REGULATORY HORIZONS COUNCIL

Regulating Quantum Technology Applications

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Foreword

To quote from the UK Government's Science and Technology Framework: "The UK ... is at the frontier of setting technical standards and shaping international regulations. Regulation is pro-innovation, stimulates demand for science and technology and attracts investment while representing UK values and safeguarding citizens. The government leverages its science and technology strengths and international relationships to secure influence over regulations and technical standards."

Quantum technology is a disruptive technology generating new capabilities in sensing, imaging, communications, and computation which are likely to transform our world in the coming decade. Across the world we see major initiatives to link research, commercialisation and standards in this exciting area of science. Nations are investing billions as the pace to develop a quantum enabled economy accelerates.

Developing sensible frameworks to enable the technology to deliver optimal outcomes whilst enabling it to safely coexist with existing infrastructure is a challenge that this review addresses.

Regulation should be seen as an enabler, adding confidence to users and developers, removing hurdles to adoption, and especially knowing when action is needed and when a watching brief is sufficient.

This report identifies a valuable framework to link regulatory frameworks, standards and Technology Readiness Levels. Responsible governance is essential to ensure ethical considerations come into play and provide the necessary assurance to users and the general public. I commend this to all those working to realise the potential of this remarkable technology.

Sir Peter Knight
Chair of the National Quantum Technology Programme Strategic Advisory Board

Executive summary

Quantum technologies represent a groundbreaking shift in capabilities. They have the potential to surpass classical computing power, enhance communication capabilities and increase precision in measurement, and are poised to redefine numerous sectors from healthcare to national security. The UK is at the forefront of this, and understanding and harnessing quantum technologies' transformative power will be important for maintaining global competitiveness, with pioneering advances promising immense societal and economic benefits.

The 2023 McKinsey Quantum Technology Monitor indicates a vibrant and flourishing quantum ecosystem.[1] It expects the global quantum computing market to reach $93 billion by 2040, with the overall quantum technology market potential estimated at $106 billion; quantum sensing, timing, imaging, and communications, each have an estimated market size ranging from $1 billion to $7 billion by 2040. This highlights the sector's potential impact on the UK's economic landscape, and establishing the right regulatory approach will be important in realising these opportunities.

Quantum technologies are at various stages of development, and we agree with stakeholders that it is 'too early' to jump to legally based regulation given the nascency of many quantum technologies. It is, however, important to have regulatory discussions and to plan around quantum-related products and services. The lack of clarity around timings, scope and shape of expected regulation can impede investment and long-term planning for businesses challenging. This report proposes developing a pro-innovation regulatory framework aimed at nurturing a robust quantum ecosystem. The UK has a strong academic and vibrant startup community, the framework seeks not only to retain domestic talent and investment but also to attract international developers and investors looking for regulatory clarity and a commitment to responsible innovation practices. This approach also reduces the risk that the benefits of quantum technologies are realised outside the UK rather than within.

The recommendations in this report promote a regulatory approach underpinned by principles of proportionality, adaptability, responsibility, and balance. These principles must pervade the quantum ecosystem, guiding not only regulation but also the innovation process itself. The RHC's definition of regulation and governance includes standards, policies, best practices, codes of conduct, and procedures – extending beyond just legislation. Responsible Innovation should be championed through these regulatory approaches and embedded in the development of quantum technologies from the outset, considering their societal, ethical, and environmental implications.

A proportionate and flexible regulatory framework is needed, particularly as potential applications get closer to market readiness, to ensure responsible development and safeguard against potential ethical, safety and security challenges, and also to foster an environment where innovation can thrive by providing much-needed certainty for investors and developers. Fostering an ecosystem where the potential benefits are maximised, and risks are mitigated requires collaboration. Taking account of the uncertainty surrounding the development of some quantum technologies, it is

[1] McKinsey & Company: Quantum Technology Monitor (2023). Available at: https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/quantum%20technology%20sees%20record%20investments%20progress%20on%20talent%20gap/quantum-technology-monitor-april-2023.pdf

reasonable to expect many transformative innovations are likely to emerge over the next decade. The nature and power of these future innovations will depend on how well we manage the governance of today's early steps along the quantum innovation trajectory, emphasising the degree of responsibility faced by all involved in the ecosystem.

- **Academia** can lead in fostering quantum literacy, while instilling a culture of responsible innovation.
- **Government** can act as a facilitator through funding and pro-innovation policies, being an early adopter of new technologies to spur market confidence, and as a guardian of public interest.
- **Innovators** must pioneer new developments, pushing the boundaries of the technology while engaging with regulators to consider the most appropriate governance instruments (regulations, standards and/or best practice guidance) and engaging in responsible innovation.
- **Regulators and standards bodies** will play a critical role in ensuring that, as quantum technologies develop, they do so within an environment that protects consumers and the public interest without stifling innovation.

The report emphasises the importance of getting the timing right and intervening at the right stage of development, thus not calling for quantum-specific regulations or the establishment of a quantum regulator. Instead, we are suggesting a more nuanced approach ensuring that regulatory bodies and policymakers can become quantum ready.

Quantum regulatory pathway
Section 4 consolidates insights from previous RHC reports to offer specific recommendations for a pathway of proportionate and adaptive governance for quantum technologies. Recognising the diverse and sector-specific nature of quantum technology applications, regulatory initiatives should target quantum-related products and processes, rather than the platform technology[2] itself, with a range of regulatory approaches to match specific properties of these products and the needs of manufacturers, distributors, and consumers.

Domain-specific regulatory requirements
Recognising the broad spectrum of quantum technology applications, section 5 explores specific domains[3] such as quantum sensing, timing, imaging, communications, and computing, analysing each for market readiness, transformative potential, and specific regulatory challenges, providing tailored recommendations for each area.

Recommendations
Sections 4 and 5 outline a series of recommendations aiming to guide the development of a regulatory framework that is adaptable, proportionate, and balanced. This aligns with the UK's broader strategic objectives as set out in the UK's National Quantum Strategy, positioning the UK

[2] Platform Technology: In the context of this report, this refers to a foundational technology that serves as a base upon which other applications or technologies are developed. In the context of quantum technology, a platform technology implies a set of quantum capabilities or systems that underpin a broad range of potential applications across various fields. These are not tailored to a specific end-use but provide the core technological capabilities that enable the development of specific quantum applications.

[3] Domain: In the context of this report, this refers to a specific area of application or a field of use within quantum technology. It denotes a specialised segment that utilises quantum technology for particular practical applications or purposes. For example, 'domain-specific quantum technologies' include quantum computing, communication, sensing, and imaging, each representing a distinct area of application with their own unique regulatory and technological requirements.

as a leader in developing a pro-innovation regulatory environment for quantum technologies. This report aims to provide greater certainty and establish responsible innovation practices at the core of quantum technology regulation. The recommendations are split into three broad categories:

- **Regulatory Frameworks and Governance**: The report underlines the necessity for developing application-specific regulatory frameworks that are adaptable and proportionate to the unique properties and development stages of quantum innovations (Recommendation 1). Key recommendations also include establishing a Quantum Regulatory Forum (Recommendation 2), implementing foresight methods for regulatory requirements (Recommendation 3), and providing awareness training (Recommendation 4).
- **Standards and International Collaboration**: The importance of developing standards and international harmonisation in quantum technology is highlighted. This includes the enhancement of the UK Quantum Standards Pilot Network (Recommendation 6) and advocating for the UK's strategic involvement in international regulatory forums (Recommendation 9). The report focuses on interoperability standards in quantum communications (Recommendation 11), addressing security concerns related to quantum communication (Recommendation 12) and addressing the unique regulatory challenges of quantum computing, advocating for a balanced approach based on standards and responsible innovation (Recommendation 14).
- **Innovation Funding and Market Development**: The recommendations include the necessity to integrate regulation and responsible innovation practices into the development of quantum technologies. Recommendations include establishing testbeds and sandboxes with regulatory components (Recommendation 5), leveraging procurement strategies to create markets for quantum technologies (Recommendation 7), and tailoring the translational funding environment to support quantum innovation (Recommendation 8). The report also stresses the importance of regulatory policies and funding for mature quantum applications (Recommendation 10) and ensuring compliance with legal frameworks like the Online Safety Act (Recommendation 13).

While the Council does not make decisions regarding the acceptance of these recommendations for regulating quantum technologies, it stands ready to offer support where needed to facilitate their successful implementation.

1. Introduction

1.1 Regulatory Horizons Council (RHC)

Technology is advancing at a rapid pace and government should be proactive in anticipating the implications of emerging technologies. This requires establishing a regulatory environment that fosters and supports innovation while incorporating safety and mitigating risks. It was for this reason that in the 2019 White Paper on 'Regulation for the Fourth Industrial Revolution', the Government established the Regulatory Horizons Council (RHC).[4] The Council is an independent expert committee, sponsored by the Department for Science, Innovation and Technology (DSIT). Its role is to identify the implications of technological innovation, and provide government with impartial, expert advice on the regulatory reform required to support its rapid and safe introduction. The RHC has produced several sector specific reports, including Artificial Intelligence (AI) as a medical device, neurotechnology, drones, and fusion energy, among others.

1.2 Quantum review background and scope

The RHC was commissioned by the Office for Quantum through the UK's 2023 National Quantum Strategy, "to undertake a regulatory review of Quantum Technology applications".[5] The report draws on the Council's collective expertise, experience, and lessons from previous work programmes on regulating other emerging technologies, as well as input from stakeholders across the quantum landscape. Our methodology and a detailed list of engaged stakeholders can be found in Annexes A and E.

The overarching question the review seeks to answer is:

> *"What regulatory and governance approaches and measures are needed now, and in the near future, to facilitate the rapid and safe introduction of innovative quantum technology applications?"*

The RHC defines 'regulation' and 'governance' as broad terms that capture legislation, standards, guidance, policy, best practices, industry or professional codes, requirements, and procedures.

Quantum technologies can be broadly defined as "devices and systems which rely on quantum mechanics to provide capabilities that 'classical' machines cannot".[6] The evolution of quantum technologies can be broadly described as:

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[4] Department for Business, Energy & Industrial Strategy: Regulation for the Fourth Industrial Revolution (2019). Available at: https://www.gov.uk/government/publications/regulation-for-the-fourth-industrial-revolution/regulation-for-the-fourth-industrial-revolution

[5] Department for Science, Innovation and Technology: National quantum strategy (2023). Available at: https://www.gov.uk/government/publications/national-quantum-strategy

[6] Department for Science, Innovation and Technology: The UK Science and Technology Framework (2023). Available at: https://www.gov.uk/government/publications/uk-science-and-technology-framework

- **Quantum 1.0**: This stage involves technologies based on the fundamentals of quantum physics. Many of today's devices, including smartphone chips, lasers in checkout scanners, fibre-optic broadband and MRI scanners are examples of Quantum 1.0 products.
- **Quantum 2.0**: This report focuses on more advanced quantum 2.0 technologies, encompassing a range of domains and their applications – imaging, timing, computing, and various sensors including detecting gravity and magnetic fields, as well as communication technologies.

These new technologies have anticipated capabilities beyond those achievable with non-quantum classical techniques, which are likely to impact substantially on society and the economy. This is amplified by the Government recognising quantum as one of the five critical technologies in the UK's Science and Technology Framework.[7] However, these new quantum technologies will not completely replace their classical counterparts. Instead, they will be complementary, and interoperability will be important to ensure the strengths of both types of system are used to produce optimal results. This includes hybrids, which add quantum enabling technologies to existing classical hardware (such as Quantum Random Number Generators), forming complementary infrastructures.

Quantum technologies include a wide range of different technology domains and applications. These can be broadly split into four categories, aligning with the four National Quantum Technologies Programme (NQTP) quantum themes; quantum computing and simulation, quantum communications, quantum sensing and timing, and quantum enhanced imaging. This report includes recommendations for **quantum as a platform technology**[8], and for **domain-specific**[9] quantum technologies and applications. In our domain-specific section (section 5), we have chosen to include quantum imaging along with sensing and timing, given their similar regulatory implications.

Some quantum technologies are 'dual use' technologies by their nature, meaning they have potential civilian and military applications. While there are national security implications relating to quantum technologies, these areas are not in scope because this will limit the ability for the report to be fully published and furthermore it is in recognition that there are existing work programmes already addressing some of the national security implications.

1.3 Review objectives

The UK's National Quantum Strategy ambition is that the recommendations in this report "will lead to the development of a work programme to guide the evolution of proportionate and pro-

[7] Department for Science, Innovation and Technology: The UK Science and Technology Framework (2023). Available at: https://www.gov.uk/government/publications/uk-science-and-technology-framework

[8] Platform Technology: In the context of this report, this refers to a foundational technology that serves as a base upon which other applications or technologies are developed. In the context of quantum technology, a platform technology implies a set of quantum capabilities or systems that underpin a broad range of potential applications across various fields. These are not tailored to a specific end-use but provide the core technological capabilities that enable the development of specific quantum applications.

[9] Domain: In the context of this report, this refers to a specific area of application or a field of use within quantum technology. It denotes a specialised segment that utilises quantum technology for particular practical applications or purposes. For example, 'domain-specific quantum technologies' include quantum computing, communication, sensing, and imaging, each representing a distinct area of application with their own unique regulatory and technological requirements.

innovation regulation for the sector" and will inform the approach to the national strategy goal to "Create a national and international regulatory framework that supports innovation and the ethical use of quantum technologies, and protects UK capabilities and national security".[10] The RHC's 2022 cross-cutting report on 'Closing the Gap' between regulatory principles and practice highlighted the ways in which regulation can either impede or stimulate innovation is relevant here.[11] For example, regulation can help to create the conditions under which people feel confident to adopt and implement technological innovations.

The Council recognises there is significant potential for quantum technologies, and that premature legally based regulations can hinder the development of these technologies. However, considering early regulatory initiatives now could help unblock future hurdles and allow the UK to achieve responsible and more rapid innovation. There is also a great deal of publicity and promotion around quantum technologies, some of which is justified, and can be useful. However, over-hyping the capabilities of these technologies can be a barrier to innovation as it can reduce trust from investors and stakeholders, and translate into exaggeration of concerns and risks, leading to disproportionate and overly precautionary regulatory measures.

Discussions around the regulation of quantum has increased recently. This report aims to bring new considerations and more depth to these discussions by suggesting ways to support the development of quantum technologies through appropriate regulation (including standards and guidance) while building on the steps outlined by the UK's National Quantum Strategy.

Regulatory experience in the past thirty years has demonstrated the problems that emerge when we attempt to regulate highly innovative technology platforms on the basis of the technology itself, rather than the benefits and hazards of the products and processes that emerge from it. This is particularly the case where the technology is in the early stages of development, is potentially transformative and is evolving rapidly to deliver new technological capabilities.[12]

Proposing one overarching regulatory approach, and one regulator, to cover all applications of quantum technologies, would inevitably lead to inhibition of innovation for some quantum-related developments, to inadequate governance of others and would quickly become obsolete as new, unexpected capabilities emerge from quantum-related research. We have emphasised throughout this report that regulatory initiatives should target the range of products and processes emerging from quantum-related research with an equivalent range of regulatory approaches, to match their specific properties, and the needs of manufacturers, suppliers, and consumers.

Stakeholders highlighted that some quantum technology applications are likely to fall within scope of existing regulatory systems, while for others in earlier stages of development it is too early to consider legally based regulation, but appropriate to consider soft law approaches to governance. Thus, while it is 'too early' to discuss regulating some of the new products and processes arising from quantum-related research and development, lack of clarity around the timing, scope, and

[10] Department for Science, Innovation and Technology: National quantum strategy (2023). Available at: https://www.gov.uk/government/publications/national-quantum-strategy

[11] Regulatory Horizons Council: Closing the gap: getting from principles to practice for innovation friendly regulation (2022). Available at: https://www.gov.uk/government/publications/closing-the-gap-getting-from-principles-to-practice-for-innovation-friendly-regulation

[12] Regulatory Horizons Council: Regulatory Horizons Council report on genetic technologies (2021). Available at: www.gov.uk/government/publications/regulatory-horizons-council-report-on-genetic-technologies

shape of expected regulation for an emerging technology can impede investment and make business planning risky. Developing a pro-innovative regulatory framework can help retain domestic developers and investors, as well as attracting those from abroad who seek regulatory certainty and want to develop their products in a responsible manner. This reduces the risk that the UK's strong academic and research capabilities are commercialised and only scaled abroad, resulting in economic losses, and weakening the UK's geopolitical position due to its dependence on external quantum innovations.

Quantum in the UK

The UK has ambitions to be among leading nations in the development and deployment of quantum technologies, and in the adoption of smarter approaches to regulation. Achieving these ambitions is not just about technological prowess but also about setting ethical, responsible, and globally recognised standards in the deployment of quantum technologies. The UK's National Quantum Technologies Programme (NQTP), in operation since 2014, is internationally recognised for its forward-looking approach and close coordination between government, academia and industry. The programme has made significant strides in research, development, and early-stage commercialisation. The NQTP was expanded in 2023 to focus more on deployment, scaling, and international collaboration and this regulatory review has been commissioned to support these developments. The right regulatory pathway can help create conditions in which investors feel confident, companies develop solutions relevant for global markets, and commercial scaling and supply chain challenges are bridged.

1.4 Cross-cutting challenges and lessons from Artificial Intelligence (AI)

Quantum technologies, while promising, are at an early stage and as we explore the regulatory requirements for these applications, it is essential to understand quantum's unique challenges. This section outlines the 'cross-cutting' challenges that extend across various applications, sectors, and domains, identified through our stakeholder engagement, highlighting their implications for regulatory systems.

Many technical challenges relate particularly to quantum computing hardware, software and algorithms. However, this report does not explicitly focus on the technical challenges faced by quantum technologies, but rather the regulatory environment to accelerate its commercialisation. Regulation, in its broadest sense, can offer a framework to ensure quantum technologies flourish while mitigating these challenges and ensuring innovation is responsible and safe.

The rapid development and implementation of AI offers instructive insights for the evolution of quantum technologies. There is also direct overlap, as quantum technologies have the potential to enhance AI. For example, quantum computers have the potential to significantly boost AI's processing power. Quantum-AI hybrids will require smart decisions on which regulatory precedent(s) to follow. However, it is important to delineate between quantum technologies and AI, recognising quantum's specific benefits and challenges, and that their trajectories might diverge.

- **Proactive governance**: AI has raised ethical and responsible innovation concerns that have been difficult to promptly address, which could require expensive and difficult retrospective course corrections. Therefore, ensuring early dialogue about potential societal, environmental, and other concerns will be important.

- **Regulatory models**: This report advocates regulatory initiatives that target quantum-related products and processes, rather than the platform technology itself. The UK's AI regulatory model, detailed in the white paper "Establishing a pro-innovation approach to AI regulation", is underpinned by a set of cross-sectoral principles tailored to the specific characteristics of AI.[13] While our report explores quantum technologies' specific characteristics, several of its aims correspond with ours; proportionate and adaptive regulation (two of our principles from section 3.2), context-specific (similar to our Recommendation 1 in section 4.1), and coherent (similar to our Recommendation 4 in section 4.4).
- **Standardisation, benchmarking, and measurement**: Standardising processes and benchmarks for evaluating the performance of quantum technologies is essential to ensure that developments across sensing, imaging, computing, and timing are comparable and meet industry standards.
- **Ethical, privacy and security concerns**: quantum-based products and processes have the potential to introduce challenges, and the swift pace of change magnifies the need for proactive safeguards.
- **Access:** the hardware required for quantum technologies demands intricate construction and steep costs, which could restrict its democratisation. Given the transformative potential capabilities of these technologies, enabling and maintaining equitable access will be important. The UK's National Quantum Strategy Missions highlight the importance of access in Mission 1: "By 2035, there will be accessible, UK-based quantum computers capable of running 1 trillion operations".
- **Encryption:** quantum computers have the potential to undermine contemporary encryption techniques, posing significant threats to data protection and security: What frameworks are necessary to ensure the robustness of privacy mechanisms? How can quantum technologies themselves generate countermeasures?
- **Sustainability:** similar to AI, quantum technologies have both their own sustainability concerns, and the ability to help achieve sustainability goals. Quantum technologies can offer sustainability solutions through contributing to applications such as detecting gas leaks, expediting data processing and drug discovery, and optimising resource consumption.
- **Privacy:** quantum imaging has the potential to see through walls and round corners, requiring the establishment of clear ethical guidelines on usage.
- **Explainability:** similar to, or even more than AI, the outputs from quantum computers are difficult or even impossible to explain, based on probabilistic quantum algorithms, creating a challenge for increasing uptake and developing regulations.

The overarching objectives for quantum technologies' regulation remain to ensure quantum innovations flourish while developing in harmony with societal values and ethical norms, with robust governance involving vigilant oversight, public dialogue, and a balanced, proportionate, and adaptive regulatory framework.

[13] Department for Digital, Culture, Media and Sport: Establishing a pro-innovation approach to regulating AI (2022). Available at: https://www.gov.uk/government/publications/establishing-a-pro-innovation-approach-to-regulating-ai/establishing-a-pro-innovation-approach-to-regulating-ai-policy-statement

2. Technology Readiness Levels & the transformative nature of quantum technologies

2.1 Technology Readiness Levels

Quantum innovations leverage quantum mechanics to produce a wide range of technologies and applications. These technologies are at various stages of development, from basic foundational research to commercial market availability. In this report, we propose that regulation should target quantum-related products and processes, rather than the platform technology itself, using Technology Readiness Levels (TRLs) as indicators of the readiness of a specific technology for a specific application. TRLs are therefore useful in informing policy decisions about the appropriateness or timeliness of different regulatory interventions. While identifying the TRLs applicable to different quantum technology domains, we have used the Organisation for Economic Co-operation and Development's (OECD) proposed categorisation[14] of the usual nine-point TRL scale[15] into four levels: basic research (TRL 1-3); technology development (TRL 4-5); technology demonstration (TRL 6-7); and early deployment (TRL 8-9).

Along with TRLs, other important factors are the variation in the current and prospective capabilities of these technologies (some of which are novel), and the extent to which they will be transformative or disruptive in a commercial or societal sense.[16] Given the differing rates of TRL development in various end-use sectors, it is imperative to consider the context-specific nature of these technologies when making regulatory decisions.

Given the widespread adoption of TRLs as an aid to technology policy decision making, the concept of 'readiness' is increasingly being advocated in other innovation-related contexts: regulatory readiness, investment readiness, and market readiness, among others.[17] However, the achievement of a TRL in a commercial context inherently incorporates these aspects of readiness. Thus, although some reports and papers on quantum technologies are beginning to incorporate a range of readiness levels, we have decided not to follow that trend here.

The RHC asked stakeholders for their views on timelines for the commercialisation of quantum technologies. While the quantum-related products and processes of each domain span the

[14] Paul Ekins: Eco-innovation for environmental sustainability: Concepts, progress and policies (2010). Available at: https://ideas.repec.org/a/kap/iecepo/v7y2010i2p267-290.html

[15] European Association of Research & Technology Organisations: The TRL Scale as a Research & Innovation Policy Tool, EARTO Recommendations (2014). Available at: https://www.earto.eu/wp-content/uploads/The_TRL_Scale_as_a_R_I_Policy_Tool_-_EARTO_Recommendations_-_Final.pdf

[16] Throughout the report we generally use 'transformative' when referring to a marked change in the capabilities of the technologies, whereas 'disruptive' generally refers to the impact these technologies have on industry.

[17] Examples include; Emily Sotudeh, UKRI: Understanding market readiness level: From idea to IP (2022). Available at: https://www.innovateukedge.ukri.org/blog/understanding-market-readiness-level# and Abhishek Purohit and others: Building a quantum-ready ecosystem (2023). Available at: https://arxiv.org/pdf/2304.06843,

spectrum of TRLs, there was a consensus that at least some leading applications in the imaging, timing, and sensing, as well as communications domains, are at the technology demonstration (TRL 6-7) and early deployment (TRL 8-9) stages, with some products already on the market. Quantum computing, on the other hand, is generally considered to be at the technology development stage (TRL 4-5), with some hybrid quantum computers already deployed, and progress frequently being made. The TRLs of different quantum products are explored in more detail in the domain-specific section (section 5).

It is important to note that quantum technologies are rapidly evolving, and we can expect new and surprising developments in all areas where quantum technologies are being developed. Some of these will be even more transformative than the quantum products being developed today in areas like imaging, sensing, and timing, and their regulation will need to be considered accordingly. As such, foresight methods will be needed to help regulators anticipate these advances and determine and coordinate proportionate regulatory initiatives, as we propose in Recommendation 3 in section 4.3.

2.2 Incremental and disruptive/transformative innovation

It is important to consider the nature and impact of the innovation itself (i.e., to what extent does it disrupt the business models or markets of incumbent companies). Quantum technology products span the spectrum from incremental to disruptive/transformative. If an innovation is incremental, it will fit into existing business models and value chains, enabling stepwise improvements in a company's current innovation system, creating competitive advantages within the same sector without challenging the prevailing business models along the value chain. For these products there will often be a clear, effective regulatory precedent.

Conversely, if an innovation is disruptive/transformative, it potentially leads to the creation of new applications, industry sectors or radical re-structuring of existing sectors. This disruption can differentially impact stakeholders within quantum value chains, from technology providers to end-users, as each grapple with the integration and adoption of new quantum technologies in their respective business models. For this category there is usually no clear regulatory precedent, and this can be a source of uncertainty discouraging investment in the technology.

This is not a binary classification. There are degrees of disruption that will vary from one technology or product to another. Also, a new product can be disruptive of the business model of one application or sector, or one part of the value chain, but not the others. An understanding of the degree of disruption and of the sectoral location of the disruption is important to guide future regulatory decisions. Incorporating the perspectives of a quantum value chain's diverse stakeholders is essential to fully comprehend the sector-specific impacts of these innovations and to develop regulatory frameworks that are both robust and flexible.

2.3 Impacts on the quantum value chain

As we delve into the nature and impact of quantum innovations, we need to understand the quantum ecosystem's diverse stakeholders and their unique journeys. This understanding helps to contextualise the varying degrees of disruption caused by quantum technologies across different sectors and it also informs the development of regulatory frameworks that are adaptable to the evolving quantum landscape.

Technology Providers: At the core of the ecosystem are the technology providers, ranging from startups to large corporations. They play a key role and are deeply embedded in the fabric of quantum development in advancing quantum-related developments. They possess a profound understanding of the technical challenges but may lack comprehensive solutions. These 'deep tech' organisations are the nexus between theoretical advances and practical applications.

Supply Chain Participants: These stakeholders provide necessary components such as lasers, control systems, and vacuum systems to technology providers. Their awareness and understanding of quantum technologies' technical challenges varies significantly. Some may not realise their potential role or the opportunities quantum technologies offer, highlighting the need for increased awareness and engagement in the quantum ecosystem.

End Users: End users apply quantum products and services across various industries, shaping the practical implications of these technologies. Industries like healthcare, cybersecurity, logistics, and energy are poised to undergo significant transformations due to quantum advances. Understanding the needs and readiness of these end users is crucial for aligning quantum innovations with market demands. The readiness and receptivity of these end users significantly influence the adoption and integration of quantum technologies in their respective sectors.

Supporting Services: A wide array of services is required, from the supportive periphery of the quantum ecosystem: patent attorneys, investors, networking groups, training organisations, and innovation hubs. These stakeholders play a crucial role in facilitating the growth and development of quantum technologies through various means of support.

Each group within this ecosystem is on a distinct journey from initial awareness to full advocacy of quantum technologies and their demands and interactions with the quantum landscape change accordingly. For instance, the supply chain and sector-based end users may seek varying levels of "quantum assurance" from their suppliers, reflecting their position in the awareness-to-advocacy spectrum. Those in the early stages of awareness might focus on understanding quantum technologies' potential impacts on their business, while advocates lead by example, setting trends and standards in their respective fields.

This spectrum of engagement underscores the importance of considering the quantum ecosystem's diverse perspectives in developing regulatory frameworks. Regulations should be adaptable to accommodate the varying degrees of innovation disruption and stakeholder readiness. Understanding where each stakeholder stands in their quantum journey allows for more targeted and effective governance strategies, facilitating the seamless integration of quantum technologies into existing and emerging market sectors.

2.4 Proportionate and adaptive governance of quantum technologies

In the context of technology development, the RHC believes the Proportionate and Adaptive Governance of Innovative Technologies (PAGIT) framework offers a nuanced blueprint for the selective adoption of standards, guidance, and regulations at different points in quantum technology development (Figure 1, below).[18]

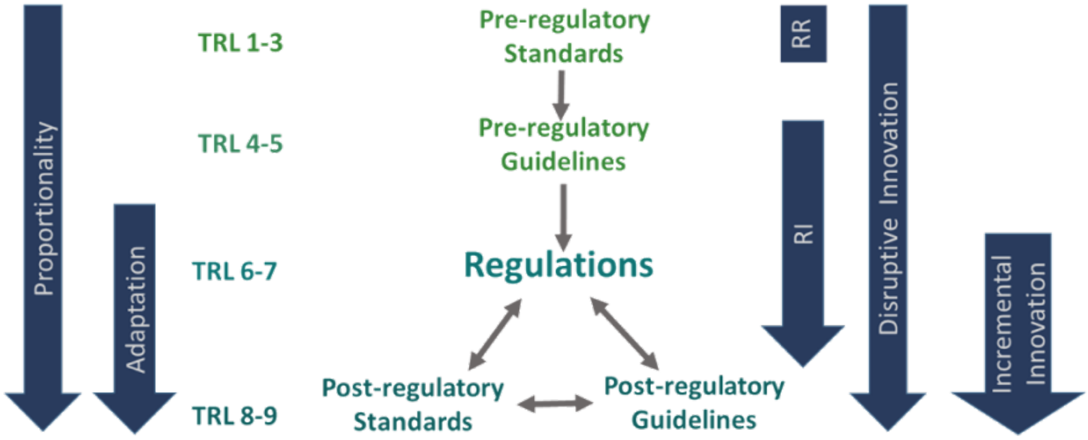

***Figure 1**: Generic PAGIT Framework diagram*[19]

Decisions about the adoption of formal, legally based regulation should be delayed until around TRL 6-7 – when there is a clearer grasp of the technology's capabilities, applications, benefits, and risks, and hence its regulatory requirements. Up to that point, effective governance of the technology can be assured through the adoption of standards and guidelines that are easier to adapt than legally based regulations, if needed as the understanding of a product's properties becomes clearer. The decision here should be about the need for legally based regulation or whether the continued reliance on standards and guidance would be sufficient to control future development of the product or service. This is an example of the need to base regulatory decisions on the properties of specific applications of quantum technology, not the overarching quantum technology platform.

Where there is a legally based regulatory system, some of the standards in place in the later TRLs will be to support compliance with the regulations. Other technical standards may focus on aspects such as interoperability. It is important to consider the principle of proportionality from the earlier TRLs to ensure that governance initiatives do not unnecessarily inhibit innovation, and at later TRLs to consider their adaptability in the face of evolving understanding of the properties of the products (adaptation principle).

In the context of quantum technologies, the regulatory journey might look like this:

- **TRL 1-3 (Pre-regulatory Standards)**: Here, the focus should be on consensus standards. These standards can underpin an understanding of the quantum technology's properties, identifying potential benefits and risks and determining future optimal development and management strategies.

[18] Joyce Tait, Geoffrey Banda, Andrew Watkins, Innogen Institute Report to the British Standards Institution: Proportionate and Adaptive Governance of Innovative Technologies: A Framework to Guide Policy and Regulatory Decision Making (2017). Available at: https://www.innogen.ac.uk/reports/1222

[19] Joyce Tait, Geoffrey Banda, Andrew Watkins, Innogen Institute Report to the British Standards Institution: Proportionate and Adaptive Governance of Innovative Technologies: A Framework to Guide Policy and Regulatory Decision Making (2017). Available at: https://www.innogen.ac.uk/reports/1222

- **TRL 4-5 (Pre-regulatory Guidelines)**: Building upon the initial standards, more defined guidelines can emerge. These could subsequently lay the groundwork for a future regulatory system. Importantly, decision-makers should remain receptive to the idea that these guidelines alone might suffice in ensuring the safety, quality, and efficacy of the quantum product or process – rendering legally based regulations unnecessary.
- **TRL 6-7 (Regulations)**: Decision points at this stage involve discerning the relevance of existing regulatory systems or, in the case of exceptionally transformative quantum innovations, contemplating a fresh regulatory approach. Legally based regulations should be articulated in broad terms, focusing on desired outcomes, and bolstered by subsequent standards and guidelines, ensuring proportionality towards quantum-related products and processes and adaptability in the face of future changes.
- **TRL 8-9 (Post-regulatory Standards and Guidelines)**: Here, standards (including technology and interoperability standards, along with consensus standards) and guidelines can be crafted to facilitate compliance with regulatory systems by those engaged in quantum product development.

In the early TRLs, behavioural standards (including those defining responsible innovation principles) can be used to ensure safe early development of the technology. In these TRLs, understanding of the properties of the products, their benefits and risks, and their intended markets will change, requiring future adaptation of prospective regulatory systems. There may be circumstances where it is necessary to resort to legally based regulation at these earlier stages to ensure compliance. However, this should be as a last resort, as prematurely imposed legal regulations will be difficult to adapt to changing circumstances, whereas standards and guidelines can be trialled in these early stages and modified as circumstances change. At the TRL 6-7 decision point, the choice may be to continue governance of the technology without resorting to regulatory instruments, i.e., a higher TRL should not automatically denote that regulations are required. Instead, this requires a nuanced understanding of the risks and benefits of the application and the impact of regulatory intervention. For certain applications, a proportionate response can be to maintain a 'watching brief' with a view to making a decision once the technical and other uncertainties have been resolved.

3. Responsible Innovation and regulatory principles

Quantum technologies represent a paradigm shift with profound implications for academia, industry, and society. As we enter this new era, there is a need for a framework that encourages Responsible Innovation (RI) to align with the ethos of accountability during early-stage technology development and to serve as a compass for directing future developments towards sustainable and ethical outcomes.

In this evolving landscape, large corporations and startups play complementary roles in advancing quantum-related developments. Large corporations, with their extensive resources and experience, can lead the way in implementing RI practices, serving as exemplars for the industry, while the agility and innovative spirit of startups can guide future products in more innovative, transformative directions. Smaller companies, often driven by a culture of rapid development, bring fresh perspectives and breakthroughs to the field. Recognising these different perspectives, it is essential to support all innovators in embedding RI into their growth and development processes, ensuring that their speed and creativity harmonise with ethical standards and societal interests.

This section outlines the vital role that RI and its associated principles play in the quantum technology ecosystem. It provides an outline for organisations to manifest their social responsibility and to ensure that innovation progresses in harmony with the principles of transparency, equity, and integrity.

3.1 Responsible Innovation for quantum technologies

The need for companies to demonstrate responsibility in their actions has become increasingly well recognised in recent years and the widely adopted. International Standards Organisation (ISO) Social Responsibility Standard (ISO 26000) has defined what constitutes responsible behaviour by organisations such as commercial companies and research organisations. An organisation should:

- Be accountable for its impacts on society, the economy, and the environment.
- Show transparency in its decisions and activities that impact on society, the economy, and the environment.
- Demonstrate ethical behaviour based on the values of honesty, equity, and integrity.
- Show respect for stakeholder interests and consider and respond to them.
- Show respect for the rule of law.
- Show respect for international norms of behaviour.
- Show respect for human rights.[20]

The EU initiative on Responsible Research and Innovation (RRI) similarly includes requirements relating to: human rights, labour practices, openness and transparency, citizen and stakeholder engagement, research ethics, the environment, fair operating practices, consumer issues, and

[20] International Organization for Standardization: ISO 26000 and OECD Guidelines: Practical overview of linkages (2017). Available at: https://www.iso.org/files/live/sites/isoorg/files/store/en/PUB100418.pdf

community involvement.[21] These principles are not exclusive to quantum technologies but are essential for all industries, including those that are highly innovative. RI should be a universal consideration, not confined to any single sector. In the context of quantum technologies, we have outlined in the report how RI can be addressed to ensure that quantum innovations are aligned with global RI standards.

Likewise, most of the principles listed in Figure 3 (Annex C) can be seen as elements of responsible behaviour at the organisational level. These are general practices that all companies or organisations, including those developing quantum technologies, would be expected to apply.[22]

In this report, we concentrate on the additional RI-related behaviours that are relevant specifically to the development of quantum technologies across all TRLs. These are related to responsibility to deliver innovative quantum technology products that entail societal benefits, and to take action to eliminate any associated harms. Regulation, including standards, will play a critical role in supporting this delivery of benefits and avoiding harms.

The British Standards Institution's (BSI) Publicly Available Specification (PAS) 440 is a guide to RI that includes the social responsibility elements that would apply to all companies concentrates mainly on additional elements that will be technology specific.[23] It also emphasises the need for companies to be able to show evidence to all stakeholders that they are innovating responsibly.

It is relevant here to consider the question, 'Who needs to behave responsibly?' and much of the discussion in this report is concerned with the behaviour of commercial companies, research organisations and other innovation support organisations. In addition, governments, including in the UK, are increasingly requiring regulators, standards bodies and policymakers to take responsibility for the impact of their actions on innovative technology developments, as highlighted in the Quantum Strategy, "We will ensure that regulatory frameworks drive responsible innovation and the delivery of benefits for the UK, as well as protecting and growing the economy and the UK's quantum capabilities".[24] Today's approach to governance of innovative technologies requires a balance of responsibilities between innovators and regulators to develop an innovation ecosystem that responds best to the needs of innovative technologies while protecting expected standards of safety, quality and efficacy.[25]

3.1.1 Responsible Innovation in practice

BSI's PAS 440 RI Guide proposes the framework in Figure 2 (Annex C) as a template to be used by companies in undertaking RI in any technology area. Elements to be considered include expected benefits and risks of products or processes under the headings 'societal',

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[21] European Commission, Directorate-General for Research and Innovation, Responsible research and innovation: Europe's ability to respond to societal challenges (2014). Available at: https://op.europa.eu/en/publication-detail/-/publication/2be36f74-b490-409e-bb60-12fd438100fe

[22] For more information, see: https://www.era-learn.eu/support-for-partnerships/governance-administration-legal-base/responsible-research-innovation

[23] British Standards Institution (BSI): PAS 440, Responsible innovation – Guide (2020). Available at: https://pages.bsigroup.com/l/35972/2020-03-17/2cgcnc1?

[24] Department for Science, Innovation and Technology: National quantum strategy (2023). Available at: https://www.gov.uk/government/publications/national-quantum-strategy

[25] Andrew Bennett, The Entrepreneurs Network (TEN): Responsive Regulators, in Operation Innovation: how to make society richer, healthier and happier (2023). Available at: https://www.tenentrepreneurs.org/operation-innovation-1

'environmental', 'health-related' and 'ethical', including where these benefits and risks will mainly be experienced.[26] Information on the choice of elements to be considered under these headings can be gleaned from direct engagement with all relevant stakeholders. While direct stakeholder engagement often yields richer insights than secondary sources, small companies and similarly constrained organisations might find this difficult. Other relevant sources of information would be stakeholder websites, participation at conferences and meetings, or publications of various kinds in the public domain. However, even small entities should strive, if possible, for occasional direct interaction with stakeholders, perhaps through periodic surveys or online feedback platforms. All those with an expressed interest or concern related to the company's activities should be considered as part of the stakeholder community.

Value chain elements are also important, including the extent to which other companies involved in a product value chain at all stages of its development are able to demonstrate that they are innovating responsibly. Companies might consider implementing periodic audits or certifications for value chain business partners to ensure consistent responsible innovation practices across the board.

As for regulatory elements, compliance with existing relevant regulations is a standard operating procedure and building relationships with regulatory bodies is also good practice. Companies can also consider the nature of expected future regulatory initiatives and the extent to which they will be proportionate and adaptive to the needs of specific innovative quantum technology products. Periodic regulatory foresight, participating in industry consultations, and engaging in dialogue with policymakers can offer insights into potential future regulatory changes.

A company's Responsible Innovation Framework should be publicly available as part of its public assurance of responsible behaviour. This can be achieved by disclosing overarching principles and commitments without disclosing proprietary processes and, like any other component of a company's risk register, it should be updated regularly as the product goes through various stages of development. Companies might also consider setting up an independent review or advisory board comprising experts, stakeholders, and lay representatives to periodically review their Responsible Innovation Framework.

3.2 Regulatory principles for quantum technologies

Several sets of principles relating to quantum technologies have already been proposed (see Figure 3, Annex C). Many of these principles are related to how quantum technologies are developed and would be better described as 'objectives' or standard operating procedures and are therefore not useful as an aid to effective regulatory policymaking. Others are corporate social responsibility principles applying to good business practice in general, unrelated to the specific properties of individual technologies, and covered by the social responsibility element in RI.

The Quantum Strategy's principles (which detail government's approach to regulation, rather than principles designed to control their use) were described by many stakeholders as rather abstract or generic, with more detail needed to make them relevant to tangible governance-related outcomes. Several stakeholders we consulted questioned the compatibility of two potentially contradictory

[26] Environmental, Social, and Governance (ESG), available at: https://www.oecd.org/finance/esg-investing.htm, and other similar frameworks developed in the private sector are likely to be compatible with the PAS 440 approach.

principles, “stability" and "agility", and there was stakeholder consensus on the importance of co-designing principles. The principles proposed by the World Economic Forum (WEF), which relate solely to quantum computing, were recognised for their specificity and considerations of sustainability, but here stakeholders pointed out the absence of a principle on ethical responsibility.

In light of these discussions, the RHC has proposed four core principles for the development of quantum-related regulation to stand alongside the more general social responsibility principles which would apply to all companies, government, and regulators: **proportionality**, **adaptability**, **responsibility**, and **balance**. These principles are designed to be general enough to capture the wide range of future quantum-related applications and we reference them throughout the report to highlight how they can be achieved in practice for quantum technologies. These principles should ensure that quantum-related regulation is agile, able to evolve with changing technologies and circumstances, and meets the requirements of consumers and active citizens.

- **Proportionality**: This principle ensures that regulatory actions are appropriate to the level of risk or benefit associated with a specific quantum technology application. It aims to match the type and degree of regulatory intervention with the magnitude and nature of potential impacts, avoiding overregulation of low-risk applications while ensuring sufficient oversight for higher-risk ones.
- **Adaptability**: The quantum innovation landscape is rapidly evolving, along with its potential applications and implications. Adaptability emphasises the need for regulatory frameworks to keep pace with technological advances - a static regulatory framework will quickly become outdated and ineffective while an adaptive framework would anticipate and respond to future shifts and adjust accordingly.
- **Responsibility**: The responsibility principle as applied to companies and the process of innovation is discussed in section 3.1. The principle could also be applied to regulators themselves and their responsibility to ensure that the regulations they implement are proportionate and adaptive to the properties of quantum technologies and balanced in their implementation.
- **Balance**: This principle involves finding a fair and equitable middle ground. It focuses on striking a harmonious balance between the diverse and sometimes competing interests of different stakeholders, including commercial viability, ethical considerations, and public safety. Balance requires a nuanced approach, considering the broader societal context and ensuring that the innovative growth needed from quantum industry does not compromise security, ethics, or societal well-being.

4. Quantum regulatory pathway

Regulation is often seen as a mechanism to exclusively ensure consumer protection, however, when developed well, it can also catalyse innovation. This requires a balanced approach and is not just about legislation. The RHC approach is that 'regulation' and 'governance' are broad terms that capture legislation, standards, guidance, policy, best practices, industry or professional codes, requirements, and procedures. The combination of these actions can influence technological development, market dynamics, procurement, funding strategies and international collaboration objectives. The lack of clarity around timings, scope and shape of expected regulation can impede investment and make business planning challenging.

Sections 4 and 5 present our main conclusions on quantum regulation, along with our recommendations. These recommendations are seen as an integrated set, working together to deliver the expected benefits from future quantum developments across the spectrum of domains of application.

This section brings together insights from previous sections, culminating in specific recommendations on the overarching approach to regulating quantum technology products and processes. Insights and recommendations relevant to specific quantum technology domains will be considered in section 5.

4.1 Regulate the application not the platform technology

We proposed in section 1 that regulation should focus on applications of the technology, rather than the platform technology[27]. For instance, the more incremental quantum innovations in sensing or imaging should have tailored regulations that fit their specific use-cases and developmental stages, rather than stringent regulations designed for more transformative quantum computing-related developments. This concurs with the Digital Regulation Cooperation Forum (DRCF)'s existing 'technology neutrality' approach: the regulators do not regulate a technology as such but instead the products and services built on the technology, and DRCF "do not approach quantum technologies any differently to other emerging fields".[28]

Incorporating the RI principle ensures that any regulatory approach considers the broader societal and ethical implications of these technologies, as outlined in ISO 26000 and EU RRI standards. There may, however, be a need to ensure coordination among different quantum sectoral/product regulators, to avoid an unnecessarily fragmented regulatory landscape, and to support learning from other technology domains, such as AI (see Recommendation 2).

[27] Platform Technology: In the context of this report, this refers to a foundational technology that serves as a base upon which other applications or technologies are developed. In the context of quantum technology, a platform technology implies a set of quantum capabilities or systems that underpin a broad range of potential applications across various fields. These are not tailored to a specific end-use but provide the core technological capabilities that enable the development of specific quantum applications.

[28] Digital Regulation Cooperation Forum (DRCF), Horizon Scanning and Emerging Technologies project team: Quantum Technologies Insights Paper (2023). Available at: https://www.drcf.org.uk/publications/papers/quantum-technologies-insights-paper/_nocache

Recommendation 1: Recognising the broad range of sectors involved in developing quantum processes and products and the range of TRLs covered, quantum technology governance should focus on developing application-specific regulatory frameworks that are adaptable and proportionate to the properties of individual innovations and their stage of development. DSIT should work in collaboration with other government bodies and regulators to promote the necessary collaboration and ensure timely and effective development of domain specific regulations that are focused on specific classes of application as outlined in the following recommendations.

A) For potentially transformative innovations at early TRLs, the regulatory framework should be proportionate and flexible, and ensure that responsible innovation become expected best practice.

B) For incremental innovations at early TRLs, the focus should be on finding the most appropriate regulatory precedent that fits best with the properties of the quantum innovation.

C) For both incremental and disruptive innovations at later TRLs, the government should support the use of a range of regulatory options and choose the most appropriate domain-specific regulations on an application-by-application basis.

4.2 Governance structures

The rapid evolution of quantum technologies requires an equally agile and iterative approach to governance. As we have noted, a broad-brush regulatory approach that uniformly covers all quantum technologies is inadvisable, e.g. where there is a clear and viable existing regulatory precedent, as is the case where innovation is incremental or path-dependent (see section 5). However, coordination may still be useful: to prevent regulatory fragmentation; ensure streamlined communication among stakeholders and regulators; and share domain-specific expertise.

Governance structures are needed to foster closer collaboration between regulators, the quantum research community and policymakers. Advocating for sector-specific codes of practice, akin to suggestions made in the Ada Lovelace Institute paper,[29] and identified in the terms of reference for the National Quantum Standards Network Pilot,[30] could provide a roadmap for expanding quantum industry domains. For startups, it is important to have a signposting system to guide them through the relevant regulatory pathway, where one exists. The establishment of the Office for Quantum is a step in this direction, a dedicated institutional effort towards coherent quantum technology governance, but the quantum technology landscape could benefit from a forum to ensure collaborative regulatory efforts and the harnessing of collective expertise.

[29] Ada Lovelace Institute: Regulate to innovate - A route to regulation that reflects the ambition of the UK AI Strategy (2021). Available at: https://www.adalovelaceinstitute.org/report/regulate-innovate/

[30] For more information, see: https://www.gov.uk/government/news/new-technologies-on-show-at-quantum-showcase-as-science-minister-drives-forward-uks-25-billion-quantum-strategy#:~:text=Quantum%20Standards%20Network%20Pilot,-The%20National%20Physical&text=It%20will%20provide%20a%20focal,the%20potential%20of%20quantum%20technologies

Having a dedicated Regulatory Forum for Quantum Technologies in place can help to avoid fragmentation, facilitate collaboration and knowledge sharing, minimise duplication of work, and anticipate potential challenges, offering guidance even in the absence of legally based regulations. Regulators we engaged with noted that such forums can generate significant value, and this forum should incorporate the RI principle and those ensuring that regulatory approaches are proportionate and adaptive.

As noted previously (section 4.1), DRCF is already engaged on some quantum-related issues,[31] with the individual regulators within DRCF are exploring specific aspects of quantum technologies such as quantum sensing for healthcare. However, as quantum technologies span a wide range of domains (see section 5), there is a need for a dedicated Regulatory Forum for Quantum Technologies that can offer specialised insights across the quantum governance system.

Additionally, given that regulators are often faced with resourcing challenges, with limited access to quantum experts the forum can be a mechanism to develop and share quantum expertise. As a Regulatory Forum will inevitably have resource implications itself, regulators highlighted to us the importance of having a clear idea of what the achievable outputs should be. We have highlighted some key initial activities, and a preliminary exercise could be undertaken to look at opportunities to exploit synergies with existing forums, refine the scope, and prioritise areas of highest value. It is also important to recognise the value of investing in a forum at this stage, as in the long term it will be beneficial compared to making inappropriate regulatory decisions and subsequent effort to unpick them.

Recommendation 2: A Regulatory Forum for Quantum Technologies should be established to address short- to medium-term governance issues, supporting regulators to become quantum-ready, ensuring quantum technology regulatory-systems are appropriately integrated, and avoiding unnecessary fragmentation of quantum regulatory practices. Recognising similar initiatives, we suggest that DSIT should support regulators to establish this forum, drawing on insights from DRCF.[32] Membership should include the full spectrum of relevant regulators with the scope to expand to enable more regulators to become quantum-ready. This forum should consider input from industry representatives, the Responsible Quantum Industry Forum and other stakeholders to ensure a wide range of voices are heard. Key activities for this forum should include:

A) Anticipating and identifying gaps or areas where quantum applications interact with current regulations, or where a quantum application poses issues for regulators that span multiple regulatory agencies, building on the experience of DRCF.

B) Organising symposiums, workshops and roundtable discussions among quantum researchers, industry experts, and regulators to ensure effective information exchange and knowledge transfer.

[31] Digital Regulation Cooperation Forum (DRCF), Horizon Scanning and Emerging Technologies project team: Quantum Technologies Insights Paper (2023). Available at: https://www.drcf.org.uk/publications/papers/quantum-technologies-insights-paper/_nocache

[32] The ICO leads the AI Regulators' Working Group on AI regulatory issues, and the DRCF leads the Regulators' Round Table on digital issues.

C) Commissioning research to anticipate the potential societal, economic, and ethical impacts of quantum advances on regulation, building on, for example, existing work by the National Quantum Computing Centre (NQCC).

D) Collaborating with international counterparts to gain a global perspective on quantum governance and regulatory best practices.

4.3 Getting the timing right

Quantum technologies are a rapidly evolving field, leading to a perceived urgency to mould its regulatory landscape. The UK's current standing in the quantum area is pioneering, but in the absence of proactive dialogue and strategic governance-related initiatives, the resulting regulatory uncertainty could dampen investment and progress. The significance of timing in quantum regulation cannot be overstated and stakeholders universally agreed that it is premature to jump to legally based regulation given the nascency of most quantum technologies. There are two different factors at play here:

1. Getting the timing right regarding the proportionate governance measures required, related to the TRL of the specific technology being considered. The PAGIT framework's emphasis on TRLs is relevant, recommending that it is premature to contemplate legally based regulation before TRLs 6-7 and instead focusing on pre-regulatory standards and guidance (see Figure 1) to support industry convergence on best practice. Guidance, best practices, and soft law (pre-regulatory guidance) at TRL 4-5 in the PAGIT framework, can enable innovation to thrive while ensuring responsible development of products and processes. For technologies at TRL 6-7 or beyond, the debate should focus on whether it is necessary to introduce formal, legally based regulations, or whether safety, quality and efficacy can be maintained using existing and/or additional standards and guidelines. In the RHC's report on 'Closing the Gap', the Council also outlines relevant approaches that should be considered.

2. The more rapid the pace of development, the more rapidly adaptive the regulators will need to be in responding to changes in product development with appropriate, proportionate initiatives.

Recently in AI we have seen sudden upsurges in societal concern (stemming from the accelerated growth of transformative products) and calls for global impetus to create effective regulatory pathways to be implemented rapidly, with the EU's AI Act and the related high-profile tech industry advocacy setting a precedent.[33] Given quantum's similarities and direct links to AI, the lessons learnt from the above should be considered as a component of the future governance of quantum technologies in the UK to avoid the introduction of inappropriate, disproportionate, or non-adaptive regulations.

Foresight techniques such as horizon scanning, road mapping, scenario planning and monitoring should play a part in decision making on when and how to regulate innovative technology products and processes, aiming to anticipate future quantum-related challenges and identify potential pitfalls, barriers, and regulatory intersections. The Government Office for Science (GO-Science)

[33] Jillian Deutsch: Big Tech Wants AI Regulation — So Long as Users Bear the Brunt (2023). Available at: https://www.bloomberg.com/news/articles/2023-06-27/big-tech-companies-fight-ai-regulation-in-europe-ask-us-lawmakers-for-oversight?leadSource=uverify%20wall

published a Futures Toolkit in 2017 which covers a variety of methods including horizon scanning.[34] Here, horizon scanning, is defined as a desk research process aimed at looking for early warning signs of change in the policy and strategy environment. The Cabinet Office commissioned a review in 2013 also making some best practice recommendations for horizon scanning.[35] In addition, a nuanced approach to risk assessment is crucial. Before considering more interventionist regulatory scenarios, it is essential to thoroughly understand these risks and benefits to ensure that any regulatory actions are proportionate and do not unnecessarily inhibit technological progress. This balanced approach, as recommended in the RHC's 'Closing the Gap' report[36], is vital for maintaining a dynamic and conducive environment for innovation in the quantum sector.

Regulators benefit in such cases from a balanced and collaborative approach, involving inputs from industry, academia, and civil society. Agencies like DRCF and the National Quantum Computing Centre (NQCC) are already undertaking such forward-looking activities, and their insights would prove invaluable. The Financial Conduct Authority (FCA) has been proactive in requesting more information from firms thinking of transitioning to quantum security, whereas regulators like the Office of Communications (Ofcom) are concerned with existing sectors and where their regulation should be tweaked to accelerate competition.

However, for the UK quantum technology sector, difficulties for horizon scanning could arise due to:

- the fact that much development is abroad (and it is not clear that UK civil institutions historically have had an external focus);
- that the issues arising from quantum technology may well be specific and detailed, rather than generalisable and highly visible from a distance;
- some of the technology developments may well make a transition from defence sector development to civil application, and therefore bypass mainstream reporting.

It is therefore recommended that DSIT considers the use of horizon scanning and other foresight techniques to provide additional inputs to bodies involved with planning the UK approach to quantum regulations and standards.

Recommendation 3: DSIT should consider methods for providing foresight of regulatory requirements. This could be in collaboration with GO-Science, NQCC, the National Physical Laboratory (NPL), and the Regulatory Forum for Quantum Technologies proposed in Recommendation 2. This capability should:

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[34] Government Office for Science: The Futures Toolkit, Tools for Future Thinking and Foresight Across UK Government (2017). Available at: https://assets.publishing.service.gov.uk/media/5a821fdee5274a2e8ab579ef/futures-toolkit-edition-1.pdf

[35] Cabinet Office: Review of cross-government horizon scanning (2013). Available at: https://www.gov.uk/government/publications/review-of-cross-government-horizon-scanning

[36] Regulatory Horizons Council (RHC): Closing the gap: getting from principles to practice for innovation friendly regulation (2022). Available at: https://www.gov.uk/government/publications/closing-the-gap-getting-from-principles-to-practice-for-innovation-friendly-regulation

A) Build on existing road mapping activities to undertake horizon scanning for future regulatory requirements as part of product development support.

B) Establish a short-term focused (1-3 year) horizon scanning mechanism for quantum technology applications at or beyond the technology demonstration TRLs, and on a longer-term basis for applications at earlier TRLs.

C) Aim to be objective and realistic about the capabilities of the technology domains and be based on practical timelines to anticipate benefits and risks to coordinate proportionate regulatory initiatives.

4.4 Regulator support, training, and resources

Quantum systems, are a novel technology paradigm, are complex, and require a concerted effort to understand. Quantum regulation, as for other technologies, is about consumer and environmental protection and cultivating an ecosystem where innovation thrives without compromising security, ethical considerations, or the public interest. To do this effectively regulators and policymakers must have a basic understanding of quantum mechanics and its applications.

Expertise in quantum technologies varies across regulators and policymakers; while some have related academic and technical knowledge, others have minimal experience. Training modules and opportunities for knowledge sharing are therefore needed, including hands-on experience with quantum technologies, developed in collaboration with industry and academia. This training should also include the RI framework to instil these practices as a default mode of working.

Quantum technologies, by virtue of their foundational nature and their broad sectoral scope will require regulators, policymakers, and others in the quantum ecosystem, to be adequately resourced to facilitate smoother commercial transitions. The large anticipated economic benefits, particularly from the more transformative quantum technologies, mean this is of public interest with significant economic impact.

For regulatory bodies it is essential both to address immediate governance issues and to remain aware of future potential. This increased awareness will help in anticipating regulatory barriers and working with other relevant regulators and stakeholders to ensure that governance processes are well attuned to the special demands of quantum products and services.

It is also important that the broader public, journalists, opinion leaders, and businesses are appropriately informed of the status and potential impacts of quantum technology. Ensuring this group of stakeholders are well-informed about the technology's benefits, reassured about the availability of proportionate and adaptive governance instruments, and shielded from undue hype and misinformation, could help mitigate calls for premature and disproportionate regulation.

Recommendation 4: Appropriate quantum technology awareness training should be made available for policymakers, regulators, businesses, and the public on the capabilities, applications, and limitations of quantum technologies. This will support the development and acceptance of proportionate, timely, and adaptive regulatory systems, and improve public understanding of the regulatory challenges around quantum technologies. DSIT should keep an overview of the quality and effectiveness of training materials already being made available by the quantum community. Where necessary, DSIT should also, support relevant bodies such as the Royal Society, Royal Academy of Engineering and other professional science and engineering institutions, industries body such as UKQuantum, and NQCC to deliver further training, In addition:

A) For policymakers and regulators: a secondment programme could be set up, allowing individuals to spend time with quantum research institutions and industry partners, getting hands-on experience and understanding of quantum technologies. Specialist workshops, roundtables, and expert briefing sessions would also provide in-depth insights into the capabilities, challenges, and opportunities presented by quantum technologies.

B) For the public and businesses: awareness campaigns, including digital media, webinars, information sessions, and interactive platforms can reach a broad audience and be employed to explain the realistic capabilities of quantum technologies, the associated potential benefits and risks, and to highlight ongoing work in developing proportionate, adaptable, and timely regulation, along with responsibility in innovation.

4.5 Testbeds and sandboxes

The integration of quantum technologies into practical applications is a technical and commercial endeavour embedded within a complex ecosystem of government policies, regulatory challenges, and societal, ethical, environmental and welfare considerations. Quantum testbeds and sandboxes, incorporating the RI principle, could be powerful instruments for supporting navigation of this complex landscape. For example, the Small Business Research Initiative (SBRI) competition delivered by Innovate UK (IUK) for NQCC invited proposals for the development and delivery of prototype quantum computer testbeds. This initiative is multifaceted, exploring technological bottlenecks, enhancing the understanding of technology readiness and performance, and aiding benchmarking. These initiatives would offer regulators a controlled environment to observe and assess quantum innovations and also catalyse technological advances.

The Quantum Strategy recommends the establishment of testbeds and sandboxes to lead the way in trialling quantum technologies in the UK. Sandboxes are controlled environments that allow for the testing and development of new technologies under regulatory frameworks. However, it is equally important to ensure that these sandboxes are not isolated systems; they should be designed with clear pathways for successful innovations to transition from the sandbox environment to the broader market. This 'exit strategy' is vital, as it enables the practical application and commercialisation of technologies, ensuring that the benefits of sandbox experimentation are realised in real-world scenarios.

Some stakeholders contacted for this report were uncertain whether testbeds and sandboxes should include a regulatory element at this stage, but sections 2 and 3 of this report make the case for early exploration and understanding of the range of potential governance approaches at different TRLs to guide future regulatory decisions. An example is NQCC's quantum computing testbeds which could set a precedent for further collaborations between innovators and regulators.

Recommendation 5: The RHC supports the Office for Quantum's ambitions to establish testbeds and sandboxes that include regulatory components from their inception, to ensure proactive integration of governance insights in future regulatory decisions. Regulators and standards bodies should be involved either as core partners or interested observers (recognising there will be some cases where it is unclear whether it intersects with a regulator's remit).

The aim should be to ensure a clear understanding of potential use cases and building knowledge across the ecosystem. At late stage TRLs, regulators should play an integral role in both shaping the regulatory experimentation and assessing potential regulatory challenges. These regulatory testbeds and sandboxes should be designed with a clear focus on how quantum innovations within them can transition to the market effectively. An emerging area that could benefit from such an approach is the identification and implementation of mitigations to the security challenges posed by a cryptographically relevant quantum computer. This includes supporting industry in the adoption and transition to Post-Quantum Cryptography (PQC).

4.6 Collaboration with industry in developing standards

Quantum technologies require the establishment of new standards and the adaptation of existing standards. The National Quantum Strategy, recognising this need, outlines a commitment to work with key partners to coordinate national engagement in quantum standards development. As discussed in sections 2.3 and 4.2, standards will also be expected to play an important role in the overall governance of quantum technologies, allowing agility in the development of regulatory systems while products and processes are in early TRL stages and supporting the implementation of regulations in later stages.

As members of the UK Quantum Standards Network Pilot (QSNP), the British Standards Institution (BSI), National Physical Laboratory (NPL), and other network members will foster industry involvement in the development of standards and the emergence of a consensus. This effort should explicitly integrate the RI principle to support UK industry in the development and adoption of quantum technologies, as well as to advise the UK government on policy implementation. The aim of the QSNP to develop initial plans for industry outreach, standard development road mapping, and international engagement is a positive step forward. If implemented well this can address the fragmentation of responsibilities on quantum standards across different UK organisations.

A UK strength in the quantum sector is the collaborative spirit demonstrated by the quantum community, as seen in networks like UKQuantum, which includes private firms, and through participation in international standards bodies such as the European Telecommunications Standards Institute (ETSI). Recognising the emergent phase of quantum technology development, a voluntary, consensus-based approach to standards is appropriate. BSI and NPL guide this process with expertise in concepts like standardisation readiness, ensuring that the development of standards is appropriately aligned with the technology's maturity.

One challenge to a collaborative approach is the limited engagement of small and medium-sized enterprises (SMEs) in standards development, particularly at international levels. The entry points to standards negotiations are often expensive, and the extended duration of the process of forming international standards is not feasible for many SMEs, given the time and resources involved. Recognising this gap, we understand that NPL and BSI are exploring avenues to include more voices of SMEs.

Based on stakeholder feedback, current progress in areas such as quantum communications and post-quantum cryptography (PQC) seems particularly promising. Furthermore, the UK government could subsidise these costs as part of its Research, Development, and Innovation (RDI) investment to alleviate some of the barriers for SMEs and ensure a broader representation in these discussions. The QSNP actively outlines ambitions to explore avenues to ensure that SME voices are represented, providing them with the necessary weight when negotiating with more substantial industry entities. This approach should be balanced rather than skewed towards one specific domain e.g. quantum computing, a concern that stakeholders across several different quantum technologies have shared with other standards forums.

BSI has attempted to establish a dedicated body for discussing quantum standards, and strategic organisation will be essential to translate such discussions into actionable outcomes. These discussions are valuable for tracking international standards activities and coordinating UK representation. However, the effectiveness of these initiatives depends on the voluntary commitment of time and expertise by participants. The establishment of the QSNP, similar to the AI Standards Hub supported by DSIT, and led by NPL, is a step towards a more structured approach. It is crucial that the QSNP's nature, functions, and scope in the regulatory process are clearly defined.

Recommendation 6: The RHC welcomes the launch of the UK Quantum Standards Pilot Network as a collaborative approach to developing standards, including those to be applied to products in later stages of development including sensing, timing, and imaging.[37] This Pilot Network (and any future iterations) should also include behavioural standards, particularly responsible innovation practices. These should be embraced in early development stages to ensure effective governance of quantum products without prematurely resorting to legally based regulation. The network should work with quantum trade associations, SMEs, and multinational corporations to identify benefits and risks for the UK. The insights gained from this should inform the UK's approach to engagement with international regulatory forums.

4.7 Market creation - government as a customer

With the exponential growth of quantum technologies over the last decade, there is a role for governments to support innovation-appropriate regulation and to integrate innovative technologies into their operational matrix. The Government, by adopting RI principles, can set the tone for ethical and societal considerations in the use of quantum technologies.

The commercialisation of new technologies often faces challenges due to the initial high costs and lack of proven benefits. Thus, when a government body takes on the role of early adopter it serves

[37] For more information, see: https://www.npl.co.uk/quantum-programme/standards/network-pilot

as a confidence booster for the industry and the market, supporting the technology application and helping to develop future supply chains, potentially leading to lower costs, and creating new markets. Government as a customer can drive the development of quantum technologies through RI practices that align with public interest and ethical standards. It also helps to redefine product requirements which can translate to other markets, providing further confidence for companies to invest in product development.

Based on RHC discussion with stakeholders in Canada and the USA, the 'government as a customer' model appears to be well established in North America. An example of this model is the U.S. Department of Agriculture's (USDA) BioPreferred Program, which aims to increase the purchase and use of biobased products through mandatory purchasing requirements for federal agencies, spurring economic development, creating new jobs, and providing new markets.[38] Such initiatives communicate trust in the technology to other potential customers and stakeholders.

The Quantum Government User Group, set up as an action under the National Quantum Strategy, seeks to raise awareness across departments to explore government requirements for quantum applications, and the Quantum Catalyst Fund is exploring how to address these challenges. This Small Business Research Initiative (SBRI) competition, funded by DSIT and IUK, takes a two-pronged approach, a comprehensive desk study to understand the potential applications, followed by a demonstrator phase to test the feasibility of proposed solutions. The sectors of interest include, but are not limited to, transport, health, defence, space, and the goal of achieving net zero. This competition represents only the starting point. The UK government should move beyond exploratory phases to active adoption, ensuring that the applications and solutions developed through such competitions find a practical place in public sector operations and assisting with crossing the translation gap.

However, feedback from industry suggests a perceived hesitancy from the UK government in undertaking this early adopter role for quantum communications, despite several large-scale manufacturers already producing quantum-based products. The National Cyber Security Centre (NCSC) does not endorse the use of Quantum Key Distribution (QKD) for any government or military applications. Stakeholders in quantum communications that we engaged with perceive this stance, and a lack of guidance about readiness in this area, as a barrier to its broader acceptance and industry use, which could result in the UK falling behind as a pioneer in this space. This particular point is explored in further detail in section 5.2.

Recommendation 7: Government departments have the potential to play a pivotal role in creating markets for quantum technologies through well-structured procurement strategies. These strategies, bolstered by funding from entities like DSIT and Innovate UK, can leverage resources from the Quantum Catalyst Fund and the Quantum Government User Group.

[38] For more information, see: https://www.biopreferred.gov/BioPreferred/faces/pages/AboutBioPreferred.xhtml

A) The government should extend and enhance existing initiatives and competitions, or alternatively, develop new pathways that transition exploratory projects into actionable procurement strategies. This approach is geared towards ensuring the swift application of quantum solutions within the public sector. The procurement of these products and services should be made following a statement on responsible innovation, highlighting the core tenets of these guidelines. For quantum systems, this emphasis on responsible innovation should be extended, where practical, to all companies participating in a value chain.

B) In its role as a first adopter, the government should embed relevant regulators in projects and programmes involving quantum technology procurement. This early regulatory engagement ensures that regulatory considerations are integrated from the outset. This approach not only supports market development but also enables regulatory frameworks to evolve with procurement processes.

4.8 Translational funding

Some quantum technologies will require translational funding support, along with the other forms of innovation support described above. This section will consider how the UK government can tailor their approach to deliver optimal outcomes, including using public funding to encourage company alignment with the RI principle to ensure that funded projects contribute positively to societal and ethical objectives, and doing so without disadvantaging SMEs.

The National Quantum Technology Programme (NQTP) provides a positive route to address the gap between translating basic research funding into tangible economic growth. Stakeholders involved in investing in quantum technologies noted that there may be a tendency for some start-ups to base their business models on chasing public funding, rather than commercial sources of capital. While public funding is and will continue to be important, the real challenge for the UK lies in converting this globally recognised academic potential into market-ready applications. Solutions to this problem will include: ensuring that state funding for quantum technology development is more market-oriented; creating greater incentives for venture capital companies to be located in the UK; and boosting the transfer of technology from UK academia to the commercial sector.

The Government's commitment to investing £2.5 billion over a decade from 2024, launching numerous programmes, and establishing the Office for Quantum, reflects a clear strategic direction.[39] The RHC supports this comprehensive approach, from promoting talent development and international collaborations to revisiting regulations and protecting key quantum capabilities. Although the UK boasts the largest public and venture capital investments in Europe, this still falls well short of the investments by the USA and China and there is a need for the UK strategy to continue to be precisely and cost-effectively targeted and focused closely on outcomes.

[39] Department for Science, Innovation and Technology: National quantum strategy (2023). Available at: https://www.gov.uk/government/publications/national-quantum-strategy

Recommendation 8: DSIT, in collaboration with Innovate UK, should seek ways to ensure that UK government translational support for quantum technologies is embedded within an overall system that rewards an innovation mind-set and related expertise, including the following elements:

A) Embedding Responsible Innovation practices, including a demonstrated understanding of, and compliance strategy for, existing quantum technology regulations.

B) Assisting companies, through industry bodies such as UKQuantum and techUK, with engaging in regulatory discussions, encouraging (where required) the amendment and development of regulations that reflect the challenges faced by quantum technology innovators.

C) Dedicating resources for regulatory training by building on existing regulator and government initiatives. This should ensure SMEs and startups are well-equipped to navigate the evolving regulatory landscape in the quantum sector.

4.9 International collaboration

The UK has excellent research capabilities, strong domestic structures (the NQTP has been emulated by many countries) and is home to the largest number of quantum technology start-ups, with the greatest amount of capital investment in Europe.[40] The UK, with its reputation as an innovative regulatory system, has an opportunity to play a role on the international stage in developing standards, guidelines and regulations, forging alliances and finding common ground between various international efforts.

Stakeholders noted that if the UK fails to align with international standards this could both inhibit access by UK companies to global markets and discourage innovative companies from locating here. This calls for a dual strategy with the UK contributing to areas where it can make a significant impact while aligning with international standards where it enhances the UK's strategic interests. The UK is already involved in the work of international standards bodies, for example, through NPL's involvement in developing quantum communications standards (see section 5.2). Also, the NQCC has opportunities to test and define international measurement and benchmarking standards for quantum computers. The UK should use these platforms to advocate for its approach to quantum technology regulation, emphasising transparency, security, and Responsible Innovation. Industry should play an important role alongside government to ensure that UK companies are not disadvantaged, particularly SMEs that struggle to engage with these international bodies.

International organisations working on the development of standards include: International Organization for Standardization (ISO), International Electrotechnical Commission (IEC), International Telecommunication Union (ITU), Internet Engineering Task Force (IETF), the European Telecommunications Standards Institute (ETSI), the Institute of Electrical and

[40] Based on information from; McKinsey & Company: Quantum Technology Monitor (2023). Available at: https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/quantum%20technology%20sees%20record%20investments%20progress%20on%20talent%20gap/quantum-technology-monitor-april-2023.pdf; and DSIT internal analysis using Quantum Insider data (2023).

Electronics Engineers (IEEE), and Organisation for Economic Co-operation and Development (OECD). Imminent international initiatives seeking to galvanise these efforts include The North Atlantic Treaty Organization's (NATO) Standardization Agreement (STANAG) and the upcoming NATO quantum strategy. BSI are the UK member or have strong links with many of these bodies, including sitting on the board of ETSI. The proposed UK strategic approach should build on these links and will be needed to give support to UK experts, particularly SMEs, to channel a unified and targeted voice and to ensure that UK representation is not dependent on individual company initiatives.

Even with a more strategic and coordinated approach it will be challenging to compete with countries such as USA and China in influencing future standards and regulations. The UK should develop strategic partnerships with other nations whose interests align with ours to foster the development of 'quantum coalitions', enhancing the UK's strategic influence and allowing it to shape the direction of global quantum policy more effectively.

An example of the UK taking a leading role in driving conversations forward internationally can be seen in the work being undertaken to ensure the safe and responsible development and deployment of AI through the work of the Frontier AI Taskforce which hosted the world's first major AI Safety Summit, and the AI Safety Institute.[41] Quantum examples include the UK's involvement in the OECD Global Forum of Technologies[42] and the World Economic Forum's Quantum Economy Network,[43] and being chosen to lead ISO's new international quantum technology committee.[44]

Recommendation 9: The UK (DSIT, BSI, NPL, NQCC and regulators) should build on its strong involvement in the development of international standards and regulation, leveraging its expertise and position globally to support international harmonisation. This should be achieved by:

A) Determining and prioritising the international governance forums that best align with the UK's strategic priorities. For every governance forum, the Government (in partnership with BSI and NPL) should set clear, outcomes-based objectives for the development of global quantum standards.

B) Providing support and resource to UK experts from across the regulatory landscape (standards bodies, industry, and academia) to push for these objectives.

C) Supporting organisations such as UKQuantum and techUK to facilitate the involvement of SMEs in standards development (including in international standards bodies).

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[41] For more information, see: https://www.gov.uk/government/publications/ai-safety-institute-overview/introducing-the-ai-safety-institute

[42] For more information, see: https://www.oecd.org/digital/global-forum-on-technology/

[43] For more information, see: https://initiatives.weforum.org/quantum/home

[44] For more information, see: https://www.bsigroup.com/en-gb/insights-and-media/media-centre/press-releases/2024/january/uk-chosen-to-drive-global-standardization-around-quantum-technologies/

D) Establishing further strategic partnerships (following those already established with the US, Canada, Australia, and the Netherlands) with similarly ambitioned and sized countries. These partners should have good records of working on standards in other sectors with a transparent approach. This will ensure existing and future partnerships include focus on channelling a unified voice in international forums for a multilateral approach to standards and regulation development.

4.10 Future regulatory considerations

Commercial concentration

Commercial concentration is not an issue specific to quantum technologies. However, the anticipated exponential capabilities of quantum technologies, especially quantum computers, could in future create a strong 'first mover advantage', which then could translate into commercial monopolies engaging in anti-competitive practices. On the other hand, a choice of regulatory system that slows down or halts the development of beneficial quantum products and processes can create a first mover disadvantage. There is a delicate balance to be struck, particularly getting the timing right of any future regulatory action, as any potential anti-competitive behaviour is difficult to dismantle once established, but premature or inappropriate restrictions could stifle innovation.

While other concerns are currently of higher priority than monopolisation, this situation should be monitored to enable timely action if and when required. In their Quantum Technologies Insights Paper, DRCF regulators have highlighted that they "seek to ensure that quantum technologies develop in ways that promote open, competitive markets" and that they "will continue to monitor emergent markets for competition issues arising and can use existing competition powers to act where necessary". These current regulations include the Digital Markets, Competition and Consumers Bill (2023), the 2003 Communications Act, the 2000 Financial Services and Markets Act, and the 1998 Competition Act. This monitoring will be crucial to ensure timely implementation of these regulations, and to discover areas where challenges fall outside of these existing remits.

Export controls and supply chains

Quantum technologies will be significantly influenced by international regulations such as export controls including the International Traffic in Arms Regulations (ITAR), shaping their global trajectory and supply chain mechanisms. Navigating these export controls has been cited as a barrier to export sales by some quantum technology innovators. Some stakeholders have also noted that while navigating export controls for dual-use goods is not new, applying these controls to quantum products may present challenges.

These regulations, including the ITAR and various national and international export controls, can significantly influence the global development and supply chain of quantum technologies. For startups, understanding and complying with these regulations is critical, yet can be daunting due to their complexity and the rapid evolution of the technology. Startups must be adept at navigating these regulatory landscapes to ensure compliance, avoid legal pitfalls, and facilitate international collaboration and market access. This requires a strategic approach that balances security concerns, legal compliance, and the promotion of global technology sharing and development. Establishing partnerships with legal experts and staying informed about the changing regulatory environment are key strategies for startups to manage these challenges effectively.

Some export controls are grounded in international laws and treaties, making substantial changes challenging. However, providing detailed guidance can significantly aid quantum innovators in navigating these regulations. To assist innovators clear guidance and streamlined processes are essential for managing dual-use products. This support is crucial for startups that may be unfamiliar with the complexities of export control regulations for dual-use technologies.

Additionally, the role of supply chains in the regulatory framework is important. Sole reliance on critical components sourced from a supplier or country represents a risk to UK companies. Development of broad supply bases from many regions will limit such a risk.

Intellectual Property (IP)

Intellectual Property rights are an important aspect of fostering innovation. Over the last decade the European Patent Office has reported that quantum computing products in particular “show a higher growth rate than in all fields of technology in general”.[45]

The opportunity to file multiple patent applications can lead to 'patent thickets', where a multitude of patents around foundational technologies may hinder innovation due to the risk of inadvertent infringement. In the extreme case, this can lead to ‘patent trolling’, where 'a company hoards intellectual property without making any real products, generating most of its money from lawsuits'.[46]

A way forward could be adopting innovative IP models like Quantum Delta NL's joint IP pool. Such models allow for standardised technology transfer processes and proactive IP policies, fostering an environment that supports both individual IP protection and collaborative development. This collaborative approach is particularly relevant in quantum technologies, where advances are often the result of cumulative, cross-sector efforts.

The goal is to strike a balance between robust IP protection and fostering an ecosystem of open innovation. This balance will enable quantum technologies to advance through both individual achievements and shared research efforts.

[45] European Patent Office: Quantum Computing, Insight report (2023). Available at: https://link.epo.org/web/epo_patent_insight_report-quantum_computing_en.pdf

[46] Financial Times: Apple Accuses Qualcomm of acting as a ‘common patent troll’ (2017). Available at: https://www.ft.com/content/6b44f5f0-d519-11e7-8c9a-d9c0a5c8d5c9

5. Domain-specific regulatory requirements

Introduction

As noted in previous sections, the key to successful governance of quantum-based technologies will lie in a consolidated understanding of the technology readiness, the extent to which the technology will be incremental or disruptive/transformative to the business models of incumbent companies or sectors, and identifying for which sectors it will be most disruptive. It has also been noted that regulations should target quantum-related products and processes, rather than the technology domain[47] as a whole.

Applications of quantum technologies already nearing market readiness are likely to be those that:

1. Are least disruptive of the business models of incumbent companies.
2. That have a recognised role in an already-existing value chain; and
3. Where the regulatory system in place for products that are part of that value chain is unlikely to be challenging for the innovative quantum-related product.

Where a technology or product will be disruptive of the business model of at least one set of companies involved in a value chain, depending on the degree of disruption, there are more likely to be regulatory challenges at one or more TRLs in product development. At the extreme, where a product is so disruptive that there is no pre-existing or established value chain regulatory challenges for the technology will be at their greatest.

This section assesses the areas of quantum technology as defined by the NQTP hubs. Recognising similarities in stakeholder feedback and potential regulatory implications, quantum sensing, timing and imaging have been grouped together, followed by separate sub-sections on quantum communications, and quantum computing and simulation. Within each of these domains, there are products and processes at different levels of maturity but more of them are further advanced in the sensing, timing, and imaging domain than in quantum communications, and quantum computing is generally the least advanced. For each of these domains, this section will consider the TRLs, including the market readiness of the furthest advanced products and the extent to which these are incremental or disruptive for incumbent business models, the existing regulatory challenges highlighted by stakeholders, and the regulatory approach proposed, including the roles of principles and standards.

[47] Domain: In the context of this report, this refers to a specific area of application or a field of use within quantum technology. It denotes a specialised segment that utilises quantum technology for particular practical applications or purposes. For example, 'domain-specific quantum technologies' include quantum computing, communication, sensing, and imaging, each representing a distinct area of application with their own unique regulatory and technological requirements.

5.1 Quantum sensing, timing, and imaging

5.1.1 Technology Readiness Levels

This report groups together quantum sensing, timing, and imaging, given their commonalities from a regulatory and TRL perspective. Based on stakeholder feedback, many such devices are already at 'early deployment' TRL stages (see section 2), either market-ready or already available on the market, while others are at earlier stages. The first applications to market are likely to be examples of incremental innovation, fitting into existing value chains, and regulatory barriers will probably not be specific to quantum technologies. In such cases, conformity with existing and future standards warrants attention. There will also be examples where, although there will be no disruption of the final consumer market, manufacturers operating at intermediate points in the overall value chain will face disruption and lose their position to a more technically advanced competitor.[48]

All three domains are characterised by a small number of products that are in the vanguard and a much larger number of potential future applications that are currently at earlier TRLs and/or are likely to be more disruptive. It is important not to lose sight of the need to prepare the future regulatory environment for these more disruptive, and potentially more commercially important, later developments.

Sensing

Quantum sensors can offer a range of advantages over their traditional equivalents, potentially being more compact and efficient. Additionally, they can unlock entirely new modes of sensing previously unattainable, with the potential to measure quantities, such as magnetic, electric, or gravitational fields, with sensitivities thousands of times greater than conventional sensing technology. The potential is for applications ranging from neuroimaging to the detection of gas leaks, and more broadly applications spanning energy, geology, navigation, medical imaging, chemistry, biology, materials science, and infrastructure. As the technology develops there is clear potential for further transformative applications to emerge.

Quantum sensors that offer incremental changes compared to their classical counterparts are unlikely to require new specific regulations at this stage, although those that are more transformative in nature may need new standards and regulatory frameworks to ensure safety and accuracy. For example, data from quantum sensors should be subject to the same data protection regulations as those collected through classical technology, provided it is in the same data category, but not if it was not previously possible to collect those data. Applying the principle of responsible innovation here means ensuring that data collected, especially from vulnerable populations, is used ethically and with a primary focus on societal benefits.

To enable market creation and commercial uptake for quantum sensors, there will be a need to address regulatory approval processes and other challenges related to public perception and trust in the technology (potentially through a RI approach). Collaborative forums that bring together stakeholders, including industry experts, policymakers, and consumers, can play a role in shaping a balanced regulatory pathway. Given the rapidly changing technology landscape for these quantum technologies, the principle of adaptability will also be important.

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[48] Joyce Tait and Davied Wield: Policy support for disruptive innovation in the life sciences (2019). Available at: https://www.tandfonline.com/doi/full/10.1080/09537325.2019.1631449

Timing
Quantum timing technology offers the prospect of timing many thousands of times more precise than existing microwave atomic clocks. Future applications of quantum timing technology are likely to range from super high-speed broadband to high-frequency trading in financial markets.[49] For instance, in communications, quantum timing can synchronise data transmissions with precision, ensuring seamless data flow without overlaps or loss. However, integrating this with existing telecommunication infrastructures presents interoperability challenges. Similarly, in financial markets, while high-frequency trading can benefit from microsecond advantages offered by quantum timing, the ethical implications and potential market distortions of such precise trading mechanisms need thorough consideration; potential advantages for firms with access to this technology can create an uneven playing field and new systemic risks. Regulators must weigh the potential economic benefits against such risks.

Regulatory and interoperability issues therefore include ensuring the compatibility of quantum timing devices with existing infrastructures, along with ensuring fairness in financial markets and other responsibility-related issues. Involving policymakers, industry stakeholders and the public in the governance of timing devices will establish a conducive environment for the uptake and responsible use of quantum timing devices.

Imaging
Quantum imaging devices include ultra-high sensitivity cameras, with enhanced resolution and performance in turbid media (for example cloudy, underwater, or underground environments), and the futuristic-sounding ability to look around corners. Application areas for such products include security, healthcare (microscopy for tumour detection and optical cameras that could replace MRI), transport (incident detection and improved traffic flow), and climate change (cameras to pinpoint the location and severity of methane and other gas leaks). In healthcare, quantum imaging could provide non-invasive diagnostics, with potentially significant implications for patient care.[50] Integrating such devices into current medical workflows, ensuring their safe operation, and developing trust in quantum products among both professionals and the public will require adaptation in regulatory oversight.

As these quantum imaging technologies move towards commercial viability, a balanced and proportionate regulatory framework will be needed, including regulations and/or standards to ensure interoperability within sectors like healthcare and transport, and responsible innovation criteria to facilitate their ethical deployment. The potential for misuse of quantum imaging, especially in sectors like security surveillance with the ability to capture detailed images without directly illuminating subjects, creates significant privacy concerns. Ethical considerations and robust privacy protections should be at the forefront of regulatory discussions. Existing technologies such as Terahertz body scanners are an example illustrating how similar challenges have been overcome, with the technology now in widespread use, and thus presenting a pathway for quantum imaging.

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[49] For more information, see: https://www.birmingham.ac.uk/research/heroes/quantum-technologies.aspx

[50] Muhammad Shams and others, The Quantum-Medical Nexus: Understanding the Impact of Quantum Technologies on Healthcare (2023). Available at: https://pubmed.ncbi.nlm.nih.gov/38046499/

5.1.2 Market readiness

While some devices in these domains are already on the market, developing use cases and facilitating market uptake has been a challenge due to difficulty in demonstrating efficacy and building confidence in the products, along with high initial costs. NPL can play a role in addressing some of these challenges by independently testing and validating products.

Sensing: Quantum sensing technologies have numerous potential benefits, including gravity sensors to conduct underground geophysical surveys for major infrastructure projects,[51] and the ability to pinpoint methane and other gas leaks to help to meet net zero goals. Demonstrating the efficacy of these products could support industry in pursuing significant environmental and economic benefits, as well as developing a market for quantum sensing products.

Timing: As highlighted in the UK's 2023 National Risk Register, Position, Navigation and Timing (PNT) services are critical components of UK infrastructure and, to mitigate the impact of failure in a Global Navigation Satellite System, quantum technologies could offer reliable alternative timing sources.[52] Government policies and regulations can play a significant role in the uptake of such products.

The UK has established the National Timing Centre,[53] and one of the UK's missions states that "By 2030, quantum navigation systems, including clocks, will be deployed on aircraft, providing next-generation accuracy for resilience that is independent of satellite signals".[54] Additionally, aligning with the UK government's 10-point plan, there are considerations for legislative options to set minimum PNT requirements for Critical National Infrastructure sectors.[55] This along with softer regulatory initiatives like standards and best practice could also support innovation in quantum timing towards this aim.

Imaging: Regarding security and surveillance, quantum imaging devices can potentially see through obfuscating conditions, such as fog, smoke, or even in complete darkness.[56] These technologies could pose ethical challenges, and there is a need for policies ensuring they do not infringe on privacy rights, requiring the establishment of clear ethical guidelines on usage, developed through collaboration between industry, academia, and government, to ensure the benefits can be fully realised in a responsible manner.

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[51] Examples highlighting the need for such surveys include the electrification of the Great Western Route, where unexpected ground conditions contributed to severe delays and increased costs: https://www.nao.org.uk/wp-content/uploads/2016/11/Modernising-the-Great-Western-railway.pdf

[52] Cabinet Office: National Risk Register 2023 (2023). Available at: https://www.gov.uk/government/publications/national-risk-register-2023

[53] For more information, see: https://www.gov.uk/government/news/worlds-first-timing-centre-to-protect-uk-from-risk-of-satellite-failure

[54] Department for Science, Innovation and Technology: National Quantum Strategy Missions (2023). Available at: https://www.gov.uk/government/publications/national-quantum-strategy/national-quantum-strategy-missions

[55] For more information, see: https://www.gov.uk/government/news/critical-services-to-be-better-protected-from-satellite-data-disruptions-through-new-position-navigation-and-timing-framework

[56] House of Commons: Science and Technology Committee, Oral evidence: Quantum technologies (2018). Available at: https://committees.parliament.uk/oralevidence/8183/pdf/

5.1.3 Existing regulatory challenges

Lack of standards was seen by some stakeholders as a problem, particularly in the early stages of development of a technology, where clarity and consistency can significantly affect market trust. It is also important to ensure that standards are relevant and appropriate for the specific product under consideration, avoiding the temptation to create broad standards covering a range of product types. Magnetometers and gravitometers were seen as areas in need of standards-based assurance, along with mirroring processes for fibre-optic communications and micro-electromechanical systems sensor technology.[57] The USA and Japan are leading in these domains and are pioneering the development of future standards.

Measurement standards are also needed for quantum sensing, timing, and imaging products and it is important to ensure that they incorporate responsible innovation and adaptability to accommodating future technology advances. Other issues relate to measurement of the properties of the quantum products themselves and the use of quantum products to measure specific parameters. These questions are being explored by the UK Quantum Metrology Institute, which brings together industry engineers, academic researchers and NPL scientists.

One of the UK's quantum missions is that "By 2030, every NHS Trust will benefit from quantum-sensing enabled solutions".[58] A challenge is that health applications are a domain with substantial pre-existing regulatory barriers for quantum-related innovations.[59] Innovators claimed that introducing a novel technology under the NHS regulatory frameworks is a difficult task. Across all health technologies, including quantum related innovations, companies are choosing to develop new products in Canada and the USA, for clinical trials and to market the product. A McKinsey report noted that "Medical applications might need to overcome major regulatory hurdles, causing healthcare agencies to delay implementation. Navigation applications, though also highly regulated, would face a lower regulatory bar that could contribute to more rapid uptake, for example within the automotive industry."[60]

The CE mark indicates that a product complies with EU safety, health and environmental standards and can legally be sold to markets in the EU and EEA. The UK government announced its intention to extend recognition of CE marking to Great Britain indefinitely.[61] Some quantum companies are finding CE marking requirements challenging. For example, stakeholders highlighted that some CE related tests designed for current technologies, require subjecting quantum products to high radiation fields which would destroy the sensitivity of the device. There are also issues related to equipment insurance, where liability is linked to operation by third parties, or where products undergo destructive testing. Further work is required to ensure conformity

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[57] Kai Bongs, Simon Bennett and Anke Lohmann: Quantum sensors will start a revolution - if we deploy them right (2023). Available at: https://www.nature.com/articles/d41586-023-01663-0

[58] Department for Science, Innovation and Technology: National Quantum Strategy Missions (2023). Available at: https://www.gov.uk/government/publications/national-quantum-strategy/national-quantum-strategy-missions

[59] Regulatory Horizons Council: The regulation of Artificial Intelligence as a Medical Device (2022). Available at: https://www.gov.uk/government/publications/regulatory-horizons-council-the-regulation-of-artificial-intelligence-as-a-medical-device

[60] McKinsey & Company: Shaping the long race in quantum communication and quantum sensing (2021). Available at: https://www.mckinsey.com/industries/industrials-and-electronics/our-insights/shaping-the-long-race-in-quantum-communication-and-quantum-sensing

[61] Department for Business and Trade: CE marking guidance (2023). Available at: https://www.gov.uk/guidance/ce-marking

assessment bodies are prepared to introduce certification systems that meet the needs of quantum products.

Quantum innovators also highlighted the need for regulations to evolve in step with the technology, recalibrating UK regulations governing quantum sensors, timing, and imaging, and aligning them with the specifications of major trading partners. One problematic example is NPL's quantum-based clock systems which are produced in limited quantities with each iteration being a modest improvement on the previous one. They are anticipated to have a global presence but lack a supporting regulatory framework, and funds are being spent on CE marking requirements for components that will become obsolete. This is a new type of regulatory challenge specific to this one example and it underscores the requirement for a more streamlined approach in some scenarios.

Recommendation 10: DSIT should support tailoring of the policy environment, including funding for regulatory initiatives, towards the accelerated application, development, and adoption of more mature quantum sensing, timing, and imaging applications, while also preparing for products with more disruptive potential so that regulations evolve in step with the technology. Regulatory policies and funding should target the following:

A) Where it can be done without unnecessarily inhibiting the innovation potential of products or creating risks to people or the environment, build on existing domain-specific regulatory systems for equivalent products rather than developing new regulatory systems. For example, DSIT and Innovate UK can facilitate a dialogue between quantum technology developers and relevant regulatory bodies, such as the Medicines and Healthcare products Regulatory Agency (MHRA) for healthcare applications, to adapt existing frameworks.

B) Prioritise the development and adaptation of standards and guidance, rather than legally based regulations, covering interoperability, data protection, compatibility with existing infrastructures and workflows, and validation and testing of products (through e.g. NPL), including ensuring conformity assessment bodies are prepared to certify quantum products.

C) For stakeholder engagement, where possible build on existing collaborative forums involving regulators, standards bodies, industry policy makers, public interest groups and consumers to contribute to shaping balanced and technology-enabling regulatory pathways. The recently launched UK Quantum Standards Pilot Network could undertake this role, developing or modifying existing standards, benchmarking, and measurement protocols to harness the unique capabilities of quantum sensors, timing, and imaging.

D) All regulatory initiatives, and their implementation by companies, should conform with responsible innovation approaches, for example to ensure that data are used ethically and for societal and environmental benefits.

5.2 Quantum communications

Current concerns about quantum communications focus mainly on issues related to cryptography and cybersecurity. It will be important also to maintain vigilance and have early awareness of unanticipated benefits and hazards emerging as the technology progresses and to have a plan in place for rapid, concerted action to maintain effective governance.

5.2.1 Technology Readiness Levels

Based on stakeholder feedback, many quantum communication devices already range from technology demonstration to early deployment. Quantum-secured routers and quantum-enhanced data centres are promising changes in how we transmit and secure information and, when integrated into mainstream services, could reduce eavesdropping risks, protecting against cyber-espionage. The progress of applications such as quantum-secured banking transactions indicates their compatibility with existing value chains, suggesting less disruptive innovation than others that are in earlier stages of development. This more rapid progress may pave the way for highly secure financial exchanges to become the norm, limiting vulnerabilities associated with classical encryption techniques.

Quantum Key Distribution (QKD) is already relatively mature and networks using it have been established and trialled in the UK, and elsewhere such as China, and the USA. BT and Toshiba currently operate the world's first commercial quantum secure metro network in a trial in London[62], with HSBC and EY using the network for various applications including financial transactions, secure video communications, and one-time pad encryption, indicating industry's recognition of QKD's potential.

Another reason to develop QKD is that current encryption methods will be vulnerable to decryption by quantum computers at some point in the future. QKD should not be confused with PQC, which is discussed later in this section and in the quantum computing section 5.3.

Beyond QKD, the field of quantum communications encompasses a range of innovative applications. Quantum Random Number Generators (QRNGs) represent a mature technology, with commercial products already available, and QRNGs could be useful for cryptographic processes.

The potential applications of quantum communication extend beyond secure key distribution. There is ongoing exploration into how quantum technologies can be integrated into existing communication infrastructures to enhance efficiency and security. However, the extent and practicality of these applications in areas other than secure keys or scaling quantum computing are still subjects of active research and debate.

Networked quantum sensing, involving distributed quantum sensors interconnected by quantum communications, presents novel opportunities for data gathering and processing. One of the UK's quantum missions states: "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".[63]

It is important to acknowledge that quantum security is an evolving field. As such, it is crucial to maintain continuous vigilance and development to counteract emerging or existing vulnerabilities.

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[62] For more information, see: https://newsroom.bt.com/bt-and-toshiba-to-build-worlds-first-commercial-quantum-secured-metro-network-across-london/

[63] Department for Science, Innovation and Technology: National Quantum Strategy Missions (2023). Available at: https://www.gov.uk/government/publications/national-quantum-strategy/national-quantum-strategy-missions

Standards for QKD are being developed but there is a need for further development and standardisation for it and quantum communication in general. It is essential to align these advances with global standards to ensure interoperability and widespread adoption.

5.2.2 Market readiness

Several quantum communication device prototypes and early commercial systems, such as QKD systems and Quantum Random Number Generators (QRNGs), have been successfully demonstrated and some are commercially available. For instance: QKD has been used to securely transmit keys to help secure voting data in real-time during government elections in a few countries. China has launched the Micius satellite, dedicated to quantum communication experiments, in 2024 the European Space Agency will launch the Eagle-1 with similar capabilities, and in 2024 the UK will launch the Satellite Platform for Optical Quantum Communications to demonstrate in-orbit quantum key distribution from space to the Hub Optical Ground Station[64].

QKD-based services use trusted-nodes (secure locations common in current national-scale high-security networks) to support long-distance communications. Entanglement-based quantum communications (work on which is planned for the next NQTP hub phase), however, require new solutions, like quantum repeaters, to ensure secure communication over extended ranges. Their successful development and integration are pivotal for the commercial scalability of quantum communication systems, ensuring consistent and reliable quantum data transmission across global networks.

Integrating quantum communication devices into the existing digital infrastructure is a challenge as, unlike classical devices using well-established protocols and standards, quantum systems often require specialised hardware, like single-photon detectors and sources. This divergence can potentially slow down the translation process and underscores the importance of parallel development in quantum-compatible infrastructure; it is also important to demonstrate they are secure when integrated into a system. While quantum communication offers security advantages, the cost of implementation is high and needs to be justified by its benefits, so there may be a strategic case for deploying today the operational infrastructure that will support future technologies and services.

It is also essential to consider the ongoing debate around the value and security implications of QKD and Post-Quantum Cryptography (PQC). While QKD provides a secure method of transmitting keys, its reliance on hardware-based security and current infrastructural limitations poses challenges. On the other hand, PQC aims to secure communications against the potential threat posed by quantum computers by replacing existing algorithms with those not vulnerable to attack by quantum computers. It is important to clarify that the choice between QKD and PQC is not binary. The integration of QKD with PQC can offer a hybrid solution that builds on the strengths of both technologies. PQC can provide essential authentication for QKD systems, enhancing the overall security framework. This approach can allow for flexibility depending on user needs but does require additional hardware, which may increase costs.

Moreover, QKD offers provable security, assuming that the hardware operates within the specified parameters. Nonetheless, discrepancies between these assumptions and practical hardware

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[64] For more information, see: https://www.quantumcommshub.net/research-community/about-the-hub/phase-2/work-package-5/the-hubs-spoqc-mission/

implementation represent a security concern. This highlights the necessity for ongoing research and development to mitigate such vulnerabilities.

Equally important is the acknowledgment that while PQC is designed to withstand known quantum attacks, there is currently no security proof guaranteeing resistance against all potential quantum computing advances. This uncertainty underscores the importance of continued vigilance and innovation in cryptographic practices to safeguard against future threats.

5.2.3 Existing regulatory challenges

A current regulatory challenge is in QKD, where work is ongoing internationally to develop standards for interoperability. Stakeholders cited the European Telecommunications Standards Institute (ETSI), as an example where progress is being made, and the International Organization for Standardization (ISO) is developing QKD security standards, integrated within the ISO/IEC 15408 framework.

Ensuring network interoperability is essential before network operators can embrace the technology. QKD security is based on assumptions about hardware performance, and discrepancies between anticipated and actual performance can present vulnerabilities. Device imperfections and potential vulnerabilities are active research areas. The UK's quantum mission 2, that "by 2035, the UK will have deployed the world's most advanced quantum network at scale" supports "further testing, demonstration, and evaluation of near-term commercial opportunities in quantum communications".[65] Stakeholders are keen to explore QKD's potential while acknowledging the complementary role of PQC in securing communications against quantum threats. This recognises the longer-term value for quantum communications, and it is important this includes developing methodologies to test and certify QKD hardware to facilitate adoption.

Although QKD technology is maturing, the UK National Cyber Security Centre (NCSC) 'does not endorse the use of QKD for any government or military applications and cautions against sole reliance on QKD for business-critical networks, especially in Critical National Infrastructure sectors'.[66] The NCSC has highlighted what it sees as security risks associated with QKD, and advocates PQC as the best mitigation to the threat.[67] The USA's National Institute of Standards and Technology (NIST), collaborating with the National Security Agency (NSA) holds similar views.

Stakeholders highlighted the value and opportunity QKD presents and have a desire for the NCSC to reconsider and soften its position on it. Stakeholders recognise that QKD must be supported by an authentication mechanism, and therefore also do not advocate sole reliance[68].

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65 Department for Science, Innovation and Technology: National Quantum Strategy Missions (2023). Available at: https://www.gov.uk/government/publications/national-quantum-strategy/national-quantum-strategy-missions

66 National Cyber Security Centre: Quantum security technologies (2020). Available at: https://www.ncsc.gov.uk/whitepaper/quantum-security-technologies

67 National Cyber Security Centre: Next steps in preparing for post-quantum cryptography (2023). Available at: https://www.ncsc.gov.uk/whitepaper/next-steps-preparing-for-post-quantum-cryptography

68 Quantum Communications Hub: Community Response to the NCSC 2020 Quantum Security Technologies White Paper (2020). Available at: https://www.quantumcommshub.net/news/community-response-to-the-ncsc-2020-quantum-security-technologies-white-paper/

The approach taken by Germany's Federal Office for Information Security,[69] which is supporting projects on QKD and actively working on related security issues, was given as an example of a more positive approach, suggesting work is required to build trust for sensitive applications. While the NCSC's current position is unlikely to change significantly, it is noted that NCSC continues to monitor developments. Also of relevance is the NCSC's move towards a Principles Based Assurance (PBA) approach, offering a universal, risk-based methodology. This approach could guide the development and assessment of quantum communication technologies, ensuring they meet security principles while fostering innovation.

The launch of the Quantum Standards Pilot Network is a welcome step towards developing standardised interfaces for quantum communication systems, promoting interoperability, and scaling up the adoption of quantum technologies. This pilot, aligning with the NCSC's PBA approach, could play a pivotal role in coordinating the national engagement in quantum standards development and addressing the fragmentation of responsibilities across different organisations.

Rather than self-certification, the intricacies of quantum communication demand a more robust validation approach. The ongoing debate around the efficacy and security of QKD and PQC technologies plays a crucial role in shaping these validation approaches, as they determine the standards and principles against which quantum communication technologies are assessed. Certification bodies in Germany and Japan are emerging as potential avenues, but the scale of the task will require an industry-led approach as part of the process.

The initiation of a BSI panel for standards in quantum technologies, in collaboration with NPL, offers an avenue for a more coordinated approach across the UK's quantum sector;[70] but it is not clear whether this will treat quantum communications as a separate product category (as we would recommend, see section 4.1) or attempt to cover the overall quantum platform. Some stakeholders, across quantum communications and other technologies, have noted that other forums with similar intentions can become focused towards quantum computing. While this is also important, there should be specific discussions on quantum communications standards.

Stakeholders also raised concerns about the Online Safety Act (which received Royal Assent in October 2023), who understand it to require the ability to provide access to encryption offered by Internet Service Providers (ISPs). Their view is that UK providers would not be able to offer end-to-end security to their users and may have implications for these ISPs in the UK, and also for the providers of secure communications technologies. For quantum technologies, providing access in this way works against the scientific principles behind the technology. While there are valid reasons for the introduction of the Act, there are concerns around how the powers it grants to Ofcom will be implemented. Further discussion between legislators and the quantum communications industry is needed.

[69] Federal Office for Information Security, Germany: Quantum Cryptography (2022). Available at: https://www.bsi.bund.de/EN/Themen/Unternehmen-und-Organisationen/Informationen-und-Empfehlungen/Quantentechnologien-und-Post-Quanten-Kryptografie/Quantenkryptografie/quantenkryptografie_node.html

[70] For more information, see: https://www.bsigroup.com/en-GB/insights-and-media/media-centre/press-releases/2024/january/uk-chosen-to-drive-global-standardization-around-quantum-technologies/

Recommendation 11: The UK Quantum Standards Pilot Network should contribute to a globally aligned approach to standardisation for quantum communications, including particularly interoperability standards, and methods for testing and verification. A specific area of focus could include data security in quantum communications.

Recommendation 12: Given the NCSC's concerns about the security benefits of QKD and the potential value and demand seen by the industry, DSIT, the NCSC, and other quantum technology stakeholders should collaborate to ensure the UK's leadership in QKD research and development is not inadvertently eroded. To achieve this:

A) DSIT should encourage an expansion of the ongoing dialogue between the NCSC and quantum technology stakeholders to continue regularly reviewing this position, ensuring alignment with the evolving technological and security landscapes.

B) As the technology develops, BSI and NPL, in partnership with key stakeholders and the NCSC, should continue to develop standards and assurance needed for QKD to be a recognised trusted technology. DSIT should help facilitate this coordination in line with responsible innovation practices.

Recommendation 13: DSIT should facilitate dialogue between government and quantum communications experts to ensure that the Online Safety Act does not inadvertently restrict quantum product development. This could include, if possible, providing clear guidelines to ensure compliance with the Act without undermining quantum security principles.

5.3 Quantum computing

5.3.1 Technology Readiness Levels

Some quantum computing applications are in the technology demonstration phase, with products already available commercially, in what is termed the Noisy Intermediate-Scale Quantum (NISQ) era, where processors are being developed but are not yet capable of universal fault-tolerance. Hybrid computers, combining elements of classical and quantum technologies, are on the market now, or are likely to be in the near term, and they provide an example of where classical and quantum functionalities might coexist. Although some commercial systems are already available and show signs of outperforming classical computers on artificial problems, quantum systems with ‘advantage’ or ‘practicality’ (solving real-world problems that would be classically intractable) are still in the development stage, with predicted market readiness in 5 to 20 years.

Future algorithms in quantum computers promise exponential increases in speed for certain tasks. For example, in drug discovery, quantum computers could simulate the quantum behaviour of molecules, a task impractical for classical machines, and the financial services sector is currently exploring quantum solutions for tasks like portfolio optimisation and market forecasting. There is speculation that automotive, chemicals, materials, and healthcare sectors all could significantly benefit from quantum computing advances.[71]

A significant challenge for cryptographic security is the potential capability of using large, general-purpose quantum computers to solve the mathematical problems that underpin existing methods of Public Key Cryptography (PKC). To protect against this requires transitioning algorithms to PQC, which are thought to be resistant to classical and quantum computational attacks. Timelines for further development and subsequent implementation and transition to these algorithms, coupled with 'harvest now, decrypt later' narratives, make this an area requiring close attention.[72]

The fact that quantum optimisation and other quantum computing-related innovations offer transformative solutions that disproportionately benefit early adopters is unavoidable, but it will require careful policy and governance attention to maintain the desired open, competitive innovation ecosystem. While the impact on cryptography has been anticipated and mitigations are being developed, as discussed below, the exact nature and extent of quantum computing's future capabilities are not yet fully understood. As such, governance decisions should be agile and adaptive, with regulators keeping an open mind and monitoring developments closely. QuTech Delft recommends that governance of quantum computing should champion public values such as security, safety, resilience, trust, privacy, equal access, and net neutrality,[73] the corporate social responsibility elements of the RI principle.

5.3.2 Market readiness

Companies have unveiled quantum systems that, while catering today primarily for research communities, hint at broader commercial applications in future. UK companies, such as ORCA Computing and Oxford Quantum Circuits, have already sold quantum computers and are working directly with customers in government and industry to explore real-world applications. Similarly, quantum software companies are exploring quantum algorithms for drug discovery or for solving complex optimisation problems.

Quantum computing is subject to considerable publicity. This can lead individuals either to overestimate quantum capabilities, viewing them as panaceas for all computational challenges, or to misunderstand their true potential and future use cases. This gap in understanding creates a need for better public and stakeholder education. An example of this is IBM's "Qiskit" platform which offers tools for quantum research and also provides educational resources that aim to demystify quantum computing.[74]

5.3.3 Existing regulatory challenges

Most of the existing regulatory challenges identified in relation to quantum computing relate to the vulnerabilities of existing cryptographic systems, as noted above for quantum communication, including the widely used RSA algorithm. Potential adversaries, adopting the practice of "harvest

[71] McKinsey Digital: McKinsey Technology Trends Outlook 2023 (2023): Available at: https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/the-top-trends-in-tech#tech-talent-dynamics

[72] National Cyber Security Centre: Next steps in preparing for post-quantum cryptography (2023). Available at: https://www.ncsc.gov.uk/whitepaper/next-steps-preparing-for-post-quantum-cryptography

[73] For more information, see: https://www.tudelft.nl/over-tu-delft/strategie/vision-teams/quantum-internet/impact-governance/governance

[74] For more information, see: https://qiskit.org/

now, decrypt later", could store encrypted data today, while planning to use quantum machines to decrypt it in future, emphasising the need to start preparing for a migration to PQC.[75] This transition must be carefully planned and managed; the establishment of the ETSI standards and working groups are steps in the right direction.

In the US, NIST has been proactive in laying the groundwork for PQC, developing standardised algorithms as part of an international endeavour.[76] Passed in 2022, the US Quantum Computing Cybersecurity Preparedness Act encourages “federal government agencies to adopt technology that will protect against quantum computing attacks”.[77] While this could be seen as a model for the UK to follow, careful consideration is needed to factor in both immediate concerns and long-term implications.

As quantum technologies evolve, there is a need for clarified taxonomies, for example distinguishing between a photonic device and a quantum device, definitions that can shape industry norms, regulatory protocols, and investment strategies. Misclassifications or misrepresentations can potentially skew industry investments or mislead stakeholders, underscoring the importance of global endeavours, like the ones by ISO/IEC, which aim to develop a coherent quantum vocabulary.

Concerns around competition and commercial monopolisation leading to anti-competitive behaviour (see section 4.10) are particularly relevant to quantum computing, given anticipated first-mover advantages. Organisations like the Competition and Markets Authority (CMA), responsible for preventing anti-competitive practices, need to be aware of how advances in quantum technology can reshape market dynamics. While the initial specifications of early machines might seem limited, the sheer magnitude of some problems can grant substantial advantages to early adopters of quantum technology, an issue linked to concerns around ensuring fair and equitable access. These complexities and costs mean that access to quantum computers may well be through technology giants. Such dominance could restrict access, stifle innovation and raise ethical and economic issues. Open-source quantum initiatives and public-private partnerships will therefore be important in democratising access to quantum resources.

As quantum computers are scaled up there will be a need to ensure that they remain and become more energy-efficient and current trajectories suggest quantum computers might not align with the relevant UN Sustainable Development Goals (SDGs), although arguments to the contrary are also made.[78] Sustainability constraints will not necessarily inhibit innovation, but they spotlight the need for Life Cycle Analysis (LCA) in charting the future trajectory of quantum technologies, particularly computers.

Concurrently, quantum systems, especially those involving AI (which also meets similar challenges), could lead to outputs that are difficult or even impossible to explain, with decisions

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[75] It is worth noting that PQC is a classical approach in response to quantum computers, rather than a quantum approach itself (such as QKD).

[76] For more information, see: https://www.nist.gov/news-events/news/2022/07/nist-announces-first-four-quantum-resistant-cryptographic-algorithms

[77] Congress, United States of America: Quantum Computing Cybersecurity Preparedness Act (2022). Available at: https://www.hsgac.senate.gov/wp-content/uploads/imo/media/doc/Quantum%20Computing%20Cybersecurity%20Preparedness%20Act.pdf

[78] techUK: Could Quantum Computing hold the key to sustainability? (2021). Available at: https://www.techuk.org/resource/could-quantum-computing-hold-the-key-to-sustainability.html

based on probabilistic quantum algorithms. This could have profound consequences, for example where quantum machine learning algorithms are making healthcare recommendations. Without a clear understanding of how these algorithms arrive at their conclusions, developing trust in them creates challenges for the development of regulations and for increasing uptake. To mitigate this, there is a growing emphasis on the development of 'explainable AI' (XAI) systems that aim to make the results of complex algorithms more understandable to humans. In the quantum realm, integrating XAI principles could help to make quantum machine learning more transparent and trustworthy. Another approach could be implementing oversight mechanisms where critical decisions made by quantum algorithms are reviewed or confirmed by human experts, especially in sensitive fields like healthcare. Establishing these practices can help in developing a regulatory framework that ensures the reliability and safety of quantum machine learning while maintaining public trust and facilitating wider adoption.

Even taking account of the uncertainty surrounding the development of quantum computing, it is reasonable to expect many transformative innovations are likely to emerge over the next 5 – 20 years. The nature and power of these future innovations will depend on how well we manage the governance of today's early steps along the quantum innovation trajectory, emphasising the degree of responsibility faced by regulators, standards bodies and policymakers.

Recommendation 14: Quantum computing and related applications are potentially the most transformative quantum-related developments, with the most significant economic, societal and environmental impacts. This is where adoption of our proportionate, adaptive, balanced, and responsible principles will be most important (section 3.2), at this stage requiring a regulatory framework based on standards, guidance and responsible innovation practices, linked to vigilant oversight of future technology and market developments.

A) It is important to avoid premature, legally based regulation for quantum computing, instead relying on standards and guidance until there is more clarity on potential benefits and harms. DSIT, in partnership with BSI, NQCC, NPL and industry, should consider what types of standardisations are most appropriate in the near-term to set the standards, nationally and internationally, for quantum computing.

B) Recognising the nascency of quantum computing, DSIT should work with industry to establish responsible innovation practices within its regulatory frameworks (as described in section 3.1.1) and include specific components for quantum computing and cryptography, to mitigate current and future risks and to foster public trust in the technology.

Annex

Annex A: Methodology

The RHC followed the following process to develop recommendations:

1. A scoping process to decide the areas of focus within quantum technologies that would add the most value. This was developed and refined in consultation with the DSIT quantum policy team, now referred to as the Office for Quantum, and other close stakeholders such as the Digital Regulation Cooperation Forum (DRCF) and Innovate UK.

2. As part of our evidence gathering phase, extensive stakeholder engagement took place through interviews, roundtables, and an online survey. These included regulators, academics, government, innovation and research organisations, and commercial, industry and international partners and bodies. A full list can be found in Annex E.

3. Alongside stakeholder engagement, evidence was gathered through desk research on sources regarding quantum specifically and also on cross-cutting innovation-friendly regulation. Particular thanks go to the Imperial Policy Forum team, who conducted a review on the RHC's behalf into the existing landscape of quantum regulations both in the UK and internationally.

4. Further stakeholder engagement was conducted after drafting the initial version of the report to test findings and recommendations, with recommendations further developed in an iterative process following input from key stakeholders.

Annex B: Terminology and definitions

Quantum technologies: "devices and systems which rely on quantum mechanics to provide capabilities that 'classical' machines cannot".[79]

Quantum communications: "the transmission of information, utilising the properties of quantum mechanics, specifically superposition, entanglement, single photon technology or the use of conjugate variable technologies; the use of a communication network (quantum or otherwise) to distribute quantum states or quantum state information; or the establishment of cryptographic keys or the generation of provably random numbers using a quantum physical process".[80]

Quantum computing: "the simulation or realisation of systems that utilise certain properties of quantum mechanics, in particular superposition or entanglement, to acquire, encode, manipulate or process information, run algorithms or perform operations or measurements on data, including: algorithms, applications, software, error correction, noise reduction and operating systems that enable the functionality of the system; the hosting or provision of third-party access of a quantum information processing, computing or simulation cloud-based service".[81]

Quantum imaging: "utilising the phase or amplitude properties of quantum mechanics, specifically superposition, entanglement or the use of sub-Poissonian sources or detectors of photons, to create images of objects".[82]

Quantum sensing: "utilising the phase properties of quantum mechanics, specifically measurements of atoms or ions or atomic spin systems, to determine a property or rate of change in the property of an object, or the effect of an object on a measurable quantity".[83]

Quantum timing: "utilising the phase properties of quantum mechanics, specifically measurements of atoms or ions or atomic gases, and the application of associated hardware including stable frequency mixers, optical or microwave sources, crystal oscillators and frequency combs, to provide a timing or synchronisation signal, or frequency reference".[84]

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[79] Department for Science, Innovation and Technology: The UK Science and Technology Framework (2023). Available at: https://www.gov.uk/government/publications/uk-science-and-technology-framework

[80] Cabinet Office: National Security and Investment (NSI) Act 2021 (2021). Available at: https://www.legislation.gov.uk/ukpga/2021/25/pdfs/ukpga_20210025_en.pdf

[81] See reference 71.

[82] See reference 71.

[83] See reference 71.

[84] See reference 71.

Annex C: Diagrams and tables

Figure 2: *BSI PAS 440 Responsible Innovation Framework*[85]

1.ID#	2.Elements of RI– identify positive and negative outcomes of the innovation(s) (see 7.3)	3.Record the reasons for inclusion of the element in the baseline assessment (see 7.3) and note any changes to elements since the previous iteration of the RIF (see 8.2)	4.Identify (see 7.4) and engage with (see 8.3) stakeholders	5.Take action (see 7.5 and 8.4)
1.x	Societal elements (benefits)			
2.x	Societal elements (risks)			
3.x	Environmental elements (benefits)			
4.x	Environmental elements (risks)			
5.x	Health-related elements (benefits)			
6.x	Health-related elements (risks)			
7.x	Value chain elements (RI behaviour by other significant actors)			
8.x	Regulatory elements			

Figure 3: *Examples of existing 'principles' suggested by publications for quantum regulation (and some relevant examples that were not specifically designed for quantum).*

Source	'Principles'
UK's National Quantum Strategy, DSIT, March 2023[86]	• **Stable**, coherent, and predictable • **Agile** enough to move quickly with technological development • **Simple** to understand and **inexpensive** to implement • Where possible, **co-designed** with industry • Focussed on **innovation** and industry-needs • Champion the **transparent** and **ethical** use of quantum technologies.
Quantum Computing Governance Principles, World Economic Forum, Jan 2022[87]	• **Common good:** capabilities harnessed to ensure benefits for humanity. • **Accountability:** ensure human accountability in design, uses and outcomes. • **Inclusiveness:** a broad and diverse range of stakeholder perspectives are engaged in meaningful dialogue. • **Equitability:** quantum computers are equitable by design.

[85] British Standards Institution (BSI): PAS 440, Responsible innovation – Guide (2020). Available at: https://pages.bsigroup.com/l/35972/2020-03-17/2cgcnc1

[86] Department for Science, Innovation and Technology: National quantum strategy (2023). Available at: https://www.gov.uk/government/publications/national-quantum-strategy

[87] World Economic Forum: Quantum Computing Governance Principles (2022). Available at: https://www.weforum.org/reports/quantum-computing-governance-principles/

	• **Non-maleficence:** quantum computing used in a safe, ethical, and responsible manner.
10 Principles for Responsible Quantum Innovation, Kop et al, 2023[88]	• **Information Security**: Make information security an integral part of QT. • **Dual Use**: Proactively anticipate the malicious use of quantum applications. • **Quantum Race**: Seek international collaboration based on shared values. • **Quantum Gap**: Consider our planet as the sociotechnical environment in which QT should function. • **Intellectual Property**: Incentivise Innovation while being as open as possible and as closed as necessary. • **Inclusion**: Pursue diverse R&D communities in terms of disciplines and people. • **Societal relevance**: Link quantum R&D explicitly to desirable societal goals. • **Complementary Innovation**: Actively stimulate sustainable, cross-disciplinary innovation. • **Responsibility**: Create an ecosystem to learn about the possible uses and consequences of QT applications. • **Education and Dialogue**: Facilitate dialogues with stakeholders to better envision the future of QT.
A pro-innovation approach to AI regulation, DSIT and Office for AI, March 2023[89]	• **Safety**, security, and robustness • Appropriate **transparency** and **explainability** • **Fairness** • **Accountability** and governance • **Contestability** and redress
Closing the gap: getting from principles to practice for innovation friendly regulation, RHC, June 2022[90]	• Be **proportionate** and **balance** potential benefits and risks. • Integrate **ethical** considerations and outputs from public and relevant stakeholder dialogue. • Take account of **commercial considerations** and the need to attract investment. • Include **alternatives forms** of regulation. • Get the **timing** right. • Cultivate a culture of **openness** and a **growth** mindset.

[88] Mauritz Kop and others: 10 Principles for Responsible Quantum Innovation (2023). Available at: https://law.stanford.edu/publications/10-principles-for-responsible-quantum-innovation/

[89] Department for Science, Innovation and Technology: A pro-innovation approach to AI regulation (2023). Available at: https://www.gov.uk/government/publications/ai-regulation-a-pro-innovation-approach/white-paper

[90] Regulatory Horizons Council: Closing the gap: getting from principles to practice for innovation friendly regulation (2022). Available at: https://www.gov.uk/government/publications/closing-the-gap-getting-from-principles-to-practice-for-innovation-friendly-regulation

Annex D: International comparisons

One of the UK's National Quantum Strategy goals is to 'Create a national and international regulatory framework that supports innovation and the ethical use of quantum technologies and protects UK capabilities and national security,' which this review intends to assist in informing. As such, it has been important to review the current approaches being taken by certain countries on standards and regulation for quantum technologies. This allows us to highlight important areas and methods for collaboration and learn lessons on how regulation can be conducive (or a barrier) to creating a flourishing market for quantum technologies.

International regulatory comparisons

Along with the UK, numerous countries have now published their national quantum strategies, including the US, Canada, China, Japan, India, Russia, Australia, the Netherlands, and Denmark, among others. These have varying degrees of focus on regulation, standards, and responsible innovation. Each country's strategy reflects its unique priorities and resources, indicating a wide spectrum of regulatory maturity and emphasis on quantum technology.

US: The US have recently signed into law several acts that relate to quantum technologies. The CHIPS and Science Act (2022) aims to strengthen manufacturing and supply chains, invest in research and development and the workforce of the future, and authorises critical standards work and engagement, to maintain the US a leader in industries including quantum technology. The Quantum Computing Cybersecurity Preparedness Act (2022) looks at the transition of executive agencies' IT systems to post-quantum cryptography (PQC). It gives priority to federal agencies' purchases of and transitions to post-quantum cryptographic IT systems, with the goal of safeguarding through advancement of postquantum cryptography. This approach underscores a deliberate pivot towards fostering a secure technological future, acknowledging the potential of quantum technologies to disrupt existing cybersecurity paradigms.

The US National Standards Strategy 2023 seeks to maintain and increase representation and influence on international standards, specifically highlighting quantum technologies as an area of focus. This strategic positioning is key to shaping the future global quantum ecosystem and ensuring that the US maintains a leadership role in defining the standards that will underpin quantum technologies. NIST already have work ongoing on PQC standardised algorithms. Furthermore, a 2020 presidential order requires US national aviation authorities to have alternative sources of time signals, independent of global navigation satellite systems timings by 2025, which supports quantum timing innovation. This illustrates the US's proactive measures to bolster resilience against potential vulnerabilities in critical infrastructure. Finally, NIST and the NSA have taken a similar stance to the NCSC on Quantum Key Distribution (QKD).[91] This stance on QKD was explored in more detail in section 5.2.

European Union: In 2020, the European Quantum Flagship published a Strategic Research Agenda, which highlighted the importance of standardisation. ETSI and CEN-CENELEC have ongoing areas of development for standardisation of quantum technologies. However, it is crucial

[91] National Security Agency: Quantum Computing and Post-Quantum Cryptography FAQs (2021). Available at: https://media.defense.gov/2021/Aug/04/2002821837/-1/-1/1/Quantum_FAQs_20210804.PDF

that these efforts align closely with industry needs and innovation trends to ensure that standards enable rather than hinder the commercial deployment of quantum technologies.

The European Commission’s Rolling Plan for ICT standardisation of Quantum Technologies (2023) requests several actions regarding identifying which standards are needed for which applications through a gap analysis and developing a roadmap. The roadmap may prioritise the development of flexible, robust standards that can adapt to the rapidly evolving quantum technology landscape.

In 2020, the EU’s Cybersecurity Strategy for the Digital Decade includes quantum computation and communications as priorities, aiming for quantum resilient encryption protocols for communications, similar to the US. These initiatives reflect an integrated approach to cybersecurity, considering the future implications of quantum technologies. The EU has also focused on protecting supply chains in the semiconductor industry, which the quantum industry relies heavily on (regardless of the hardware platform); the European Chips Act 2023 gives recommendations and enforces mechanisms to members states to avoid supply chain disruptions.

The Netherlands: The Netherlands have established the Quantum Delta NL Foundation (QDNL), which has the goal to accelerate the quantum technology developments in the Netherlands, by implementing the National Quantum Agenda. This localised focus on development and SME integration is critical, ensuring that the quantum revolution benefits a broad spectrum of the economy. The Quantum Delta NL SME programme has been designed to connect 125 high-tech, multidisciplinary Dutch SMEs with the arenas of quantum technology where they are needed most. They also highlight that as the quantum economy grows, it is important to have a monitoring system in place to anticipate future developments – and to signal potential dependencies early on.

Canada: Canada’s National Strategy has a focus on standardisation, particularly internationally: “Canada needs to take a leading role in the development of mutually advantageous international standards to facilitate collaborative research and enable future opportunities for Canadian industry”, with the suggestion the Social Sciences and Humanities Research Council (SSHRC) could fund studies on the societal and ethical considerations of quantum technologies, and Canada could contribute its perspective on this. This emphasis on ethics and society underscores the multifaceted impact of quantum technologies and the need for an inclusive approach to their governance.

The Standards Council of Canada will support standardisation, including “the development of policies and regulations for integrating and adopting quantum applications in ways that benefit Canadian business and society”, and highlighted the need to ensure representation internationally to achieve this. It is imperative for the UK to similarly engage in these international forums to ensure its national interests are protected and advanced, highlighted in Recommendation 9. Canada has also highlighted the important of using standardised PQC as critical in securing government systems and data.

Australia: The Australian National Strategy highlights ‘standards and frameworks that support national interests’ as a key theme, with the aim that the Australian government will “be an active participant in global standards-setting bodies to promote the development of standards…. and ensure Australia’s regulatory frameworks foster quantum-related research, support investment in quantum companies and support exports while protecting Australia’s national interests.” They seek a regulatory environment that “provides strong protections, ensures fair competition, supports national interests, and promotes integrity in the market”. This proactive engagement in international standards-setting could serve as an example for the UK to follow, particularly in balancing the promotion of national interests with global collaboration.

Denmark: In 2020, the Danish Standardisation Foundation established a Danish committee on quantum standardisation to secure Danish influence on the European work. The UK could benefit from a similar approach, ensuring that its standards development is not only domestically beneficial but also carries weight in European forums.

South Korea: South Korea is in the "Applications" stage (2025-2030) of its strategic planning for Quantum Science and Technology R&D (proving the feasibility of quantum applications and creating successful case studies). The UK can draw valuable insights from South Korea's application-focused strategy, which emphasises real-world deployment and market readiness. South Korea introduced the Act on the Promotion of Quantum Information and Communication Technology Development and Industrialisation, which includes Quantum Key Distribution (QKD). The Act aims to establish a roadmap for the development of quantum technologies, including quantum computers, communications, cryptography, and measurement. It also sets a timeline for the adoption of quantum solutions, calling for the implementation of quantum cryptography for government networks by 2020 and all commercial networks by 2025, positioning South Korea as an early adopter. The UK should observe and, where appropriate, learn from South Korea's legislative measures to support its quantum industry, particularly in terms of integrating quantum technologies into existing infrastructures and markets.

These international efforts provide valuable lessons and models for the UK. By examining the successes and challenges of other nations, the UK can refine its approach to support and regulate its growing quantum industry. Furthermore, the UK's active participation in international standard-setting and policymaking will be essential to secure its place as a global leader in quantum technology.

International public and private funding comparisons

The UK is currently in a strong position across quantum technologies, ranking highly across quantum computing, PQC, communications, sensors.[92] While the UK does not have the foremost world-leading quantum computing companies, it does have companies that are strategically important in the value chain that can deliver value for the economy. While diversity is important, it can come at the expense of strategic focus and scaling of certain companies. Some other countries have chosen to focus their public investment on more near-term quantum technologies, such as sensing, due to their proximity to commercialisation compared to the more transformative but less developed technologies. If the UK decides to follow this approach, it will need to balance its portfolio, ensuring that it continues to invest in transformative technologies while also capitalising on those closer to market readiness.

Furthermore, international counterparts have a marked difference in approach and scale of funding, with more proactive strategies and initiatives, such as DAPRA (which is discussed in more detail the following section). Some examples of funding and initiatives are given below.

[92] Department for Science, Innovation and Technology: National Quantum Strategy, Additional Evidence (2023). Available at: https://assets.publishing.service.gov.uk/media/6572db4433b7f20012b720b7/national-quantum-strategy-additional-evidence-annex.pdf

US: Government funding: “The National Quantum Initiative Act authorized up to US$1.275B in spending across the Department of Energy, the National Science Foundation, and the National Institute of Standards and Technology. According to the White House OSTP, in the 2020 financial year, US$579M in funding for Quantum Information Science research was enacted by the federal government.”[93] This substantial investment illustrates the US government's commitment to securing a leading position in the quantum landscape.

EU: The European High Performance Computing Joint Undertaking (EuroHPC JU) initiative’s total funding sums up to €7 billion for 2021-2027.[94] It aims to create a network of supercomputers under a new infrastructure, including quantum capabilities. The EU's commitment to integrating quantum technologies into its supercomputing infrastructure demonstrates a forward-thinking approach that aims to bolster its scientific computing capabilities.

Netherlands: The Netherlands have established the Quantum Delta NL Foundation (QDNL), part of which includes the SME Programme. This has a budget of €5 million per year available in the form of grants, intended for R&D projects geared towards developing products and services that serve the quantum technology roadmaps. This initiative reflects an inclusive approach, ensuring smaller innovators have the opportunity to contribute to and benefit from the quantum ecosystem. This will allow SMEs to play a role in the quantum technology roadmaps at the national and European level. The QDNL Participations €15M fund provides “the bridge between the grant-giving phase of quantum research and the 'patient capital' phase of venture investment”, transforming technical ideas into commercialised companies. They also have ‘Infinity’, which seeks to unify and revolutionise the European quantum startup ecosystem.

Singapore: Singapore's Quantum Engineering Programme (QEP) is using a practical approach to boost their quantum capabilities. They have launched the National Quantum Computing Hub and the National Quantum Fabless Foundry, but a standout is the National Quantum-Safe Network. Acting as a "living lab", it gives organisations a chance to experiment with quantum-safe communication technologies like QKD in a real-world environment. This hands-on approach can accelerate the learning curve and could serve as a model for other nations, including the UK, to promote a practical understanding of quantum technologies among stakeholders.

Israel: The Israeli government has made substantial public investments in quantum technology, most notably through its National Quantum Initiative. Launched in late 2019, this five-year initiative is backed by a budget of 1.25 billion shekels (approximately $400 million). The initiative's funding was further bolstered by Israel’s economic stimulus program during the COVID-19 pandemic, which allocated an additional $60 million for the construction of the country’s first quantum computer. This significant financial commitment underscores the Government's dedication to advancing quantum technology within the nation. Despite joining the quantum computing race later than some, Israel has attracted significant foreign investment and is expected to carve out its own niche in the field within the next five to six years.

[93] Johnny Kung and Muriam Fancy, CIFAR: A Quantum Revolution, Report on Global Policies for Quantum Technology (2021). Available at: https://cifar.ca/wp-content/uploads/2021/05/QuantumReport-EN-May2021.pdf

[94] For more information, see: https://eurohpc-ju.europa.eu/index_en

Annex E: Acknowledgements

The RHC engaged with the following stakeholders to obtain their views on regulating quantum technology applications. Particular thanks go to the four UK National Quantum Technologies Programme (NQTP) hubs, techUK, EY, and UKQuantum for convening stakeholders for our roundtables and to the Imperial College London's Policy Forum for their assistance and expertise.

Regulators

- Digital Regulation Cooperation Forum (DRCF) comprising;
    - Competition and Markets Authority (CMA);
    - Financial Conduct Authority (FCA)
    - Information Commissioner's Office (ICO); and
    - Office of Communications (Ofcom)

Government offices and departments

- Defence Intelligence (DI), Ministry of Defence (MOD)
- Defence Science and Technology Laboratory (DSTL)
- Department for Science, Innovation and Technology (DSIT)
- National Cyber Security Centre (NCSC)
- National Physical Laboratory (NPL)
- Office for Quantum (DSIT)

Innovation and research organisations

- Innovate UK (IUK)
- Knowledge Transfer Network (KTN)
- National Quantum Computing Centre (UKRI NQCC)
- QuantIC – The UK Quantum Technology Hub in Quantum Enhanced Imaging - University of Glasgow
- Quantum Communications Hub – University of York
- UK National Hub in Quantum Computing and Simulation – University of Oxford
- UK Quantum Technology Sensors and Timing Hub – University of Birmingham
- University of Oxford's Responsible Technology Institute

Commercial and industry

- Anchored In
- Arqit
- BAE Systems
- British Standards Institution (BSI)
- British Telecoms (BT)
- Cambridge Consultants
- Capgemini
- Cerca Magnetics
- Dwave
- Ethicqual
- EY
- IBM

- Intel
- Kets
- Microsoft
- Nu Quantum
- Oxford Ionics
- Phasecraft
- QLM
- Qruise
- Quantum Dice
- Quantum Exponential
- Quix Quantum BV
- RiverLane
- techUK
- Secqai
- Toshiba
- UKQuantum

International partners, bodies, and academics

- Canada – Innovation, Science and Economic Development Canada
- Denmark – Ministry of Foreign Affairs of Denmark, Danish Business Authority
- European Telecommunications Standards Institute (ETSI)
- Imperial College London: Centre for Quantum Engineering, Science and Technology (QuEST), and Imperial Policy Forum – including Elizabeth Pasatembou, Dimitrie Cielecki, Michael Ho and Kuan-Cheng Louis Chen
- Mauritz Kop – Founder and Executive Director of the Stanford Centre for Responsible Quantum Technology
- US – National Institute of Standards and Technology (NIST)