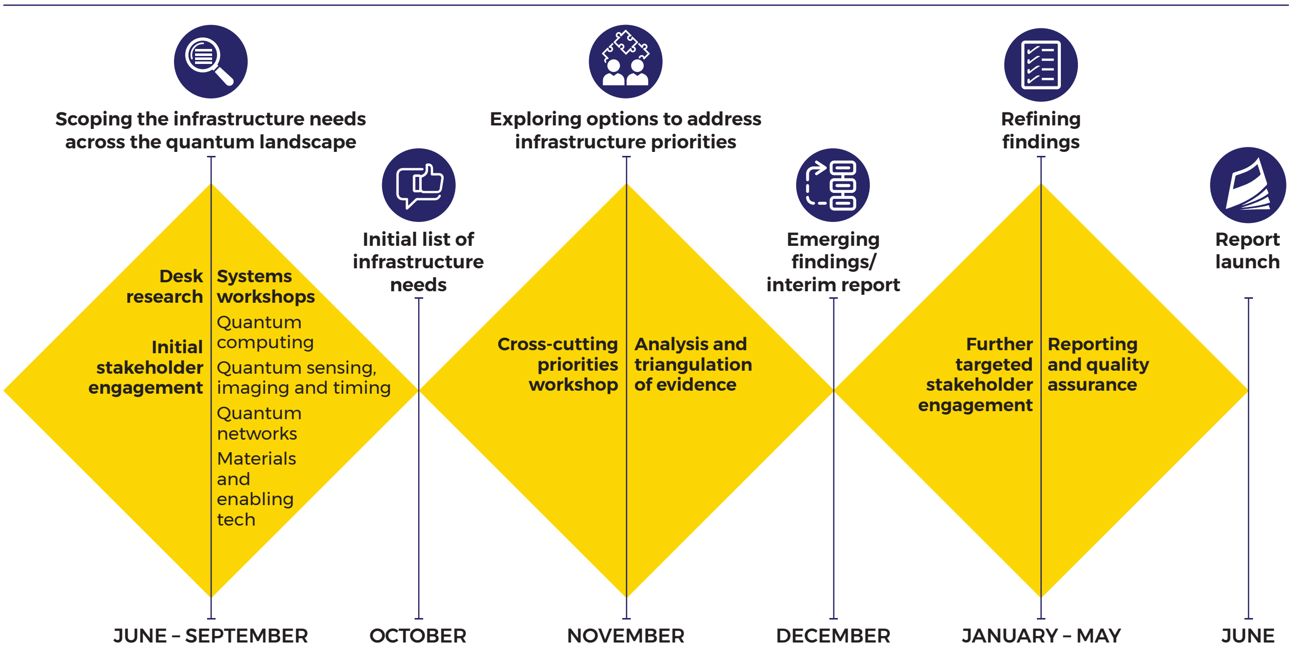

Figure 5 | Schematic of the methodology followed for this Review.

Desk research

A Rapid Evidence Assessment was conducted at the outset of this project to collect and review evidence in a systematic and structured way. A search strategy was devised with inclusion and exclusion criteria, as well as an extraction template to systematise the insights obtained from the evidence collected, with the appropriate quality assurance standards. Evidence was extracted from online sources (including reports, briefs, opinion pieces). Evidence provided by DSIT and other stakeholders (including survey findings, internal reports) was also reviewed. The aim of this phase was to: 1) assess the existing evidence base on quantum infrastructure to prevent duplicating work, 2) identify key gaps that may require more detailed investigation, and 3) tailor stakeholder engagement activities based on the gaps identified during desk research.

Stakeholder engagement

Building on the initial phase of desk research, the stakeholder engagement used a participatory systems approach to capture stakeholders' views across the quantum ecosystem on infrastructure needs. The aim of this approach was to: 1) validate the evidence collected through desk research, 2) fill in gaps in terms of the questions the study aims to answer, and 3) capture the most updated views from a diverse set of stakeholders. To fulfil these goals, the following stakeholder engagement activities were conducted:

Online workshops – Four online workshops were conducted in September, segmented by type of quantum technology to discuss sector-specific issues and their unique needs. The segmentation was: i) quantum computing (20 participants); ii) quantum sensing, imaging, timing (20 participants); iii) quantum networks (16 participants); and iv) materials and enabling technologies for quantum (20 participants). The workshops were attended by 68 participants in total (some attending more than one workshop) from different types of organisations:

- Industry-specific: consultancies, end users, Hubs/National Centres, large enterprises; and multinationals, SMEs, startups and spinouts, infrastructure providers, fabrication facilities, system enablers.
- Additional cross-cutting organisations: funding organisations, investors, IP organisations, policy organisations, professional bodies and learned societies, R&D organisations, and skills development organisations/programmes.

The workshops captured the infrastructure needs of the quantum sector. Participants were asked to consider physical infrastructure, system enablers, risks, cross-sectoral dependencies, international collaborations, timescales for the infrastructure needs, industry demand and likelihood of co-investment between government and industry.

The workshops resulted in a longlist of both physical infrastructure needs and system enablers, which were consolidated, and triangulated across all four workshops to identify overlapping needs between different types of quantum technologies. The overlapping needs identified across different types of quantum technologies provided the basis for the cross-sectoral workshop.

In-person cross-sectoral workshop – An in-person workshop was carried out in November 2023 to assess and discuss the infrastructure needs emerging from the desk research and four sector-specific workshops. The aim of this wider workshop was also to identify overlapping priorities across different types of quantum technologies, explore options for strategic investment in quantum infrastructure, assess limitations and assumptions, and provide initial thoughts on how to best articulate emerging recommendations from this work.

Over 50 participants attended from a wide range of organisations with expertise in technology translation and sector-specific issues, as well as experience with the wider quantum ecosystem.

Breakout groups were categorised along technology development and commercialisation stages (materials; design and computing; prototyping and manufacturing; integration; packaging; testing and validation). The infrastructure needs previously identified were discussed and prioritised. Participants were presented with two boards: 1) a static board featuring a definition of the technology development stage and how it relates to quantum, and a brief overview of the state of play in the UK and internationally surrounding the needs identified (Figure 6), and 2) an 'interactive' board with a list of needs to be discussed and questions to answer (Figure 7). Participants completed

Physical infrastructure requirements for scaling-up the quantum sector in the UK	
Technology development stage	
Working definition of the technology development stage for the purpose of this exercise.	
Infrastructure priority needs	**State of play (examples)**
List of infrastructure needs emerging evidence collection: • Need 1 • Need 2 • Need 3 • Need 4	Existing in the UK List of key companies operating in this field Outside of the UK List of key companies operating in this field

Figure 6 | Displays the first 'static' board prior to participants input as described above.

Technology Development Stage				
	List of infrastructure needs emerging from evidence collection			
Questions asked to participants	**Need 1**	**Need 2**	**Need 3**	**Need 4**
How should the need be addressed in the next 5 years?	**Participants' input on post-its**			
Which applications would benefit from this infrastructure?				
What would be the consequences for the UK should the need not be met?				
Where is there scope for international collaboration?				
Other considerations				

Figure 7 | Displays the second 'interactive' board prior to participants input as described above.

the interactive board using post-its, providing insight relevant from their area of expertise. Following the workshop, all the inputs were transcribed on a virtual document for analysis.

Criteria for developing recommendations

The aggregated data obtained from all phases of evidence gathering was prioritised according to the following criteria:

- Overlapping infrastructure needs across quantum technologies.
- Infrastructure needs requiring investment in the next five years.
- Infrastructure most likely to generate co-investment between industry and government.
- Alignment with other key strategies (e.g. semiconductor, PNT, telecommunications, space).
- International considerations.

The criteria were based on the research parameters provided by DSIT and were discussed and approved by the Working Group and Industry Advisory Group for this study.

Targeted stakeholder engagement

Interviews were conducted to discuss specialised insight on certain issues or gaps identified in the Review, as well as to obtain practical illustrations of existing tensions and to showcase good practice.

Interviews were carried out with several organisations covering SMEs and large companies, networking organisations, end users, international partners, national research labs and hubs, and stakeholders operating in adjacent sectors relying on quantum technologies. This included: Alter, Bay Photonics, BT, Cerca Magnetics, Fraunhofer CAP, Infleqtion, KNT, National Epitaxy Facility, NPL, NSTF, PsiQuantum, Quantinuum, STFC, Tyndall, University of Strathclyde, WMG at the University of Warwick.

Integration with other strategies

Throughout the Review, regular meetings were held with organisations leading on work related to strategies adjacent to the National Quantum Strategy. These included semiconductors, PNT, telecommunications, and space.

Reporting

An interim was submitted for review to the Review's Working Group and Industry Advisory Group at the end of 2023. This aimed to provide an initial quality check, ensuring that the evidence and recommendations captured in the report were reflective of the current state of quantum infrastructure in the UK and to allow further targeted analysis. Feedback on the interim report shaped the final evidence gathering and stakeholder engagement activities to inform the final report. The final interim report was then sent to DSIT on December 2023.

Governance

A multidisciplinary Working Group of experts in quantum and related fields was established (Annex 4). This Working Group was pivotal in shaping the Review's approach and providing regular feedback and quality assurance.

The project was also supported by an Industry Advisory Group composed of individuals working in a range of quantum and related technologies (Annex 4). The group provided insight into how to best engage with the relevant stakeholders for this work, ensuring that the evidence gathered was reflective of the needs of the quantum sector. The group was also invited to provide feedback at the reporting stage.

The Review underwent comprehensive quality assurance, including through the Royal Academy of Engineering's Engineering Policy Centre Committee (EPCC).[33]

Annex 3: International landscape

Public investment in quantum technologies: the global landscape

Australia

Through federal funding, Australia has invested AU$130 million (about £67 million) into the development of quantum technology. In addition to this, it is investing a further AU$101.2 million (about £52 million) over the next five years to support a new national quantum strategy. This comes as part of the government's AU$1 billion (about £516 million) critical technology fund. Australia has established numerous centres dedicated to quantum – two quantum-focused Centres of Excellence were established in 2017 – Future Low-Energy Electronics Technologies (FLEET) and Exciton Science. As well as this, the Centre of Excellence for Quantum Computation and Communication Technology (CQC2T) has helped make significant progress in increasing public awareness of quantum, and The Australian Research Council Centre of Excellence (EQUS) was also set up to exploit the potential of quantum science and develop the technology.[34] Additionally, the Australian National Fabrication Facility (ANFF) was founded in 2007 to support R&D and provides open access to nanofabrication facilities for the development of quantum technologies. The ANFF has received significant public investment, for example AU$36.2 million (about £19.1 million) in 2018, and acts as an enabler for local quantum spinouts and startups.[35]

Canada

Canada has invested over CAD$1.3 billion (approx. £750 million) in quantum research over the past decade. Its private sector impact is growing, along with its strong research expertise, and extensive government commitment to innovation and it is now one of the world's leading nations in quantum research. Their National Quantum Strategy was launched in 2021 following a CAD$484 million (approx. £279 million) investment by the Canadian government. A further CAD$2.9 million (approx. £1.6 million) was given to the Quantum Algorithms Institute to commercialise quantum technologies, as well as a CAD$53 million (approx. £30.6 million) investment given to Xanadu Quantum Technologies Inc to build the world's first photonic-based, fault-tolerant quantum computer.[36]

China

China began investing in quantum R&D towards the end of the 90s and it is estimated that the Chinese government has invested approximately 107 billion Chinese Yuan (approx. £11 billion) in quantum technology (this figure has not been officially confirmed). It is since believed to be a leading nation in quantum information science. This area has received recognition in China with the First Prize of National Natural Science of China in 2013 and 2015 was awarded to this field. The country aims to grow its national quantum communications infrastructure, develop a general quantum computer prototype and construct a practical quantum simulator by 2030.[37]

EU

There are several initiatives established by the European Union and European Commission to support the development and commercialisation of quantum technologies. The Quantum Flagship Programme was launched in 2018 following €1 billion (approx. £851 million) funding from the European Commission and is one of the largest and most ambitious research institutes of the European Union. Its main aim is to "consolidate and expand European scientific leadership and excellence in this research area in order to kick-start a European industry in quantum technology". The Flagship document was endorsed by over 3,500 representatives from academia and industry, and they have called on the European Commission to invest in quantum technology as a core future technology. The Quantum Flagship's new Coordination and Support Action (QUCATS) running from 2022 to 2025, will strengthen the Flagship's foundations and foster an open and inclusive ecosystem at the European and international levels. It will contribute to benchmarks and standards and improve training and education for the quantum workforce.[38]

The European High Performance Computing Joint Undertaking (EuroHPC JU) is a joint venture between the EU, European countries, and private partners to develop a supercomputing ecosystem in Europe.[39] The total investment for this is over €100 million (approx. £85 million) with participation from 17 European countries. Under the initiative, the first European quantum computers will be hosted across six sites in Europe: in Czechia, Germany, Spain, France, Italy, and Poland.

The European Quantum Communication Infrastructure (EuroQCI) will build a secure quantum communication infrastructure spanning the whole EU, including its overseas territories.

Two workforce development initiatives have been launched under the Digital Europe Programme of the European Commission: Digitally Enhanced Quantum Technology Master (DigiQ) and Quantum Technology Courses for Industry (QTIndu).[40]

The Qu-Pilot is a Horizon-RIA project consisting of 21 partners from nine different countries to develop and provide access to the first production facilities for quantum technologies in Europe. This includes access to advanced silicon, silicon photonics (including active components such as compound semiconductor lasers), diamond, and superconductor platforms. These distinct platforms are being provided by several RTOs such as VTT in Finland, Commissariat à l'énergie atomique et aux énergies alternatives (CEA) in France, Fraunhofer and Infineon in Germany as well as Interuniversity Microelectronics Centre (IMEC) in Belgium. Its end goal is to accelerate the commercialisation of European innovation in quantum technology and establish a robust and trusted supply chain.[41]

Finland

Finland's national strategy for quantum computing has committed €67.5 million (approx. £57 million) to achieve a 54-qubit quantum computer by the end of 2024.[42] This follows the government funded project of €20.7 million (approx. £17.6 million) awarded to VTT Technical Research Centre of Finland and IQM to build its first quantum computer. There has also been an extra €3.3 million (approx. £2.8 million) raised from Business Finland, a government organisation for innovation funding.[43]

France

France invests €60 million (approx. £51 million) annually in quantum technologies. The French government estimated that they will require €1.4 billion (approx. £1.1 billion) over the next five years to enable quantum research and are planning to create a national quantum strategy. The government declared that this would require private sector support. The country's strategic recommendations include deploying quantum computing infrastructure for research and industry, launching an ambitious technological development programme, establishing a programme for supporting the development of applications, foster an effective environment for innovation, implement a tailored economic security strategy and establish effective governance. In 2021, France announced a €1.8billion (approx. £1.5 billion) five-year investment plan for quantum technologies.[44]

Germany

In 2018, the German government announced a Framework Programme to bring quantum technologies to market. The German Federal Government allocated €650 million (approx. £553 million) funding to its quantum technologies programme. The programme aims to build on Germany's strong position in quantum physics, prepare for new economic opportunities and markets, establish a solid basis for a leading role in industrial use of quantum, to collaborate with international partners to ensure security and autonomy of Germany, and to involve the German population in the journey of adopting the technology.

In 2020, the German government also announced a €2 billion (approx. £1.7 million) quantum effort which supplements EU plans for €1 billion investment until 2028. In 2023, they announced a €3 billion (approx. £19.5 million) action plan for quantum technologies and the development of a universal quantum computer by 2026. Germany has also received considerable private investment to support their quantum efforts from IBM. The company recently unveiled a quantum computer in Germany which is the first outside the US.[45]

The development of quantum technologies is supported by Fraunhofer-Gesellschaft. Founded in 1949, Fraunhofer operates 76 institutes around Germany focused on key technologies. It is involved in all key areas of quantum technology.[46] Specifically, the Fraunhofer Competence Network quantum computing was established in 2020 to research and develop new technological solutions for quantum computing. They also support industry by building necessary technical skills.[47]

Japan

Overall, Japan has invested approximately 30 billion JPY (approx. £217 million) for quantum information science and technologies through the funding agencies the Japan Science and Technology Agency, the National Institute of Information and Communications Technology, the Japan Society for the Promotion of Science, and the Cabinet Office of the Government of Japan. The Quantum Leap (Q-LEAP) initiative was launched in 2018 facilitating investment in quantum simulation and computation, quantum sensing, and ultrashort pulse lasers. The Moonshot Project is also expected to invest approximately 15–20 billion JPY (approx. £105 million) to create a fault-tolerant universal quantum computer by 2050. The Japanese government established the Vision of Quantum Future Society in 2022 to help embed quantum technology throughout Japanese society and economy.[48]

Netherlands

The Dutch government recognise the strategic benefits of quantum technology and have invested large amounts into the development of the technology. Through its National Growth Fund (NGF), the Dutch government has allocated over €600 million (approx. £510 million). to ensure that the Netherlands remains at the forefront of the quantum field. However, the sector is facing challenges because of private investors being hesitant to invest in quantum startups because of the journey to ROI and the high risks associated.[49] The NGF has recently awarded more than €10 million (approx. £8.5 million) to 19 quantum technology research projects covering a wide variety of topics as part of the quantum technology programme and administered by the Dutch Research Council (NWO) and Quantum Delta NL (QDNL).[50] Quantum Delta is an NGO which works to connect different part of the quantum ecosystem and help to communicate to industry potential uses of quantum, and what quantum means for them to encourage involvement and investment.

The National Agenda on Quantum Technologies was published in 2019 outlining four areas of focus: breakthroughs in R&I; ecosystem development, market creation, and infrastructure; human capital, education, knowledge; and societal knowledge on quantum technology. It aims to cement the Netherlands' position as a leading centre and hub for quantum technologies, already being leaders in quantum internet, quantum algorithms, and post-quantum cryptography.[51] In 2022, House of Quantum opened in Delft, offering an interconnected network of labs, makerspaces, and workspaces in the Netherlands. It provides the physical and digital space to allow those in the field to collaborate and serves a global community. This initiative is powered by QDNL.[52] The Netherlands is also home to PHIX photonics assembly, a packaging foundry for photonic integrated circuits and MEMS, with a facility aimed at supporting the global development of the technology.[53]

South Korea

South Korea's Quantum Computing Technology Development Strategy was launched in 2019 and has since committed 3 trillion KRW (approx. £1.8 billion) until 2035. Quantum computing research in South Korea will include 52 billion KRW (approx. £30.8 million) for five years to develop the core technology for quantum computing and expand its research base to a capacity of 2,500 researchers to position the country on the global stage for quantum technologies. Links with the US have been established, for example Sungkyunkwan University's Quantum Information Research Support Centre (Q-Centre) embarked on a three-year partnership with IonQ in the US for the development of research quantum advancement. Ties have also been made with IBM Quantum In the US.[54] South Korea is also investing 15 billion KRW (approx. £9.2 million) in ICT technology including ultra-high-performance computing knowledge data convergence, system software, software engineering, information and intelligence systems, and Human-Computer Interaction (HCI).[55]

US

The US' National Science and Technology Council (NSTC) set out the strategic approach to quantum technologies, providing a roadmap for opportunities and priorities in the quantum sector. The US has positioned itself as a leader in the quantum technology landscape, having invested at least $4.0 billion (approx. £3.1 billion) through the NQI and other funding initiatives. The NQI announced 2024 to be a critical year for quantum, proposing to strengthen quantum research and advancement. Through agencies such as the NIST, the Cybersecurity & Infrastructure Security Agency (CISA), National Science Foundation (NSF), and Department of Energy (DoE), the NQI aims to accelerate quantum development for the economy and security.[56] It is an all-of-government approach to ensure US leadership in quantum technologies and it has focused efforts to coordinate activities and provide guidance through the National Quantum Coordination Office (NQCO) and the National Quantum Initiative Advisory Committee (NQIAC). The CHIPS and Science Act aims to strengthen domestic technology companies, as well as providing support for the skills ecosystem. The National Strategic Plan for Quantum Information Science and Technology Workforce Development was also launched to target the shortages in quantum skills.[57]

Furthermore, the DoE is establishing five National Quantum Information Science Research Centres, four of which are similar to the UK's Quantum Technology Hubs, plus a Quantum Systems Accelerator. An important difference is that each of the DoE centres has its own foundry element, for example Q-NEXT will build two national quantum foundries. An example of one of the foundries is the $115 million funded SQMS centre.

The UK's comparatively lower investment into quantum technologies than international comparators matches that of its investment into semiconductors. The UK plans to invest £1 billion in semiconductors over the next decade, but this is dwarfed by international plans.[58] For example the US is investing $11 billion (approx. £8.5 billion) in semiconductor related R&D,[59] Germany plans to invest €20 billion (approx. £17 billion) to attract global chipmakers to set up sites in the country[60], and India has announced investment of 1.26 trillion INR (about £11 billion) for semiconductor production.[61]

Existing global alliances and agreements

- The UK is a member of the European council for Nuclear Research (CERN) which established its Quantum Technology Initiative (CERN QTI) in 2020 aiming to foster international collaboration to develop new quantum computing, detector, and communication systems. The initiative has produced a roadmap and will establish research, educational, and training to support quantum computing infrastructure.[62,63]
- QuantERA is a collaborative initiative which the UK is a partner of and is a programme of 41 publish research funding organisations. Its goals are to promote research and collaboration in quantum technologies.[64]
- AUKUS is a trilateral security agreement between Australia, the UK and the US signed in 2021. Its goal is to allow the three nations to cooperate closely on key defence capabilities including quantum technologies.[65]
- The UK and Australia signed joint statement on cooperation in quantum science and technologies in November 2023. The aim is to enable more investment, research exchange, and expertise and explore new applications of quantum technologies to mutually benefit both nations.[66]
- A UK-US joint statement on cooperation in quantum information sciences and technologies was signed in 2021 setting out a shared vision to promote joint R&D between national quantum programmes, contribute to the growing global markets, and provide training opportunities for scientists and engineers.[67]
- A memorandum of understanding was published between the UK and Netherlands in 2023 for cooperation in quantum science and technologies. It aims to pursue operation between the national quantum programmes to discuss policy issues, enable interactions between academia and industry, scoping demonstrations and exploring end use cases, and enhancing public outreach initiatives.[68]
- Over £4 million was announced in 2023 to strengthen collaborative R&D through Canada-UK partnerships to support the commercialisation of quantum technologies.

Annex 4: Acknowledgments

Working Group

This Review was overseen by a Royal Academy of Engineering Working Group made up of the following experts[69]:

Chair: Dr Dame Frances Saunders DBE CB FREng
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69 Each member of the Working Group was requested to sign a Conflict of Interest form prior to joining the project.

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What we do

TALENT & DIVERSITY

We're growing talent by training, supporting, mentoring and funding the most talented and creative researchers, innovators and leaders from across the engineering profession.

We're developing skills for the future by identifying the challenges of an ever-changing world and developing the skills and approaches we need to build a resilient and diverse engineering profession.

INNOVATION

We're driving innovation by investing in some of the country's most creative and exciting engineering ideas and businesses.

We're building global partnerships that bring the world's best engineers from industry, entrepreneurship and academia together to collaborate on creative innovations that address the greatest global challenges of our age.

POLICY & ENGAGEMENT

We're influencing policy through the National Engineering Policy Centre – providing independent expert support to policymakers on issues of importance.

We're engaging the public by opening their eyes to the wonders of engineering and inspiring young people to become the next generation of engineers.

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