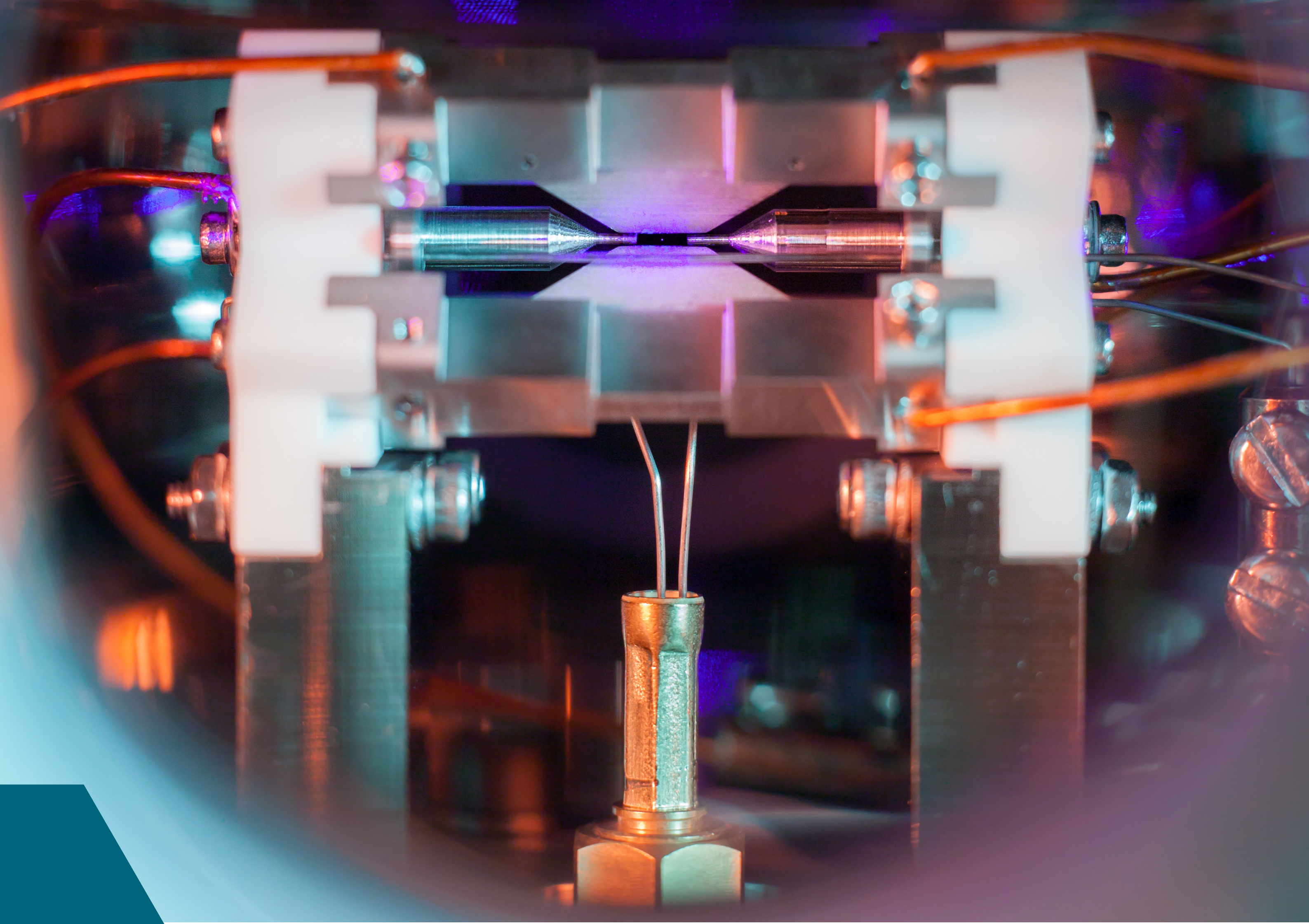

ADOPTION OF QUANTUM TECHNOLOGIES AND BUSINESS MODEL INNOVATION

WHITE PAPER

UNIVERSITY OF CAMBRIDGE
Department of Engineering

Quantum Computing & Simulation Hub

IfM MANAGEMENT TECHNOLOGY POLICY

Published by the Institute for Manufacturing, University of Cambridge.

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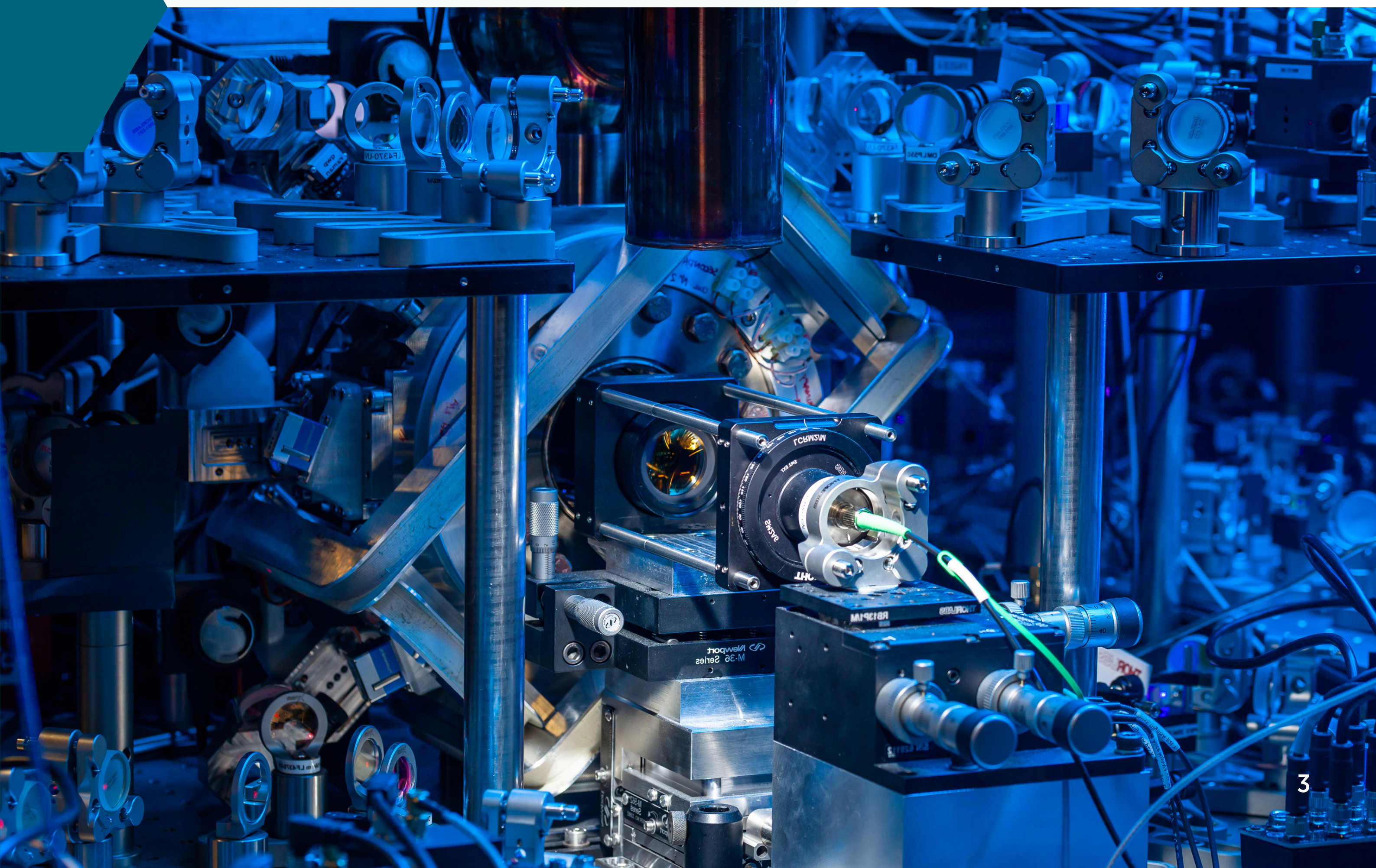


FOREWORD

The QCS Hub (and its predecessor, the NQIT) has been advancing quantum computing technologies since 2014, with a mission to address critical research challenges and to support the programme goal of making the UK "quantum-ready".

We are very pleased to have been able to collaborate with the Institute for Manufacturing (IfM) at Cambridge University Engineering Department in their thorough and extensive investigation into the emerging UK ecosystem. This report contains substantive recommendations worthy of serious consideration, and we are pleased to have played a part in its delivery.

Dominic O'Brien
QCS Hub Director
Professor of Engineering Science
University of Oxford

Productivity is the engine that drives economic growth. The UK and other major economies have experienced a significant slowdown in economic growth despite the prevalence of digital technologies. A significant number of research studies have attempted to better understand this "productivity puzzle". However, many of these studies have tended to focus on past technological adoption or current challenges in firms adopting digital technologies to improve performance. One of the major areas where we lack understanding is how firms and policymakers need to prepare to adopt technologies that are emerging from research in science and engineering but which are only likely to be adopted in the future. We believe that quantum technologies are suitable for such a study.

Quantum technologies promise major benefits to society but have yet to be fully ready for commercial deployment. We are very pleased to have worked jointly with the QCS Hub on this research. Our study aims to better understand the enablers and barriers of business model innovation in order to accelerate quantum technology adoption. We hope our findings and recommendations will help to develop the framework needed to ensure that we get the timely benefits of quantum technologies through productivity improvement and economic growth.

Chander Velu
Professor of Innovation and Economics
University of Cambridge

November 2022

EXECUTIVE SUMMARY

Quantum technologies are rapidly advancing from scientific propositions to commercial realities. The UK National Quantum Technologies Programme (NQTP) has successfully advanced quantum science and technology to a point of maturity where commercialisation and business model design are increasingly becoming a major topic among policymakers and managers in industry (EY, 2022). Quantum technology (QT) offers potential new applications in computing and simulation, communications, sensing, imaging and timing. However, the route to commercialising QT is still highly uncertain and risky, which presents challenges for firms adopting the technology, innovating their business model and delivering the potential benefits to consumers and society.

The aim with this White Paper is to explore the enablers and barriers to the adoption and commercialisation of QT in the UK. To this end, we conducted 61 interviews with various stakeholders in the UK quantum landscape, such as senior managers of large and established firms, CEOs and founders of start-ups, investors, government representatives, consultants and academics. In addition, we held three roundtable discussions in Cambridge, Oxford and London to better understand the adoption and commercialisation challenges of QT.

The insights from the interviews, roundtable discussions and continuous dialogue with the relevant stakeholders enabled us to identify the key strengths of the UK QT landscape and the challenges around the adoption and commercialisation of quantum computers. Based on the findings from the study, we propose several recommendations to strengthen UK QT adoption and commercialisation efforts.

Key Strengths of the UK QT Landscape

The UK is among the first nations to invest in quantum technology through a national quantum programme, which gives it a first-mover advantage in QT development. We identified several key strengths of the UK QT landscape. First, the UK is considered to be the leader in quantum science and engineering. Second, it has effective funding programmes (e.g. Innovate UK) to support the development of QT. Third, the UK has a high-quality talent pool in quantum science and engineering and a knowledgeable workforce with a more general background in maths, physics and computer science that can be reskilled to be quantum-ready. Fourth, the UK has a considerable venture capital (VC) and business angel community to fund quantum start-ups in early-stage funding. Lastly, the UK has a vibrant start-up community with over forty start-ups spun out directly or indirectly through the UK NQTP.

Adoption and Commercialisation Challenges

Despite the key strengths, we identified several challenges that could hinder the adoption and commercialisation of quantum technology in the UK. Those challenges revolve around market demand and adoption, supply and ecosystem, regulation and policy, funding and skills, as follows:

1. An inability to build a credible business case and uncertain demand because of changing policies and the lack of government role as a buyer.
2. Inadequate incentives for enabling technology providers (e.g. photonic firms) to get more involved in quantum technologies, an absence of technological standards and a lack of systems integrators affecting the supply-side ecosystem development.
3. Uncertainty around the longevity of government support for NQTP, the perceived lack of clarity around the role of NQCC, emerging geopolitical issues and the protection of intellectual property (IP).
4. Insufficient funding schemes to support commercialisation and manufacturing capabilities and a lack of private-sector funding to help scale up homegrown start-ups.
5. Shortages of available quantum-related talent and skills and domain experts with an understanding of QT.

Recommendations for the Way Forward

Based on the findings on the strengths and challenges for quantum technology development in the UK, we propose six recommendations to strengthen QT adoption and commercialisation efforts, in order to benefit society and deliver economic growth:

1. Initiating *mission-driven* funding calls as an addition to the UK NQTP, involving a combination of key stakeholders across the end-to-end of the value chain, with a focus on using QT to solve industry-wide and/or societal challenges for the public benefit.
2. Forming a forum of systems integrators in the UK.
3. Introducing a strategic initiative that brings together quantum computing and quantum communications (network) for better synergy.
4. Developing IP policies to maintain broader accessibility, while allowing for commercialisation.
5. Preparing scale-up capabilities in both technology and manufacturing.
6. Creating training programmes with shorter timescales that increase quantum literacy and skills.

Overall, the UK is in a strong position to translate its advances in quantum science and engineering into increased productivity and economic growth. In doing so, the nation needs to strengthen its efforts to address the adoption and commercialisation challenges of QT.

1. INTRODUCTION

Almost a decade ago the UK entered a global endeavour to industrialise quantum technology (QT). The UK has committed more than £1 billion over ten years to a coordinated programme in QT under the National Quantum Technologies Programme (NQTP). The NQTP has been successful in advancing quantum science and engineering and has put the UK at the forefront of technology development. QT offers potential new applications in computing and simulation, communications, sensing, imaging and timing (Knight and Walmsley, 2019). However, the adoption of QT is proving to be a challenge given its transformative and disruptive nature. Firms attempting to innovate with QT are facing a combination of high technological and market uncertainties, which can discourage them from investing in QT and innovating their business models. Therefore, investigating the enablers and barriers for firms adopting QT is essential in order to influence commercialisation and the market trajectory in a way that will benefit UK productivity and economic growth.

The aim with this White Paper is to present the enablers and barriers of business model innovation to the adoption and commercialisation of QT in the UK. This paper is a result of qualitative research based on a collaboration between the Institute for Manufacturing (IfM) at the University of Cambridge and the Quantum Computing and Simulation (QCS) Hub. It draws on 61 semi-structured interviews and 3 roundtable discussions with various stakeholders in the UK quantum landscape, including academics, industry (incumbent and start-up firms), investors and consultants.

We highlight the key strengths of the current QT landscape in the UK. We also identify several key challenges around demand and adoption, supply and ecosystem, regulation and policy, funding and skills that could hinder the adoption and commercialisation of QT in the UK. Moreover, we propose six recommendations to strengthen QT adoption and commercialisation efforts, including: (1) initiating mission-driven funding calls; (2) building a forum of system integration; (3) introducing a strategic initiative that brings together quantum computing and quantum communications; (4) developing intellectual properties policies; (5) advancing scale-up capabilities; and (6) creating shorter-timescale training programmes.

We hope that the findings and recommendations will open a dialogue with various stakeholders in order to develop a more refined agenda for both research and practice on the commercialisation and business model innovation of QT.

2. THE EMERGENCE OF THE UK NATIONAL QUANTUM PROGRAMME

The background of the UK national programme is best introduced by quoting from the 2019 paper "UK national quantum technology programme" by Sir Peter Knight and Prof. Ian Walmsley:

> *A prerequisite for a large-scale enhancement in UK government support for quantum technology depended on demonstrated strengths of UK quantum science, identified by international review. This had been undertaken during the first decade of the 21st century, focusing on UK sector share of highly cited papers and identification of how lively the field was and the UK position world-wide. Once this had become a priority area for the UK research councils (and especially EPSRC), it was necessary to engage with the UK political leadership. Ministerial briefings (and especially of the then UK Science Minister David Willets) were critically important. The next stage was to convince Her Majesty's Treasury (the UK government finance ministry) of the economic advantage that could accrue from substantial investment in the area. The timing for all this was opportune: the UK community had identified quantum as an emerging technology just as the government was launching its Technology Strategy. That programme sought to develop eight key technology sectors within the UK, to which were added quantum technology and "the Internet of Things". The opportunity was seized to add quantum to this list with a focussed, ambitious and transformative vision.*
>
> *Driven by the efforts of a number of individuals, the UK government announced the National Quantum Technologies Programme (NQTP) in 2013 in order to take quantum information science in the UK toward a quantum technology that would provide new, world-leading information processing technology and seed a tech sector that would open new business opportunities and create economic opportunity for the UK. Community meetings and an open call for delivery mechanisms allowed a start at scale a year after the initial announcement.*

Against this background, the NQTP was established in 2014 by a group of government departments and agencies (EPSRC, KTN, Innovate UK, Dstl, NPL, BEIS, GCHQ), with the intention of making the UK a global leader in the development and commercialisation of these technologies. Building on the UK's strong base of research and enabling technology industry, the NQTP's achievements to date have been enabled by the coherent approach, involving a network of diverse organisations.

These include all UK universities with strong research groups relevant to the field and organised through four technology hubs, each with an application focus area and a sizeable number of industrial partners. Universities are also engaged through several skills hubs, a Quantum City outreach programme and several university/industry prosperity partnerships and the QT for Fundamental Physics Programme. The UK NQTP engages with the UK's national labs NPL and the new National Quantum Computing

Centre (NQCC) and with industry through its expansive Innovate UK Quantum Commercialisation Challenge Programme, the latter engaging with 141 businesses, in addition to RTO's and universities across 139 industry-led innovation projects.

Through an intricate network of formal and personal relationships and events, the UK NQTP brings together policymakers, academia, research organisations, businesses in all parts of the value chain, investors, entrepreneurs and international partners. Throughout this report, we have focused on the quantum computing elements of the programme, but many of the findings are relevant more widely in the NQTP programme.

Quantum Computing – What is it and What Can it Do?

Quantum computing takes advantage of the laws of quantum mechanics to provide fundamentally new ways of processing information. The two properties of quantum mechanics (superposition and entanglement) may allow quantum computers to solve problems that are deemed intractable with today's digital/classical computers. While a classical computer uses binary bits that can only depict either a "0" or "1", quantum computers use *qubits* that can depict a "0", "1", or any combination thereof (superposition). Therefore, the computation capacity of a quantum computer grows exponentially, since n number of qubits can represent 2^n bits of information. Moreover, entanglement makes it possible for qubits to work together and represent multiple combinations of values simultaneously. Hence, quantum computers could solve complex computational problems exponentially faster than classical computers.

Quantum computers are in a relatively early stage of development. Researchers and engineers are still experimenting with different technologies to develop a full-scale quantum computer (e.g. superconducting, trapped ions, photonics and silicon, among others). Nevertheless, they are sufficiently advanced for firms to explore applications and associated algorithms that address complex business problems that are technically and economically impossible to solve using classical computers. There are several problems where a quantum computer could potentially surpass the capabilities of classical computing, including factoring large numbers, optimising complex systems, simulating nature (e.g. molecules and fluids) and pattern analysis. These problems are at the heart of many business and commercial operations and quantum computing's problem-solving capabilities, therefore, could dramatically redefine competitive advantage and transform business models and value chains that revolutionise entire industries.

3. MOTIVATION AND CONCEPTUAL FRAMEWORK

Productivity growth has slowed down in major economies over the last decade despite the prevalence of digital technologies (Total Economy Database, 2022). Economists often call this the *productivity paradox*. In particular, the UK has experienced an acute productivity slowdown compared to other major economies. There are many explanations for the productivity paradox, such as the financial crisis still affecting the real economy, the lack of measurement of free goods in the digital economy, the dispersion among firms where large firms are doing better than smaller ones, and the skills mismatch. Although all of these are possible explanations, there could be another reason for the productivity paradox, which is that firms might be adopting digital technologies and improving processes rather than reinventing their business models.[1]

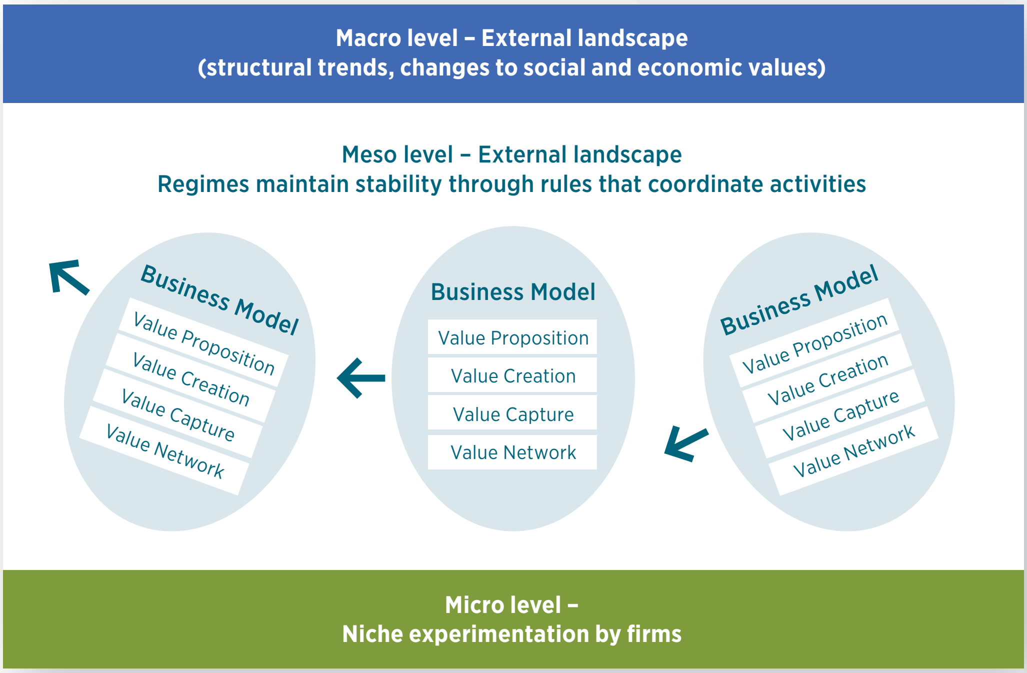
Business model innovation (BMI) has been shown to be a major source of productivity improvement following the adoption of new technologies (Wannakrairoj & Velu, 2021). For example, electric motors were invented to replace steam engines around the 1870s. The electric motors were initially used just to replace steam engines with the two-floor system and pullies were kept intact. There was no improvement in productivity for over three decades until the factories were reorganised with multiple motors and better lighting, with specialist engine providers serving the factories (David, 1990). This initial sluggish growth in productivity was repeated with digital computers and could recur with the adoption of QT. Therefore, investigating the challenges faced by firms in innovating their business models following the adoption of QT is essential in the delivery of societal benefits and stimulating economic growth.

Challenges of Technology Transitions (Micro-, Meso- and Macro-level Alignment)

Quantum technology (QT) has the potential to transform our society through technology transitions. Technology transitions occur when a technological breakthrough replaces an existing technological regime across the micro, meso and macro levels (Figure 1) (Geels, 2002). The micro level is where niche experiments are conducted, typically by start-ups. The meso level is where larger/incumbent firms try to maintain stability in the rules of exchange and the institutions in order to coordinate activities. Finally, the macro level is where there is a certain structural trend that encapsulates the social and economic forces of change.

[1] Business model (BM) is a complex system that defines the customer value proposition, the means to create the value, the network of partners needed, and the approach to capture the value for the firm. The business model defines the go to market strategy that links strategy to the operations of the firms (Velu, 2017).

Figure 1: Technology Transition, Business Models and Systems Evolution



Technology transitions occur when these forces across the three levels coalesce around some common theme that enables a new technology to be adopted and business model innovation to bring about industrial transformation and spur economic growth. However, there is high ambiguity around the ability of firms to create value from QT and to capture the value created. As such, initiatives to reduce the ambiguity through the alignment of incentives and business models are needed.

Several questions arise in enabling technology transitions towards a quantum-enabled economy. First, what is the role of government investment, that is, whether one needs *mission-oriented* state investments, or whether the government needs to play a role in addressing any market failures that might prevent a new technology from being adopted? Second, do we need to link QT to some grand or industry-wide challenges such as sustainability, global security, improved health and welfare to align the QT initiatives? Lastly, does it matter if the QT is seen as complementary or disruptive innovation (e.g. the relationship between quantum computers, digital computers and/or quantum communications). The answers to these questions could have a profound impact on accelerating the adoption of quantum technologies and contributing to economic growth for the benefit of society.

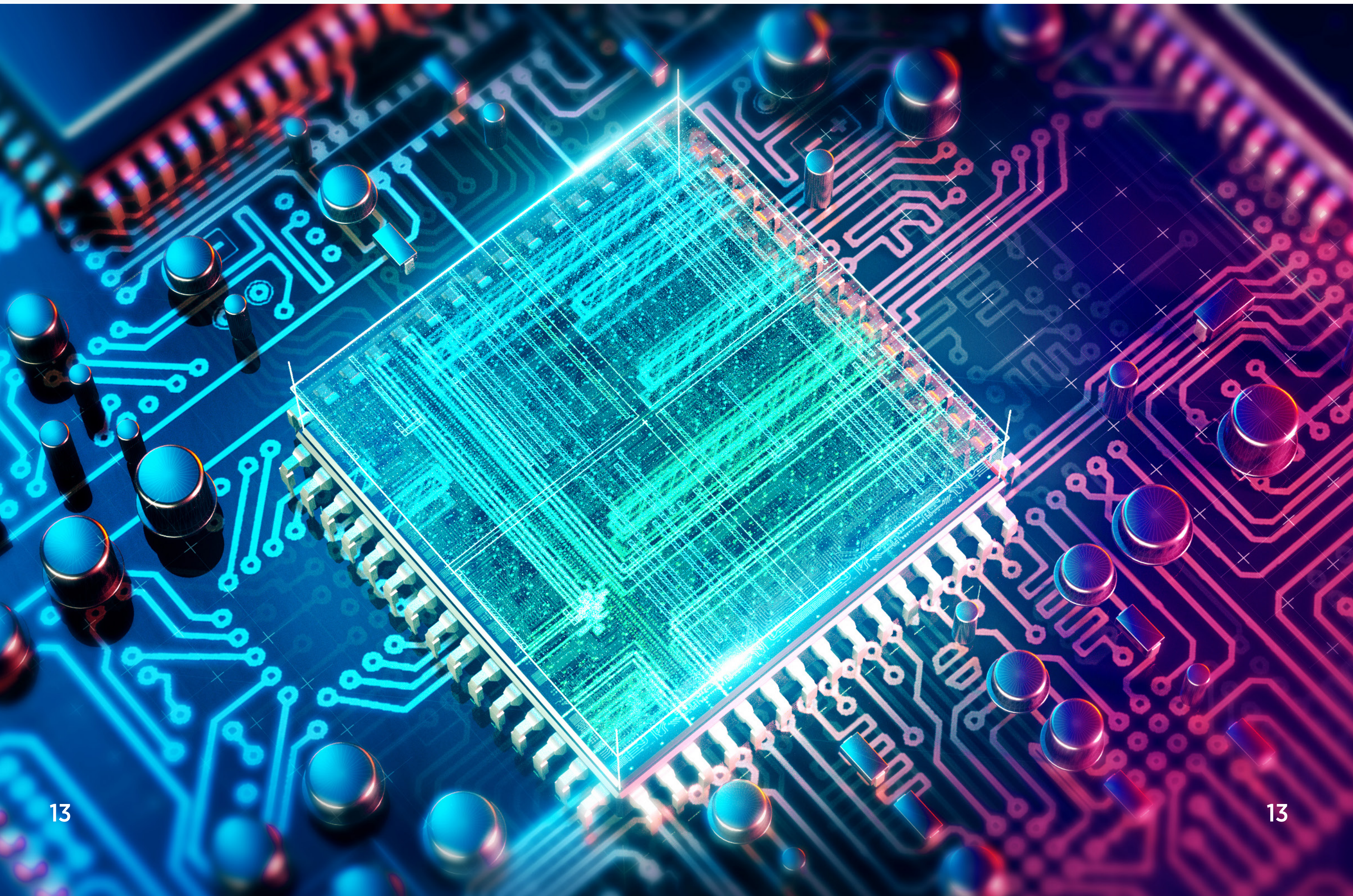
4. METHODOLOGY OF THE STUDY

A qualitative exploratory study was conducted to understand the adoption and commercialisation challenges of quantum technology – especially quantum computing – in the UK.

Semi-structured interviews were conducted with stakeholders in the UK quantum landscape, including the directors of UK quantum hubs, NQCC, Innovate UK, technology providers (incumbent and start-ups firms), potential users, investors, academics and consultants. In total, 61 interviews, with an average duration of 60 minutes, were conducted between July 2021 and September 2022.

Roundtable discussions were conducted with the respondents and beyond to present the findings from the interviews and to discuss open issues and future research opportunities. Three roundtables were held at Cambridge (May 2022), Oxford (June 2022) and London (June 2022), with a total of 40 participants.

The findings and recommendations below are based on the interviews and roundtables through a consultative process and dialogue with the relevant stakeholders.



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5. KEY STRENGTHS OF THE UK QT LANDSCAPE

As one of the first nations to have a dedicated national programme in quantum technology, the UK has several advantages that put it at the forefront of the global race in QT. Below we highlight five key strengths of the UK QT landscape.

Leaders in Quantum Science and Engineering

The UK is one of the first nations to invest in quantum technology through a national quantum programme; hence, the country has a first-mover advantage in quantum science and engineering. As noted during the roundtable discussions: *"We are the first country that has a quantum programme at a national programme [...] We are in a good position to reap the science and engineering leadership."*

In particular, the UK has an excellent reputation in trapped ion development in the laboratory, with a very strong photonics industrial base, but it also has considerable expertise in many other quantum technologies (superconductors, diamonds, silicon and cold atoms, and the associated applications, algorithms and validation methods).

The UK academic sector still has a strong reputation for attracting international talent, particularly to subjects such as physics, which have a direct impact on the country's ability to scale quantum science projects in the coming years, and more broadly in STEM subjects, which are likely to contribute to the uptake of QT in industry.

Innovate UK Funding Seen as Very Effective

The Innovate UK funding is effective in advancing technology development, having funded 139 business-led projects involving 141 UK companies. The funding increases the credibility of start-ups in attracting private investment, and it has attracted considerable private investment (estimated at around £1 billion of public/private funding).

The funding also reduces risks and brings structure, as well as discipline, to large firms to explore quantum, as stated by a senior manager of a global telecommunications firm: *"UKRI and Innovate UK have generally been very positive in bringing the UK supply chain together, bringing UK industrials and bringing academics together."*

Knowledgeable Workforce

The UK has a relatively high-quality talent pool in quantum science because of a strong quantum research programme in universities. Twenty-six of the UK's leading academic institutions have been involved directly in the UK NQTP technology hubs and more through the Innovate UK programme. They and others provide world-leading training in the theoretical and practical backgrounds required for a "quantum-ready" workforce, including highly regarded educations in physics, computer science, chemistry, materials science, mathematics and engineering. The NQTP has supported around two hundred PhD candidates in QT and well over a hundred MScs.

The UK also has a relatively strong workforce with a more general background in maths, physics and computer science that can be reskilled to become quantum-ready. Many hundreds of people in the UK are already working directly in QT, in dozens of UK-based QT supplier organisations (however, see the discussion below on the availability of new talent to the QT sector). The UK also has an opportunity to attract a more diverse workforce for this new, emerging sector, attracting talent from all backgrounds from inside and outside the UK.

Additionally, large commercial organisations with operations in the UK are starting to develop in-house expertise in QT. These include businesses operating in sectors such as pharmaceuticals, finance, energy and defence. The UK's positioning as a centre for these higher-value industries may help to attract talent with a quantum-ready background.

Funding from Venture Capital and Angels

The UK has a considerable venture capital (VC) and business angel community to fund quantum start-ups, especially in the pre/seed stage or series A funding. Estimates of VC funding in the UK alone in QT over recent years are over £135 million. The following quote from the CEO of a VC company illustrates the situation: *"I believe there was sufficient access to capital in the UK for all of these [quantum] companies. We [also] have world-class companies that have sufficient access to capital. The main challenge is how to link the technology to business applications."*

Vibrant Start-up Community

There are over forty UK start-ups that have directly or indirectly spun out of groups being funded under the UK NQTP. These include businesses developing systems for photonic qubits, quantum networks, quantum computing as a service, quantum random number generation, and many others with a specialism in both hardware and software. While many sectors in the UK economy are struggling with recruitment and attrition issues, particularly following the COVID pandemic, UK start-ups in the QT sector are, in some areas, managing to attract and retain young talent (however, see the discussion below).

6. CHALLENGES IN THE UK QT PROGRAMME

Despite the key strengths, we identified several key challenges that could hinder the adoption and commercialisation of quantum technology in the UK. These challenges revolve around market demand and adoption, supply and ecosystem, regulation and policy, funding and skills.

6.1 Market Demand and Adoption

Firms are increasingly exploring QT-related initiatives, especially in quantum computing. Their main motivation for engaging in quantum computing is to learn about the development of the technology and the potential impact on their businesses. Moreover, firms found that engaging in quantum-computing-related initiatives could enable them to position themselves in the market and put forward requirements to technology providers. Most of the quantum initiatives in established firms are predominantly organised in an R&D or CTO office and funded by the department's research budget. These initiatives are often motivated by identifying problems that are challenging to solve using existing digital high-performance computers (HPC), with a view to exploring whether quantum computers could provide a more efficient solution. For example, the quantum initiatives in a heavy equipment manufacturing firm are driven through a bottom-up approach led by researchers from the R&D unit who are trying to optimise sensor-based data from a variety of heavy machinery that needs to be coordinated in real time to provide value to customers. In contrast, there are cases where the initiatives are proposed by a central digital innovation or new strategic opportunities team. For example, quantum initiatives in an oil and gas company are driven through a top-down approach where the innovation unit explores the "art of the possible" of QT.

There is broad agreement that quantum computing will have significant business applications, especially for dynamic personalisation and optimisation of complex systems. Nevertheless, the business applications and the value propositions of quantum computing are still uncertain. Despite the uncertainties, the demand to learn about the applications of quantum computing continues to be vibrant and ongoing. Firms are partnering with universities and technology providers (i.e. quantum computing hardware and software) to identify use cases. In particular, they are experimenting with existing business problems that are "classically hard, quantum easy" (i.e. difficult or costly to solve using today's HPC). For example, a bank is collaborating with quantum computing start-ups in an Innovate UK-funded project to explore quantum machine learning algorithms to solve existing financial optimisation problems that are not economically feasible to solve using HPCs. Another example comes from a pharmaceutical company that is collaborating with a quantum computing start-up to simulate candidate molecules for drug discovery, where simulations with classical computers are not sufficiently robust.

However, managers are not yet able to demonstrate and benchmark the "quantum advantage" because of the absence of a large-scale quantum computer and the inability to transform existing problems into quantum-enabled algorithms efficiently. There are also uncertainties about the timeline of the technology development and the access of QC, that is, whether it will be on-premises, cloud or hybrid. As a result, managers have difficulties developing value propositions and dispelling the perception of quantum computers as merely "a faster computer". This quote from a senior analyst of a global consultancy firm illustrates the issue:

> *The fact that there's currently no quantum computing that is in production, I think that's probably the biggest barrier at the moment. We have the understanding that certain problems will be solved much faster, and we can kind of demonstrate that, but when it comes to actually productionising things, at the level where you actually see the quantum advantage, it's just not there.*

The inability to demonstrate the quantum advantage also results in an inability to build business cases for the adoption of quantum computing. In addition, managers are facing difficulties showing the potential impact of adoption on firms' profit and loss (P&L) and assessing the potential return on investment (ROI). In some industries, there is a lack of direct connection between enhanced computation and its impact on the bottom line of P&L. For example, quantum computers applied in the pharmaceutical or manufacturing sectors *might* result in better products, but these might take several years to develop into a viable and profitable new product proposition; indeed, quantifying the short-term ROI is a challenge. As a result, managers often find it challenging to create a sense of urgency at the board level and to convince their firm's senior management to substantially increase their investment in adoption. The quotes below from a chief product officer of a quantum computing start-up and a director of a consultancy firm (respectively) illustrate the issues:

> *The challenge is how to demonstrate quantum computer value to customers. There are some verticals where the turnaround between computation usage and revenues is quick and direct [i.e. financial industries], (but) in average industries the turnaround between computation usage and revenues doesn't exist or there is no link.*

> *When they [board members] ask "Will it solve the problem?" I can't bring evidence to them that says, "This will give you this economic advantage" because I can't test it, because [QC] doesn't yet exist.*

In addition, our respondents suggested that the government could play an essential role in reducing uncertainties around potential demand in the marketplace. Government endorsement through regulations could foster the adoption of QT. In contrast, the varying policies and lack of endorsement of certain technology such as quantum key distribution (QKD) could increase market and technological uncertainty and hamper technology adoption. In addition, the government could stimulate market demand and confidence by

"
When they [board members] ask "Will it solve the problem?" I can't bring evidence to them that says, "This will give you this economic advantage" because I can't test it, because [QC] doesn't yet exist.

acting as early users/buyers. However, the UK has historically lacked Defense Advanced Research Agency (DARPA)-like initiatives that could provide a guaranteed demand in the market, giving firms the confidence to invest in quantum technologies. The recently created Advanced Research and Innovation Agency (ARIA) initiative might go some way to addressing this shortcoming in the UK. Such initiatives where the government acts as a potential buyer would enable managers to develop a business case, thereby increasing firms' readiness to invest in QT, as noted by a senior manager: "The deal with DARPA will tell you that if you make a widget of this performance, we will buy this number. It means they can go to the board and say, *'Here's the business case'. We've got a guaranteed first market if we succeed and the DoD will buy this number."*

Overall, the challenges inherent in building credible business cases, and the lack of a governmental role in reducing the market and technological uncertainties, are major issues in the demand and adoption of QT.

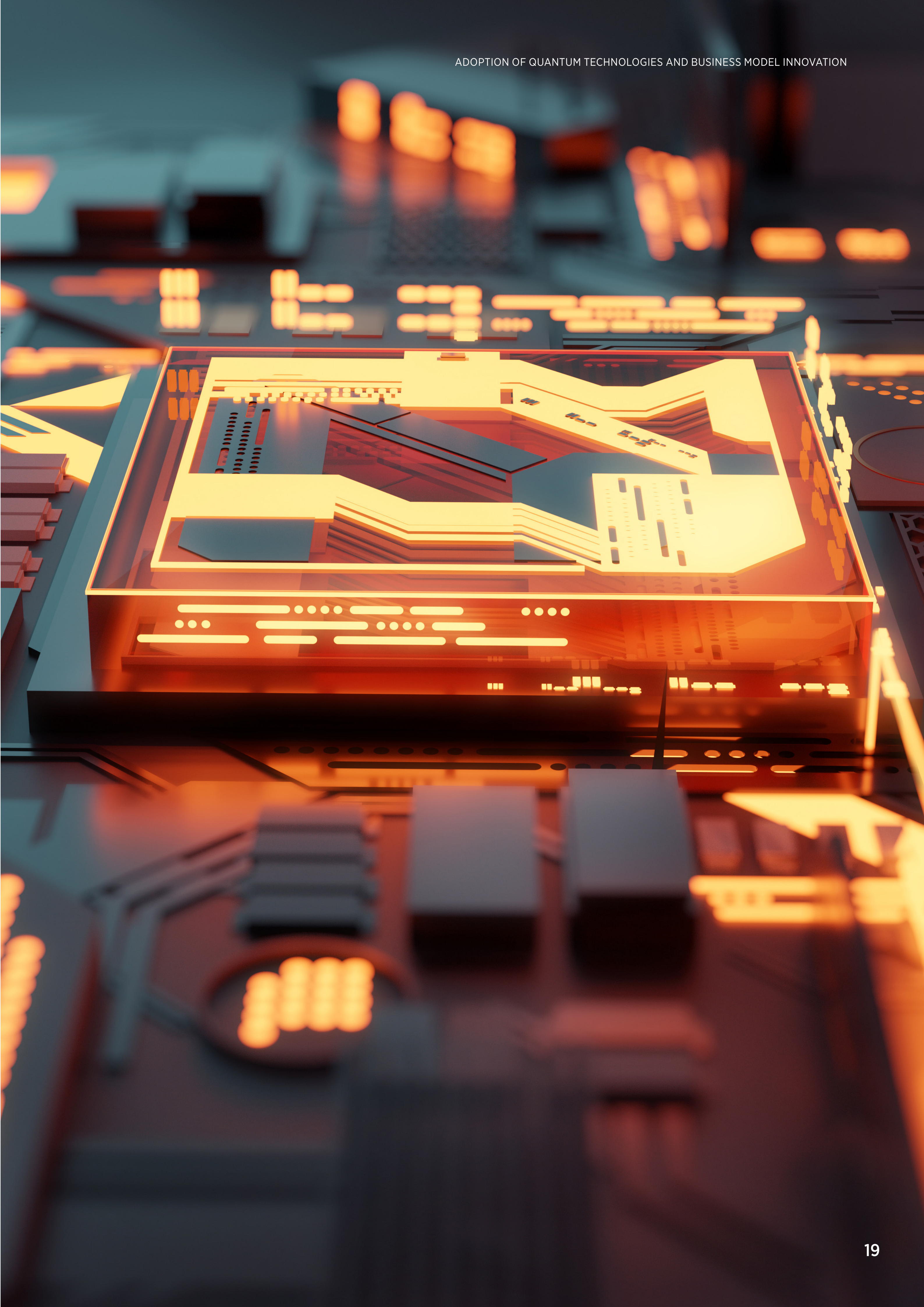
6.2 Supply Chain and Ecosystem

The UK National Quantum Technologies Programme has successfully stimulated the development of the quantum technology ecosystem and supply chain. There is increasing collaboration between QT providers, potential users and universities. However, there are still some challenges on the supply side of the ecosystem. First, there is a lack of involvement from enabling technology providers and equipment suppliers such as laser systems. Most of the respondents from the photonics industry consider the future of the QT market to be promising; yet it is still very nascent. They found that the timeline of the technology development, especially in quantum computing, is highly uncertain, which makes investment in the QT market less attractive compared to the established markets (e.g. manufacturing and metrology). Moreover, there is a lack of incentives from the government encouraging the photonics industry to become more engaged in QT; this is a missed opportunity given that the UK has a strong photonics industry that could be a source of competitive advantage in building the QT industry. The quotes from a chief executive of a major laser firm and a director of a photonics firm (respectively) below highlight the issues:

> *I can [already] make a laser that is used to manufacture every single screen on every single smartphone on the planet. And that's quite a lucrative [...] You need a credible quantum company that is selling at scale. The quantum technologies are still very scientific at the moment.*

> *I'm convinced that at some point the laser industry will be providing many laser systems for atom traps or others. But it's always difficult to be enthusiastic about developing a laser for a customer that won't be around for 10 years.*

Second, the absence of technological standards and dominant design hinders the adoption of QT. Firms engaging in quantum computing initiatives have to deal with diverse component suppliers and multiple competing technological platforms (e.g. superconductors, ion traps, photonics and silicon, among others), each with its own advantages and disadvantages. Each platform also has its own architecture to support a quantum algorithm, which creates a challenge for physicists, mathematicians, engineers



and business executives to develop solutions and applications using quantum computers.[2] This lack of standards is inhibiting the development of the supply side of the market. A quote from a senior researcher of a global chemicals company highlights the issue: *"We know how to do quantum chemistry calculations, but you can't just pick up that method and code it into a QC. Then again, it can be different if you're working with an ion trap or a superconducting machine [...] It's not a mature technology. We have to go through this as part of technology evolution."*

Third, the lack of systems integrators and large firms in the UK that could bring QT to scale is seen to be a challenge in supply and ecosystem development. Systems integrators are considered to be essential players in the development of the QT ecosystem in different sectors. Systems integrators are needed for two key roles. First, they are needed to integrate the components of a quantum computing system itself, especially if the components are provided by different suppliers. Second, systems integrators are needed to integrate quantum computing systems to existing digital and other related IT systems. These two roles are crucial in providing access to the market and solving business issues. Nevertheless, the UK lacks specialist organisations that can take on the role of a systems integrator in quantum at scale compared to countries such as the US and Germany. Government support (and potentially funding) to firms with a strong UK presence is needed to enable them to adopt the role of systems integrators in quantum initiatives. A quote from a consultant illustrates the issue: *"This is where the Americans win [because] they don't have to fund scaling because they've got Microsoft, IBM, Google and Amazon to fund scale [...] Therefore, you need to invest now in the scale-up and integration technology, because the battle will be won not by who generates the first one."*

Lastly, there are tremendous opportunities and synergies between quantum computing and quantum networks. However, the UK has been more compartmentalised in its approach to developing quantum technologies (for example, the NQTP has funded four distinct quantum hubs). Our respondents noted that the UK quantum hubs need to be more connected and collaborative going forward, given the development of the technologies. In particular, there are many potential synergies between quantum communications and quantum computing and simulation, as there are benefits between blind quantum computing and distributed computing architecture, as noted by a professor of physics: *"There are benefits in developing a more integrated approach to communication and computing by building quantum enhanced networks. The Europeans and Americans have used the idea of the quantum Internet as the framework to build convergence between them via quantum networks."*

In summary, the challenges of the supply and ecosystem development of QT in the UK revolve around the lack of involvement from the enabling technology providers, the absence of technological standards and the lack of systems integrators.

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There are benefits in developing a more integrated approach to communication and computing by building quantum enhanced networks. The Europeans and Americans have used the idea of the quantum Internet as the framework to build convergence between them via quantum networks.

[2] There are firms who dedicated to address such challenges by building a middle-layer/operating systems that could works across different platforms.

6.3 Regulation and Policy

The UK government's policies to support the national quantum programme have provided the UK with a sizeable advantage over other countries in quantum science and engineering. The combination of government-driven and industry co-funded schemes through Innovate UK is seen to be very effective in fostering industry collaboration for quantum technology development. However, there are growing concerns about the continuity of government support for the quantum programme beyond 2024. The quantum hubs have decreased funding in phase 2 and are reducing their headcounts in the next two years. The Innovate UK funding has also been fully allocated, with no current plans for further calls. Uncertainty around the continuity of government support could hamper the overall progress that has been made in the past 10 years. Moreover, the UK risks losing quantum entrepreneurs and start-ups to other countries, which are investing heavily in quantum initiatives, if funding is stopped or substantially decreased. The quotes from our roundtable discussion highlighted the issue: *"The UK is always good at being the first, but then let other countries catch up and reap the science and the engineering benefits. [...] I hope that the UK doesn't give up on the journey. A continuation of the funding is needed to maintain the UK leadership in quantum."*

Nonetheless, the development of the National Quantum Computing Centre (NQCC) is considered to be a positive initiative. The NQCC is expected to be the catalyst for QT development in the UK and the aim is to bring the whole supply chain and ecosystem together. The NQCC's initiatives to provide access to quantum computers to the academic community and to help to build ecosystems for private commercial enterprises are both very commendable. Moreover, the NQCC's help in identifying challenges across industries that might benefit from collective use of quantum computers is seen to be very positive. Nevertheless, our respondents found that there is still a perceived lack of clarity regarding the NQCC's roles, activities and range of support. There is also concern about the potential risk of "crowding out" private-sector investment as a result of such uncertainties. Such ambiguity could hamper wider stakeholder engagement and slow the development of the ecosystem. A quote from a director of a consultancy firm illustrates the issue: *"They [the start-ups] are worried that the centre [i.e. the NQCC] will pinch some of their customers. They are still not convinced that this is not going to happen, even though the centre says it's not planning to do so."*

In addition, geopolitical issues such as regulations on export control, foreign direct investment (FDI) and cross-border M&A are seen to be a challenge for QT adoption and commercialisation. Our respondents noted that the regulation of QT, especially on quantum computing, is becoming restricted by the government. Collaboration between countries can be more challenging because governments tend to see QT as a national security issue. Export restrictions may be expanded, which will ultimately

> "The UK is always good at being the first, but then let other countries catch up and reap the science and the engineering benefits. [...] I hope that the UK doesn't give up on the journey. A continuation of the funding is needed to maintain the UK leadership in quantum.

restrict the development of the supply chain and IP generation. There is also concern about the impact of the National Security and Investment Act on foreign investment in UK quantum start-ups. Moreover, the current government-based funding regulations do not allow the grant budget to be spent on resources in other countries. Such regulation is considered to be a limiting factor, especially for multinational firms that have resources (i.e. expertise) in other countries. The quotes from the CEO of a start-up and CCO of a global photonics firm below (respectively) highlight the issues:

> *The key challenges with quantum computing regulation are that the technologies are becoming restricted by the government, and that will ultimately restrict your supply chain and IP generation, and [ability] to collaborate across borders.*

> *The funding regulations do not allow us to leverage our resources in other countries. Currently, the UK government-based funding for QT can only be spent in the UK and not in other countries. For us, this is limiting, as some of the expertise might reside in the USA.*

Moreover, there is a diversity of views on the merits of intellectual property (IP) protection. On the one hand, all IP, registered as patents or copyrights, or non-registered such as know-how or expertise, will be important in encouraging sector investment because it will protect the interests of companies that invent or license such IP. On the other hand, over-zealous (or poorly understood) IP protection policies can get in the way of collaboration, either through actual barriers to access or through the perceived complexity of the arrangements required to share IP. Some interviewees highlighted the need for academia and industry to work more closely together to enable the advancement of QT by providing broad access to IP across the ecosystem, while protecting UK IP rights for the commercial and national interest.

Overall, uncertainty around the longevity of government support for the UK National Quantum Technologies Programme, the lack of clarity about the role of the NQCC, the geopolitical issues and the protection of IP are issues that challenge the commercialisation of QT.

6.4 Funding

Government funding has fostered the development of quantum science and engineering development in the UK. In particular, it has been effective in advancing technology development from proof of concept (TRL 3) to pre-production prototype (TRL 6).[3] A more dedicated funding scheme is needed to support productisation and commercialisation, as there is a lack of funding for projects/initiatives beyond TRL 6. Our respondents suggested that it will be difficult for firms to self-fund QT development to TRL 8 because of the high uncertainty. Funding support at the commercialisation stage would help firms to de-risk the investment. Moreover, there is a lack of government funding supporting the development of manufacturing and integration technologies for QT. This is seen as a constraint, since manufacturing and integration capabilities are essential to scaling up QT. The quotes from a senior manager of a telecommunications firm and a director of a photonics firm (respectively) below highlight the issues:

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[3] Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a technology. The TRL has nine levels, split into three groups: TRLs 1-3 indicating research stages of development, TRLs 4-6 indicating the developmental stages of developments and TRLs 7-9 indicating the deployment stages of development.

> *One concern I have is that we are now at the tricky stage of commercialisation. My fear is that it [the quantum strategy] will be too narrowly scoped so that those commercialisation activities don't fall in scope. And, to be honest, for us, trying to self-fund all of that is going to be really tough [...] We still need help to get to TRL 8.*

> *The real danger is if you don't invest in this manufacturing and integration technology now, you will have to export your quantum technology.*

Despite its benefits, the reporting and monitoring processes for firms involved in government-funded projects (i.e. those supported by Innovate UK) are still not considered to be ideal. Our respondents felt that the monitoring and reporting process is arduous and very costly, especially for small and medium enterprises (SMEs), which often lack the dedicated resources and processes for monitoring and reporting. The need to allocate people and time for a complex monitoring and reporting process is considered a constraint. A quote by the CEO of a quantum start-up below highlights the issue:

> *I kind of think that sometimes the role of monitoring offices is to make Innovate UK feel good, rather than actually to accelerate research. [...] They like to think that it's going to be great for SMEs. In reality, it's much easier for the larger organisations to deal with these [monitoring and reporting] because they've already got processes and people in place.*

In addition, private-sector funding is encouraging but failing to help scale up homegrown start-ups. The venture capital (VC) community in the UK has supported the rise of UK quantum start-ups, especially in the pre-seed stages. However, the UK private investment environment lacks funding to support the scale-up beyond series A. As such, start-ups need to tap into foreign capital, especially the US. Our respondents noted that US investors tend to write larger cheques and are willing to take more risks than UK investors. Therefore, UK start-ups often need to tap into funding from the US market, frequently by establishing a presence in the US. This situation creates the risk of a brain drain of UK quantum talent and skills.

The quotes below from the director of a UK-based VC company and the CEO of a quantum start-up highlight the issues:

> *The culture of scaling businesses is just at a different level in the US from where it is here. I mean, we're making progress and we aspire to, but we're just not there yet. [...] The capital is more available if you have a US presence.*

> *The UK has a disadvantage because its venture community and its corporate investment community are weak at making properly sized bets.*

Apart from seeking investment, quantum start-ups are facing challenges in building business models. Some quantum computing start-ups, for example, have gained a lot of interest from potential users but face challenges in revenue generation. The start-ups need to develop a business model that not only enables the achievement of long-term objectives but also supports short-term revenue. This is a major challenge given the uncertainty in both technology and the market, as noted by the VP of a quantum computing company: *"We try to triage who we're going to work with because we have a lot of interest [from potential users] in working with us, but everybody wants us to do it for free, which doesn't work."*

In summary, a lack of government funding schemes that support commercialisation and manufacturing capabilities, an arduous monitoring process in government-funded projects, as well as the lack of private-sector funding in the UK to help scale up homegrown start-ups, are seen as constraints in the commercialisation of QT.

6.5 Skills

As noted above, the UK is home to some of the best quantum scientists in the world, in world-leading academic institutions. However, there are still shortages of quantum-related talent and skills across both industry and academia. A lack of skills is a pipeline issue running from university research labs to industry. At the moment, firms are struggling to hire the right talent for their quantum-related initiatives. Some firms are having to forgo grants because of the inability to recruit the right talent. Such a shortage of skills and talent is being faced by both industry and academia. For example, academic research groups are struggling to find talent and skills, especially postdoctoral research associates (PDRAs). There is a concern about the talent being taken away from science/engineering research at universities, which would affect the pipeline into industry. Moreover, university PDRA salaries in the UK are stipulated based on UKRI grant funding. This is likely to leave UK universities at a disadvantage in competing for talent with private-sector salaries, which are more exposed to adjustments based on demand and supply conditions in the marketplace. There is also concern about the risk of knowledge and skills being inaccessible because of IP walls; IP is essential in incentivising firms to invest in the development of the UK. Nevertheless, to promote broader accessibility in the development of QT systems, IP protection and ownership at the individual firm level for components parts must be addressed.

In addition, most of the talent is coming from PhD programmes, which involve 3–4 years of training. There is still a lack of training programmes with a quicker turnaround than the PhD (e.g. Master's courses, short courses), which creates challenges for the development of quantum talent and skills. The quotes below from a director of a VC company and the VP of a quantum computing company illustrate the issues:

> *One of my fears is that very soon we're going to face the same problem as the ones we've been facing with AI, where you're going to have not enough people to develop these solutions and to innovate, unless you pay them a fortune.*

> *I mean, it's something where we have our eye on the challenges – you can't hire anybody directly off the street...except in rare cases. There's a lot of on-the-job training that has to happen inside our company to be effective.*

Furthermore, there are shortages of domain experts with an adequate understanding of QT with other related skills. There are many talented individuals with engineering and computer science backgrounds in the

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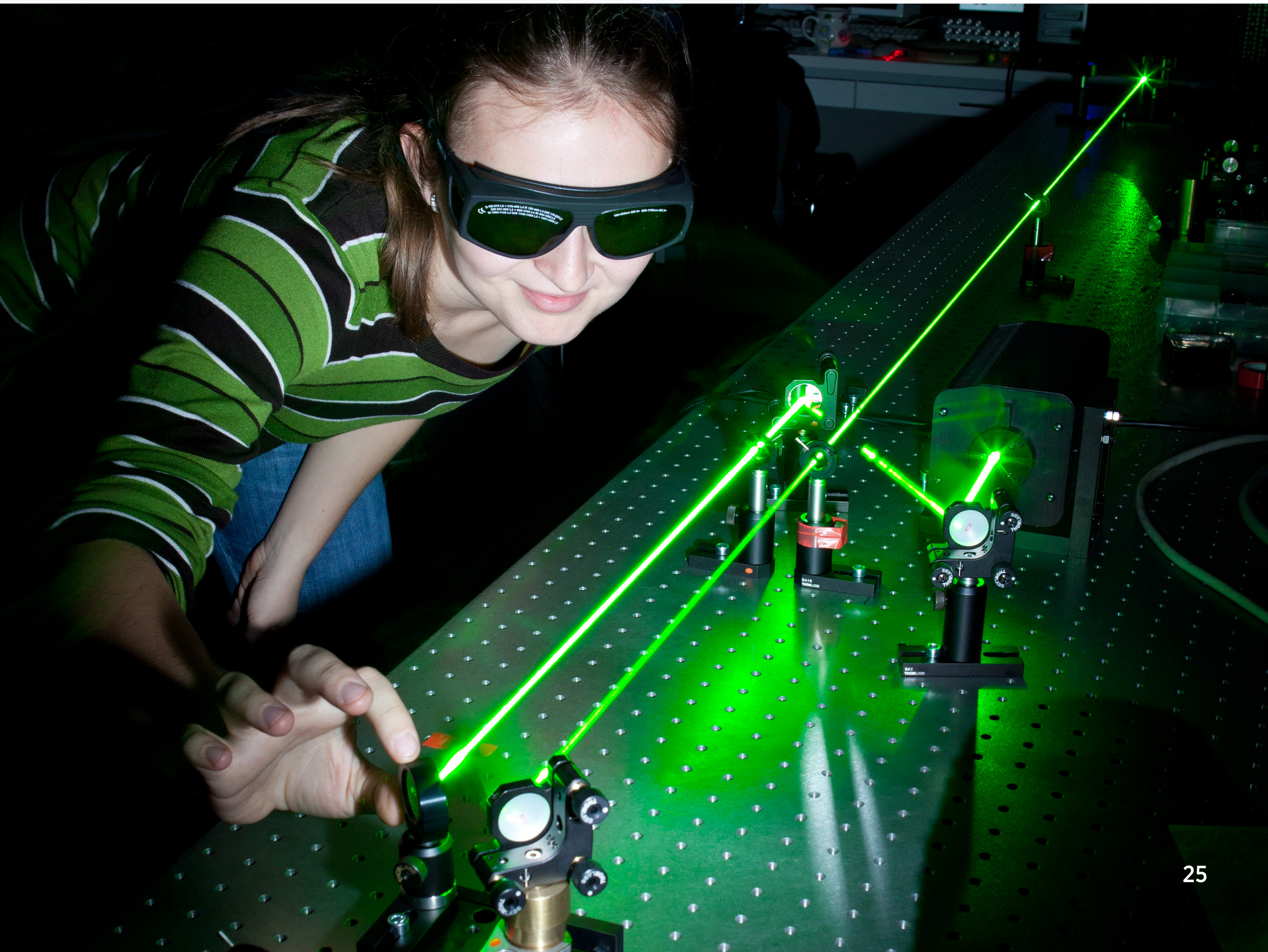
UK that could become a major resource for the development of quantum technologies. However, there are not enough training programmes for reskilling such talent to become "quantum-ready"; nor is there sufficient training in quantum systems engineering. Skills in systems engineering are needed to bring the technology together and to integrate quantum with classical systems. This lack of training programmes could hamper the adoption of QT. As with many high-tech industries, there is still much that could be done to improve diversity and inclusion in the QT sector. Reskilling could play a major part in bringing a wider resource pool to the industry.

Moreover, there is a shortage of management capability to prepare organisations for the quantum era, which may well constrain the adoption of QT in firms. Similarly, management and entrepreneurship training for people with quantum backgrounds is essential to put "quantum in context ", that is, translating quantum capabilities into business applications.

Overall, shortages of quantum-related talent and skills and domain experts with an understanding of QT are seen as major issues in skills development for the quantum-enabled economy.



7. RECOMMENDATIONS FOR THE WAY FORWARD

Based on the findings on the strengths and challenges for quantum technology development in the UK, we propose several recommendations to strengthen QT adoption and commercialisation efforts, in order to benefit society and deliver economic growth. Our recommendations include the following:

- Mission-driven funding calls to help build credible use cases for public benefit and to provide more certainty about government support.
- Building a forum for systems integrators to help build the ecosystem in the supply chain and potentially drive standards.
- Bringing together quantum computing and quantum communications initiatives to help clarify the distinctiveness of the NQCC and the longevity of government support.
- Developing intellectual property policies to help resolve uncertainty about geopolitical issues, reduce market uncertainties and encourage ecosystem development.
- Addressing scale-up challenges with industry to help funding concerns and drive home-grown market adoption.
- Creating shorter-timescale training programmes to help address the skills shortage.

We discuss each of these areas below.

7.1 Initiating Mission-driven Funding Calls to Industry, with a Focus on Using Quantum Technologies to Solve Industry-wide/Societal Challenges

Quantum technology offers potential benefits to solve complex problems of high value to society. The benefits could manifest themselves in two ways. First, private-sector firms would be able to provide unique customer value propositions, providing direct benefits through increased profits. A second benefit could be in the form of solving an industry challenge (e.g. more efficient fraud detection in the financial services industry) or society-wide issues (e.g. an ageing society, climate change and inequality), which might have public benefit but might not provide direct proprietary profit opportunities for firms. Our analysis highlights issues of market and technological uncertainties combined with the lack of the UK government role as a key buyer to reduce demand ambiguities. Hence, we believe that private-sector firms might be less incentivised to drive the adoption of quantum computing investments, as a result of the uncertain return on initial investment, but that they would be willing to invest for private benefit once the “proof of concept” is demonstrated by addressing a wider industry or societal need.

Therefore, we propose that the government initiate *mission-driven* funding for firms to address industry-wide issues or societal grand challenges with QT. Such a mission-driven programme could facilitate coordination among firms and other stakeholders to develop quantum computer applications for the benefit of the wider society. The successful proof of concept of quantum applications should be followed up with appropriate policies that would encourage the adoption of these solutions. Moreover, the proof of concept of the benefits of the quantum technologies should be made available for firms to invest in and to continue to develop the technology for private profit.

The mission-driven funding programme for quantum computers could be realised by following the broad principles below:

1. The programme should be aimed at addressing an industry-wide issue or the UK's grand challenges.
2. The government, together with the UK quantum technology hubs, NQCC and NPL, should identify industry-wide problems that provide societal benefits that might not be funded by individual firms.
3. The mission-driven funding programme should be initiated across multiple industries and should involve actors across the value chain such as start-up firms, incumbent firms, enabling technology providers, academics, regulators and other relevant stakeholders. They also need to have concrete and tangible targets to solve industry-wide problems based on QT.
4. The programme needs to encourage the involvement of systems integrators to bring together components and subsystems and provide integration with existing information and technological systems.

Overall, the initiation of mission-driven calls could provide direction on the development of QT-based solutions for the benefit of society. Such a mission-driven programme would enable the government to play its role, not only by fixing potential market failures but also by creating and shaping markets for societal benefits and economic growth. Moreover, such an approach could bridge the gap as to whether QT is seen as complementary or disruptive innovation by allowing firms to learn about the benefits within an industry wide application before committing significant resources for private benefits.

7.2 Forming a Forum of Systems Integrators in the UK

Systems integrators could play an important role in the adoption and commercialisation of QT in two ways. First, systems integrators are needed to *integrate quantum technologies with classical systems*. Second, system integrators are needed to *bring together components in the different layers of quantum computing architectures themselves* (e.g. hardware, middleware, software). Therefore, we propose the formation of a forum of systems integrators. In order to do this, we suggest a programme of active identification of potential firms from various sectors that can play the role of systems integrators in the UK, with a view to incentivising them to join the forum.

The forum may not be exclusive to UK firms but could be open to other multinational firms that have a large presence in the UK. The forum should advocate, promote and foster the common interests of the UK industry towards scaling and commercialising quantum computers. Members of the forum could find common interests and collaborate to enable the development and integration of quantum computers. Moreover, the industry-led forum could drive collaboration with academic experts (i.e. the QCS Hub) or government entities such as the NQCC to develop a *"system of systems"* that knits together various innovations in the UK. They may also develop a comprehensive roadmap to orchestrate technology development and adoption.

Ultimately, the forum of system integrators could widen the market of quantum component suppliers by purchasing and integrating components into end-products or services.

The formation of a forum for systems integrators could significantly reduce uncertainties around business model development through ecosystem-level coordination across firms from component suppliers, quantum computing providers and users. Systems integrators could play a crucial role in enabling the coalescence of incentives around the various business models, hence fostering the adoption of quantum technologies and the technological transition to a quantum-enabled economy. Moreover, the involvement of systems integrators would enable a more holistic approach to the associated governance structure in order to ensure that the benefits are fairly realised across both firms and society.

7.3 Introducing a Strategic Initiative that Brings Together Quantum Computing and Quantum Communications (Network) for Better Synergy

The UK has been successful in its initial phase of quantum computing and quantum communications development in separate hubs in order to leverage the specific skills and knowledge required for these technology applications. However, the advances and convergence of both these quantum technology applications require a more synergetic and coordinated approach. For example, integrating quantum computing and quantum communications provides advantages that can be gained from blind quantum computing and distributed quantum computing architecture. Both the Europeans and the US have progressed towards articulating a vision of the quantum Internet and/or quantum networks as the overarching framework for bringing quantum computing and quantum communications together.

The UK needs to build on its strength in quantum computing and quantum communications to develop a strategic initiative that works towards a networked quantum computer. The initiatives should leverage the expertise from both the Quantum Computing and Simulation Hub and the Quantum Communication Hub to develop an integrated system of quantum computing and quantum repeaters for entanglement distribution. By bringing the skills and expertise together, the UK could accelerate the development of secure communications, powerful quantum computing networks and large-scale quantum Internet.

7.4 Developing Intellectual Property Policies to Maintain Broader Accessibility, While Allowing for Commercialisation

A sound policy should balance the pursuit of IP protection for commercial interest with practical approaches to encourage collaboration and ability so that the brightest minds and best resources can be applied to advance existing IP.

Building a complex quantum computing system might require bringing together IP for various component parts with different owners or licensees. The UK should encourage ways to keep access to the QT-related IP as broad as possible within its own sphere of interest. Keeping access to IP open via research collaboration between industry and universities and national labs should be a consideration for the benefit of both firms and the national programme. Grant programmes from Innovate UK, the QCS Hub, PRFs and individual spin-out research collaboration agreements with their universities are good examples. In this way, academia and industries can work together to advance the development of QT while ensuring broad access to the ecosystem and protecting UK IP rights in the commercial and national interest, through the following principles:

(a) Universities continue to generate much IP and a select (well-resourced) few are the main source of spin-outs, start-ups and patents available for commercial licences. On the other hand, the majority of universities have limited resources and many struggle to capture, protect, mature and commercialise their IP. Therefore, a specific UK NQTP policy and resources to help all universities would be very helpful.

(b) Companies that develop or license IP should have appropriate assurances that commercial interests are protected when collaborating with national labs and universities. A national IP policy should provide guidance on this matter, possibly with suggested templates, and the interests of the national ambition and commercial objectives should be given appropriate priority.

7.5 Preparing Scale-up Capabilities in Technology and Manufacturing

The next phase of the national quantum strategy should address the scale-up challenges in both technology and manufacturing. The focus of the development should be on increasing the quantity and reliability of qubits and error handling. Moreover, the UK needs to have an ambition to try to build a fault-tolerant system with the support of the NQCC. At the same time, the UK can identify key components in the overall system that have the greatest potential for value capture, and it can develop manufacturing capabilities for these areas.

In particular, the UK needs to develop a strategy to build manufacturing capabilities to address the scale-up challenges of quantum technology. We recommend the following steps to develop scale-up strategies:

1. Develop a national manufacturing scale-up plan and define strategic goals by envisioning the QT ecosystem and its opportunities.
2. Conduct an assessment of national manufacturing capabilities to identify the nation's strengths and weaknesses for scaling quantum computing.
3. Identify key manufacturing capabilities and make deliberate choices about whether to develop the capabilities internally or through international partnership.
4. Create a roadmap with a prioritised, sequenced and detailed set of initiatives for capability development.
5. Develop a network of partners with other countries, while positioning the UK as a prominent player in the supply chain.

The early development of scale-up capabilities in both technology and manufacturing would enable the UK to capture the value of QT when it matures. Hence, it can transform science and technological advances into socio-economic benefits.

7.6 Creating Shorter-timescale Training Programmes That Increase Quantum Literacy and Skills

To address the shortages of quantum-related talent and skills, and to improve diversity and inclusion in the talent pool, we recommend the development of training programmes with shorter timescales that focus on quantum science, engineering and entrepreneurship. More cross-disciplinary Centres for Doctoral Training (CDT) Programmes should also be expanded to maintain advances in quantum research and engineering. Moreover, the UK NQTP should design its outreach and public information activities to encourage more women and minorities than have traditionally engaged in STEM sciences and industries.

We recommend the following training programmes:

1. Management and entrepreneurship training in quantum technologies

Executive programmes on quantum technologies could help senior executives and decision-makers in organisations to prepare for the quantum era. Entrepreneurship training would also enable quantum scientists and engineers to explore the commercial potential of QT. This would support the commercialisation of QT through venture creation.

2. Short courses in quantum technologies

Universities could work with industry and/or government to develop short courses in quantum technologies and innovation for practitioners. The courses should train the domain experts with engineering and science backgrounds to be quantum-ready. In particular, the courses should aim to upskill people in industries with quantum knowledge and skills. As such, there would be more domain experts who can put “quantum in context” in their respective industries.

3. Master’s degrees in quantum science and engineering

Master’s programmes could help to develop talent with quantum literacy and skills within a shorter timescale (1–2 years). The programmes should be open to students from different science and engineering backgrounds (e.g. physics, mathematics, chemistry and computer science). Moreover, the programmes should cover quantum systems engineering that focuses on the design, testing and certification of quantum-embedded systems.

4. Interdisciplinary doctoral training programmes in quantum technologies

CDT programmes should be designed to leverage the knowledge and expertise across universities and foster interdisciplinary collaboration. The EPSRC and Innovate UK could make interdisciplinary collaboration a requirement in funding calls to encourage more collaboration across institutions.

Currently, only a few universities in the UK (e.g. UCL, University of Bristol, University of Sussex) offer a Master’s degree in quantum technologies. Moreover, several universities have started to offer QT short courses for practitioners. For example, the University of Bristol, together with the NQCC, offers a 6-week online course for professionals wanting to engage in the field of quantum technologies. The University of Bristol also has a Quantum Technology Enterprise Centre (QTEC) that provides training and support for quantum scientists and engineers to set up start-ups. Thus, the training programmes need to be expanded across the UK to prepare for a qualified quantum workforce.

Overall, the six recommendations that we propose address some of the challenges inherent in adopting and commercialising quantum technology in the UK. Table 1 (overleaf) summarises the challenges and related recommendations.

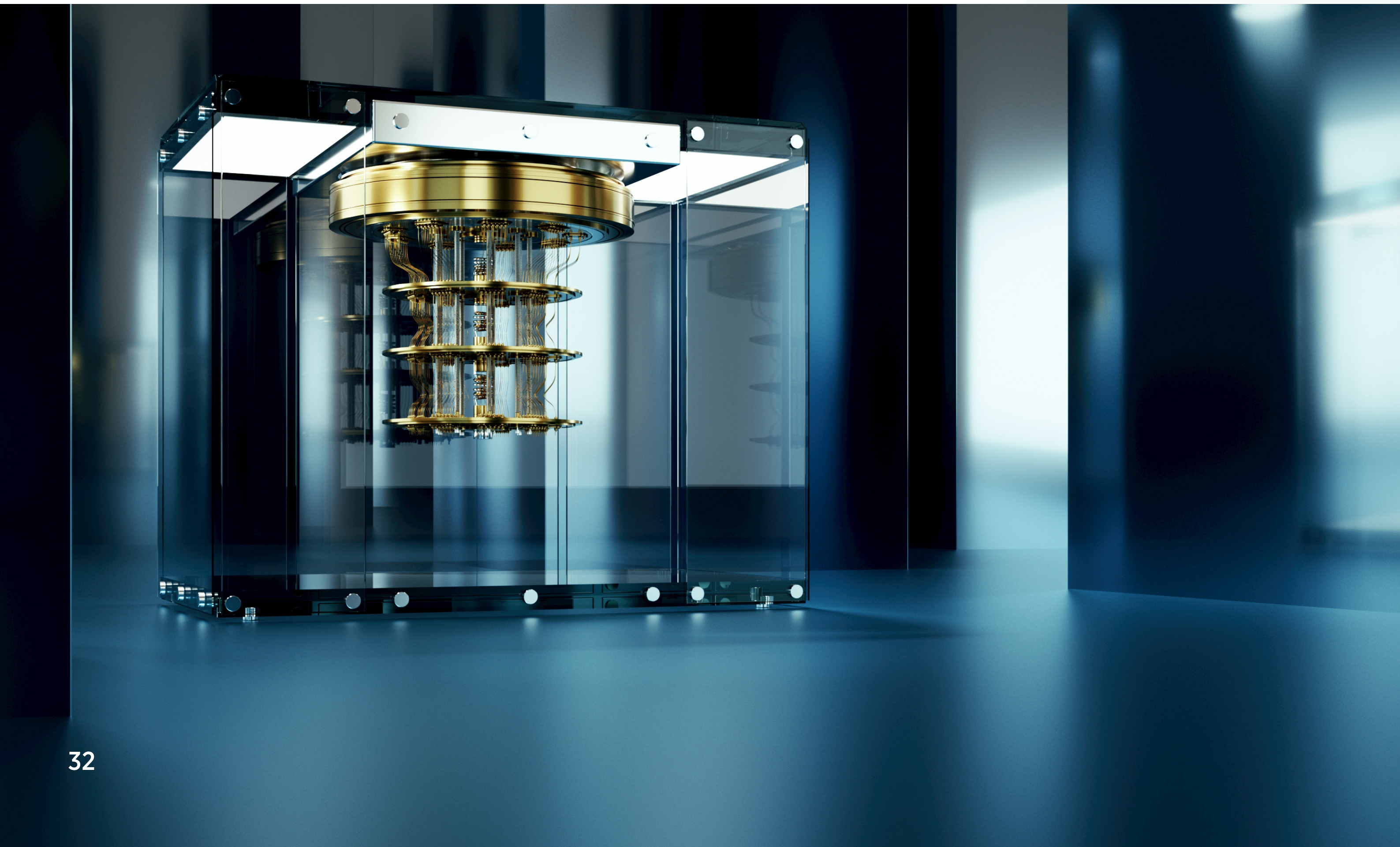
Table 1: The Challenges and Recommendations for UK QT development

COMMERCIALISATION CHALLENGES OF QT	RECOMMENDATIONS
An inability to build a credible business case and uncertain demand Uncertainty around the longevity of government support, and the perceived lack of clarity about the role of the NQCC	Initiating mission-driven funding calls to industry, with a focus on using QT to solve industry-wide/ societal challenges
Inadequate incentives for enabling technology providers, an absence of technological standards and a lack of system integrators	Forming a forum of systems integrators in the UK Developing a strategic initiative that brings together quantum computing and quantum communications (network) for better synergy
The emerging geopolitical issues prompt a new approach that enables broad access to IP while protecting UK IP rights in the commercial and national interest	Developing intellectual property policies to maintain broader accessibility, while allowing for commercialisation
Insufficient funding schemes to support commercialisation and manufacturing capabilities	Preparing scale-up capabilities in technology and manufacturing
Shortages of available quantum-related talent and skills and domain experts with an understanding of QT	Creating shorter-timescale training programmes that increase quantum literacy and skills

8. CONCLUSION

Quantum technology offers a massive opportunity for UK industry and the wider economy. Government investment in the NQTP has put the UK at the forefront of quantum science and engineering. Nevertheless, there are still adoption and commercialisation challenges that could hamper the nation's efforts to translate advances in science and engineering into increased productivity and economic growth. The next phase of the national quantum strategy should be to address the barriers to adoption and commercialisation. Addressing the challenges of commercialisation requires business model innovations that enable firms to create and capture value from QT. Moreover, business model innovation is essential to coordinating activities and aligning incentives among the different stakeholders in industry. Therefore, it is imperative to develop a dedicated research programme focusing on the business model innovation of QT that fosters adoption and the transition to a quantum-enabled economy.

We consider this White Paper to be an initial step in the process of opening a wider dialogue with various stakeholders in academia, industry, government, funding bodies and others about the commercialisation and business models of quantum technology. We hope this paper will encourage the development of a more refined agenda for both research and practice on the adoption of QT and business model innovation to increase productivity and deliver economic growth for the benefit of society.



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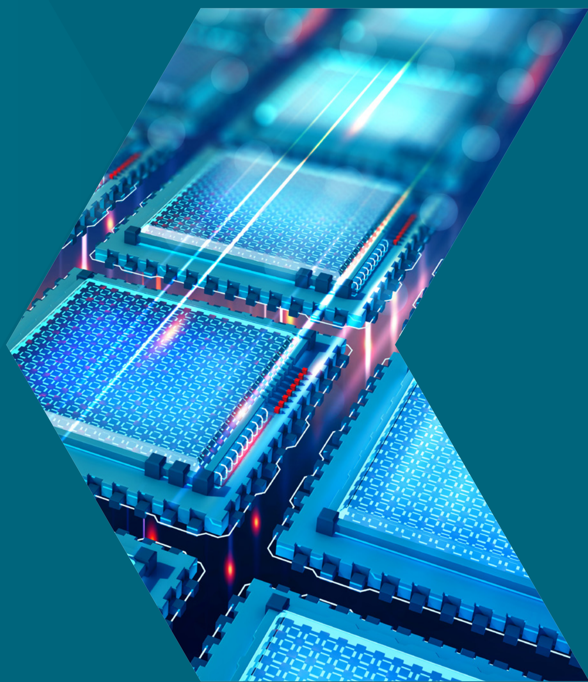

IfM

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The IfM is part of the University of Cambridge's Department of Engineering. With a focus on manufacturing industries, the IfM creates, develops and deploys new insights into management, technology and policy. We strive to be the partner of choice for businesses and policy-makers, as they enhance manufacturing processes, systems and supply chains to deliver sustainable economic growth through productivity and innovation.

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Quantum Computing & Simulation Hub

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