techUK
FOR WHAT COMES NEXT

Quantum commercialisation: Positioning the UK for success

Contents

Introduction to Report

Quantum technologies are set to play a formidable role in unlocking innovation both in the UK and internationally, enabling previously unattainable technological advancements in drug discovery, protein-folding, carbon capture, battery research and more. Such advancements will have a profound and positive impact in the UK as we build on our position as a science and technology leader and turn academic strength in quantum into economic success.

Both the UK Innovation Strategy and The Integrated Review emphasise the integral role of quantum technologies in the UK's innovation ecosystem, recognising the international strength in quantum that started with the establishment of the National Quantum Technologies Programme (NQTP) in 2014. This ten-year programme has delivered £1bn of public and private investment across quantum technologies and should be praised for building a world leading ecosystem in quantum science and technology development in the UK. Equally, the creation of the National Quantum Computing Centre (NQCC) will provide access, resources, and partnerships for the quantum industry to further push forward the quantum innovation ecosystem in the UK.[1]

This foundation puts the UK in a strong position to be a world leader in quantum. The UK Government's recent announcement to launch its first Quantum Strategy solidifies this position and strengthens the path towards commercialisation of quantum technologies.[2]

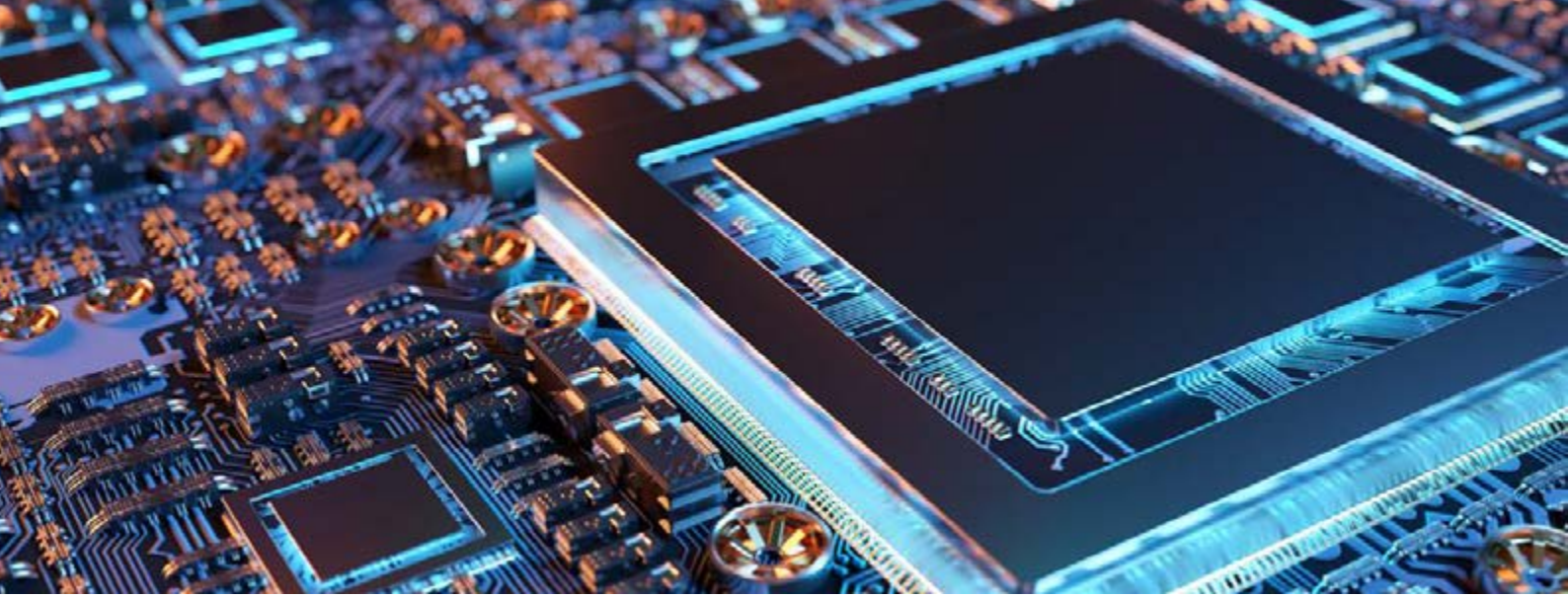
Still, we cannot be complacent. We need to sustain the UK as a leader in quantum as other nations continue to invest in the commercialisation of these technologies. techUK has highlighted the importance of quantum commercialisation through its recent Quantum Commercialisation campaign, convening the technology sector, key stakeholders, policy makers and the wider business community to explore how to create a thriving quantum market in the UK.[3] This work emphasised that commercialisation of quantum will benefit the economy from huge productivity gains and new products and services here in the UK. This report is a summation of techUK's Quantum Commercialisation Campaign, working alongside techUK's Quantum Working Group to develop a roadmap on the role of the UK tech sector in making commercialisation successful.

This report comes at a crucial time in the development of quantum technologies, as we move from research to deployment of the initial use cases across a variety of industries.

Indeed, quantum is undoubtedly accelerating toward commercial viability. Given recent advances in the maturity of the underlying technology platforms, as well as the ongoing scale-up in the UK's wider ecosystem, it seems likely that quantum will have a significant impact in manufacturing, chemicals, life sciences, financial services, energy, and telecommunications.[4]

Commercialisation of quantum technologies will underpin the success of the UK's quantum research and early-stage start-ups and facilitate the emergence of the thriving quantum ecosystem envisaged by the Quantum Strategy. We call on UK Government and industry to set clear commercial ambitions together, giving UK-based and international businesses the confidence that the UK is a promising place to achieve commercial viability.

This report addresses all quantum technologies, from sensing, communications, security and computing as these technologies unlock lots of



different use cases in the UK. Different technologies and use cases will mature at different speeds, and throughout this report we have tried to think inclusively about how the UK can support the variety of quantum hardware and software systems, and products and services, that will emerge in the coming years. These technologies do have overlapping areas of focus, such as skills, adoption and security.

We call on UK Government and industry to set clear commercial ambitions together, giving UK-based and international businesses the confidence that the UK is a promising place to achieve commercial viability.

Throughout this report techUK emphasises the complementary role other technologies like Cloud, High Performance Computing (HPC) and AI will play.[5] It is these technologies that many quantum use cases will initially rely upon, and, in turn, quantum will make other emerging technologies more powerful as convergence grows. We recommend that UK Government should think holistically about research, ecosystems, and commercialisation of these technologies together. With this in mind, a focus on commercialisation also means support for other technologies that will become part of the quantum ecosystem and enable its success.

techUK believes that without addressing these five key priorities, it will become difficult to sustain a world leading quantum ecosystem in the UK with commercialisation at the forefront. Across these priorities, techUK underscores the importance of collaboration and partnership with the wider tech sector to make this a reality. Indeed, the UK tech sector can be viewed as a vital conduit between our nascent quantum industry and the end users deploying the first use cases and their role in quantum commercialisation should be recognised and supported.

Thank you to techUK's Quantum Working Group for contribution to this report.

To achieve this vision the following activities and interventions will be critical:

1. **Ensuring access to quantum talent and developing quantum skills in the UK**

2. **Working with the UK tech sector to develop models of easy access to quantum technologies, including building pathways with other critical emerging technologies such as Cloud, HPC and AI that will be key for commercialisation**

3. **Promote international collaboration globally to help grow and develop opportunities for the UK sector, and protect the UK's capabilities**

4. **Encourage public sector procurement of quantum to grow the quantum market, offer stability, and enable commercialisation**

5. **Ensure commercialisation and innovation is achieved in a responsible and ethical manner**

Overview of the Quantum Ecosystem

The UK is developing a thriving quantum ecosystem across a broad range of quantum technologies including sensing, communications, timing and computing. With more investments in UK quantum businesses than in any other European country, the UK's quantum ecosystem is poised to be a world leader.[6] This section will showcase the key players currently operating in the quantum ecosystem, before further sections explore how to work together for commercial success in the UK.

UK Government

The UK's commitment to building an innovation ecosystem around quantum has been a key success of the National Quantum Technologies Programme (NQTP). The NQTP and its four technology hubs have brought together industry and academia to explore how to commercialise quantum technologies. With the second phase of the NQTP ending in 2024, it is the right time to evaluate the successes of this programme and how it can be used to push forward commercialisation in the UK.

So far these Government programs have been inclusive of all quantum technologies, and this should be continued as we move towards commercialisation. It is important to account for the different technology readiness levels across different quantum technologies, an approach that has been taken across other leading nations, such as in the United States.[7] For example, security is a key area for commercialisation in the coming years. We expect quantum key distribution, a technology that is becoming increasingly market ready, to enter market earlier than some other quantum technologies. Equally, due to the challenges already faced in random number generation, some expect quantum random number generation (QRNGs) to be closer to commercialisation. Therefore, depending on the readiness of each quantum technology, government and industry will need to support their journey towards commercialisation in different ways.

The NQCC will play a vital role in the UK's innovation ecosystem by convening stakeholders from across academia, business, and government to address the challenge of scaling our nascent quantum computing industry. Starting with developing a Noisy Intermediate Scale Quantum (NISQ) machine to give access to developers and stimulate the emergence of a robust UK-based quantum supply chain, the NQCC will be the foundation of the UK's quantum ecosystem in the years ahead. This should be viewed as an international exemplar in the quest for commercialisation. Furthermore, in 2021, the UK Government also invested £210 million in the Hartree National Centre for Digital Innovation, which will bring together AI and quantum computing in recognition of the convergence of quantum with classical computing.[8]

The UKRI commercialising quantum technologies challenge is forging connections between Government, the quantum industry and the wider UK tech sector. This challenge is investing £170m to develop new products and technologies based on advances in quantum science.[9] Projects like this should be encouraged and promoted, as they encourage private investment and create economic and societal benefits in quantum. They also promote the opportunity for international commercial partnerships to unfold in the UK.

How does UK Government Funding Compare?

US National Quantum Initiative Act proposes US$1.2 billion (961.3 million sterling pound) over 5 years

EU Quantum Flagship program budgeted at €1.0B (858.3 million sterling pound) over 10 years

Canada invested over CAN$1 billion (625.9 million sterling pound) over the last decade

China's National Lab for Quantum Info Science received 7B RMB (839.5 million sterling pounds) in funding

Japan set aside more than 30B yen (188.7 million sterling pound) for quantum in a 10-year research plan

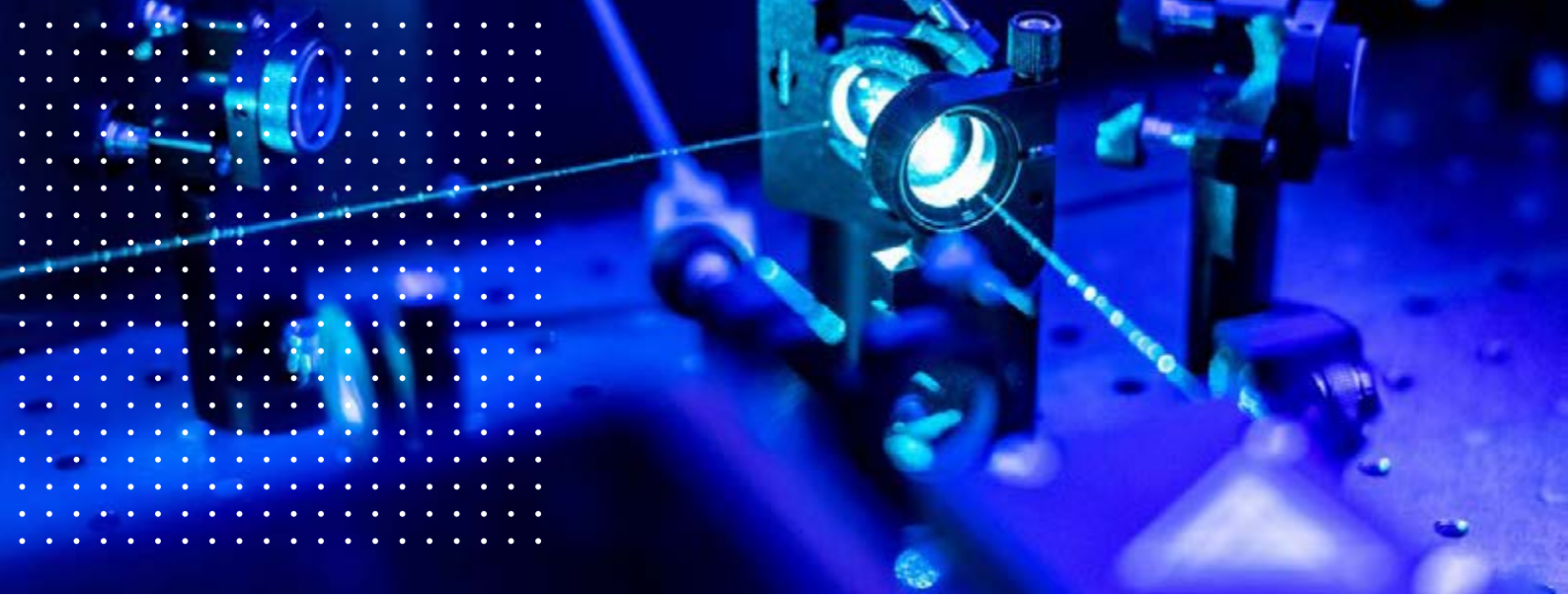
UK program has exceeded £1B in cumulative investments since 2013

Source: OSA Industry Development Associates (OIDA)

This public sector funding is competitive alongside other leading quantum nations, but ambitious initiatives in quantum technologies are taking shape across a number of countries.

Germany, for example, is investing €650m to progress quantum research to market-ready applications. China were early to deployment with the world's first integrated quantum communication network established in 2021, combining ground optical fibres with two ground-to-satellite links to achieve quantum key distribution (QKD) over 4,600 kilometres. It has the potential to power use cases from banks, municipal power grids, and e-government websites.[10] The UK has already recognised the important role Government will play in quantum research and development, but as the international race towards commercialisation accelerates, there will be a fundamental role for government working with the UK tech sector, academia, and industry to identify, develop and invest in commercially viable use cases.

The UKRI commercialising quantum technologies challenge is forging connections between Government, the quantum industry and the wider UK tech sector. This challenge is investing £170m to develop new products and technologies based on advances in quantum science.



Private Investment

The UK has a strong venture capital network and start up ecosystem. Indeed, the UK technology sector is now valued at one trillion in 2022 after growing 42% between 2020 and 2021[11], only behind China and the US, and more than double the next most valuable ecosystem, Germany, at $235bn.[12] In this ecosystem, a new technology business is created every half an hour, with nearly 19,500 registering in total across the UK during 2020.[13] This creates a favourable environment for quantum start-ups looking for a successful foundation.

The NQCC has identified over 40 UK quantum start-ups generating £135m of investment by the end of 2021. There were approximately 90 quantum investments in 2021 – this might seem relatively minor compared to other, more established, tech-based industries, this represents a steady increase from 2020 and 2019, demonstrating strong growth in the sector and investor confidence in the underlying research.[14] This ecosystem is already viewed favourably outside of the UK, and we are starting to see international quantum companies interested in the UK market, but more can be done to attract international quantum businesses to the UK, and this should be a priority for the national quantum programme. While the UK's quantum ecosystem is built on a proven foundation of academic success, it is important to note that quantum is still a "deep tech" industry that will require capital to reconcile engineering challenges and scalability required for widespread commercialisation.

Equally, developing a strong commitment to R&D will help develop a UK quantum ecosystem that is ready for commercialisation. R&D in the UK is viewed as a joint undertaking by Government and the private sector. The Government has set the target of achieving 2.4% of GDP invested in R&D by 2027. Increasing this from the 2018 level of 1.7% of GDP invested in R&D will mean achieving the fastest increase in R&D spending in over 20 years.[15]

In response, private investment in R&D has increased significantly and the share of private investment in R&D makes up a larger proportion of the UK's total investment now than it did in 1985, and in 2018 accounted for 68% of all investment in R&D. While we have seen welcome increases in public sector commitments to invest in R&D, ensuring private sector investment continues to rise will be vital to achieving the 2027 target.

With the public and private sector working together, the UK has achieved one of the greatest innovation heritages in the world, with an established legacy of turning research into development - from Turing's computer to the recent COVID-19 vaccine rollout.[16] The UK remains the fourth most innovative global economy[17], and we also have more unicorns than any other country in Europe.[18] These are all influential factors for quantum start-ups looking for a place to flourish. We are also home to high-employment, high R&D investment sectors such as telecoms, automotive and aerospace, which are key players in new technology development, and this is equally true for quantum. These factors could be major pulls for global quantum talent, catalysts for partnerships, and key tools for international influence in this space.

One recent commercial success for the UK that shows the importance of public and private partnership was the collaboration between BT and Toshiba, along with EY, who together launched the trial of a world first commercial quantum secured metro network.[19] The infrastructure will secure the transmission of valuable data and information between multiple physical locations over standard fibre optic links using quantum key distribution (QKD), of which the initial research was funded by UKRI.[20]

Private investment in numbers

£4.8 billion private investment raised globally

(Asia 5%, EMEA 25%, Americas 70%)

Over £245m UK V/C funds raised

Source: Provided by National Quantum Computing Centre

The role of the wider UK tech sector

It is also crucial that we are seeing commitment in the UK from the wider UK tech sector supporting this innovation ecosystem. Many established technology companies in the UK are developing quantum workstreams and partnering with the quantum industry, making it clear that the wider technology sector is helping develop the quantum innovation ecosystem and UK supply chain. Indeed, it is these partnerships between Government, the UK tech sector and the quantum industry that will be key to building a successful quantum ecosystem, and these partnerships should be actively sought out. This investment is coming from technology businesses working across different technologies, potentially representing the plurality of cases in which quantum can be used. The UK tech sector will also play a fundamental role in providing access to quantum technologies through cloud, high performance computing and other emerging technologies that will form part of the quantum stack. Finally, the services, applications and software developed to enable application of quantum technologies will open opportunities for the UK tech sector to bring quantum closer to their existing products and services. The increased interest already shown by the wider UK tech sector is promising for the prospect of commercialisation.

Is quantum computing the technology that will ultimately unlock a decarbonised world?

By Glenn Manoff, Chief Marketing Officer, Riverlane

It is easy to be pessimistic about our collective ability to achieve UK and global net zero targets. Headlines about continued record temperature rises and their ticking clock consequences abound.

But quantum computing has the potential to help deliver the breakthroughs we need in sustainable low carbon technologies. While there's no silver bullet right around the corner, we're starting to take the first meaningful steps in this direction.

The UK is leading the way via its Clean Growth programme, led by Cambridge based quantum engineering company Riverlane in partnership with sustainability technologies company Johnson Matthey and quantum computer makers Rigetti and ColdQuanta.

How quantum computing can provide a quantum leap

The scientific solutions to global warming are remarkably simple: we need to store renewable energy cheaply; electrolyse water efficiently; and capture CO2 effectively. The problem is the world's existing computing systems are woefully incapable of advancing these goals.

Quantum computers have the potential to deliver speeds for these calculations that are millions of times faster than today's most powerful 'classical' computers. By using the quantum concepts of superposition and entanglement they enable multi-dimensional computing that can simulate the true complexity of the subatomic world. It's a paradigm that will transform our ability to understand and model nature.

Battery materials

A major challenge is that our electricity networks effectively contain minimal facility for energy storage. So, while we can press on with the conversion to renewable power from wind, hydro and solar, their net zero impacts will be stymied until we can provide a way to produce ultra-low-cost batteries with vastly more long-term storage capacity than today's Li-ion batteries.

Current battery R&D relies on cycles of experimentation, with each cycle lasting multiple weeks. The goal is to identify better catalysts that will lead to better batteries. The problem is there are endless possibilities so it's like searching for a needle in a haystack. Quantum Computing offers the ability to accelerate the process by simulating every element of the battery chemistry in a virtual experiment at the atomic level.

With backing from UK government, Riverlane is engaged in an advanced research programme with Johnson Matthey that's working step by step toward Lithium-Air batteries and enabling a quantum version of Moore's law, where battery performance will double every year.

Hydrogen production

One of the great conundrums in the battle against climate change is our failure to produce hydrogen from water efficiently. The issue is the nature of water which, while ostensibly being a very simple molecule, is highly complex in the liquid state due to intermolecular bonding.

Today's limited quantum computers are being employed to help in the search for efficient hydrogen production by simulating the electrolysis process. In 2020 Shell worked with physicists from Leiden University to do exactly this, and IonQ, a quantum computing technology company, successfully calculated the simulation of a water molecule on one of its quantum devices in 2019. As quantum computers improve, so will these processes.

Making quantum computing real

The advances needed to deliver on operational quantum computing are in the process of being met. At Riverlane we have made huge strides in building the operating system that will run them. Once built, these models and simulations will allow us to evolve a deep understanding of nature and how to combat the existential threat of climate change.

Quantum Skills

Quantum skills is one of the five key interventions identified in this report, and techUK believes we need to rapidly address the growing quantum skills deficit in the UK to develop a thriving quantum ecosystem. This section will underscore why opening access to quantum skills, whether through Government funded internships for greater industry experience, post-graduate certificates to encourage upskilling, or opening routes for international talent, will be key for commercial success. This cannot be achieved in isolation, and a strong skills pipeline will require industry, academia and government working together.

Quantum skills are undeniably in demand. One of the biggest challenges of commercialisation is the development of a suitable talent pipeline, and the UK is in fierce international competition to create the right environment for such skills to develop.

Research by Quantum Futures provided to techUK shows that salaries in quantum are starting at £50,000, increasing to over £90,000 in five years. However, for positions in the United States salaries are reaching $250,000 (£192,000) within five years of experience in the industry.[21] It is difficult for the UK to keep pace with this level of investment and growth; this places intense pressure on both start-ups and scale-ups in the UK trying to attract quantum talent. Consequently, ramping up the talent pipeline must happen immediately and rapidly to mitigate the potential of brain drain. The development of a suitable talent pipeline in the UK will be difficult and will require the UK tech sector, the quantum industry, academia, and UK Government to actively work together to prioritise quantum skills.

In developing talent, the UK has already made progress with academic programmes with more than 30 UK universities delivering over 400 PhDs across quantum specialties – these initiatives

Quantum Computing Salary Benchmark	PhD (grad)	POST DOC (2 years)	1-2 years (industry)	2-3 years (industry)	3-4 years (industry)	5+ years (industry)
Quantam Algorithim Scientist	£50k+	£55-65k	£60-75k	£70-80k	£80-90k	£90k+
Quantam Hardware Engineer	£45k+	£50-60k	£55-75k	£70-75k	£75-85k	£90k+
Quantam Software Engineer	£50k+	£55-60k	£60-70k	£70-80k	£80-95k	£90k+
Optomechanical Engineer	£45k+	£50-60k	£55-70k	£65-75k	£70-80k	£85k+
Superconducting Circuit Designer	£50k+	£55-65k	£60-75k	£70-80k	£80-90k	£90k+
Business Development	£45k+	£50-65k	£60-70k	£65-75k	£70-80k	£80k+

Source: Quantum Futures

should be both praised and encouraged.[22] However, developing the right skills is not an academic challenge alone, and will require coordinated strategy from government and industry to get this right. This is especially crucial in the move towards commercialisation, and it is fundamental that skill development aligns with the quantum industry and the wider UK tech sector to identify the quantum opportunity and utilise quantum technologies in the UK.

Quantum commercialisation will also require the development of a quantum-literate workforce who have appropriate skills to enable the deployment of quantum products and services. This includes a quantum-literate workforce within the wider UK tech sector who are empowered to use and utilise quantum technologies and their applications. This sector will need a broad skills base from electrical engineers, materials scientists, network specialists, computer programmers and business leaders who can be upskilled to exploit the quantum opportunity.

In developing talent, the UK has already made progress with academic programmes with more than 30 UK universities delivering over 400 PhDs across quantum specialties – these initiatives should be both praised and encouraged.

The findings in this section are the result of ongoing discussions and a roundtable techUK held with its members and the Department of Business, Energy and Industrial Strategy to explore what the UK tech sector thought about key interventions on skills and how we can continue to support the sector to maintain its world-leading status as commercialisation takes hold.

Quantum skills should align with other technologies

Quantum will align closely with other forms of technologies; whether in developing new business use cases, enabling existing use cases to become more efficient or sustainable, or being deployed to solve some of the key national challenges the UK is facing in developing low carbon solutions and cyber security.

Quantum will require a plethora of skills outside of quantum engineering or physics including data science, cloud skills, broad based software development, and business skills like critical thinking, customer engagement and interview skills. Combining these skills with quantum awareness will help encourage access to quantum technologies for many businesses. Crucially, these skills are also part of the UK's baseline skills required for the modern workplace.

techUK has previously highlighted the particular importance of these baseline digital skills to ensure the UK's workforce is prepared as technology becomes more embedded and sophisticated within techUK's skills report, Fast Forward for Digital Jobs.[23] This report found that cloud computing was the most in-demand technology skill in 2020 and that AI skills have seen a resurgence, jumping 73% in six months. Both of these technologies will be deployed and utilised alongside quantum.[24] techUK members understand that many people will be working and utilising quantum technologies primarily alongside broader computing and business solutions for commercialisation. Upskilling and awareness will be fundamental to this.

This underscores the importance of Government and industry to work together on education programs that accelerate cross-disciplinary programs that bridge engineering, science, business, and social sciences to develop graduates with an understanding of the huge potential of quantum from both a technological and business perspective. The combined University of Bristol and NQCC courses, aimed at professionals, researchers or leaders in business, government, academia or commercial organisations wanting to move into the field of quantum technologies is a key example of this and a step in the right direction for UK businesses.[25]

Opening quantum education to more people beyond a PhD level

It is unsustainable to develop a talent pipeline where everyone working in quantum needs a PhD. However, at this moment, it can be difficult for those without a PhD to find technical roles within quantum. Undeniably this creates a high barrier to entry for a career in quantum - a high barrier that the UK cannot shoulder when further compounded by intense international competition and the need to scale quickly for commercialisation. It should be a priority for both the UK government and industry to reduce barriers to entry for a career in quantum, if we are to be a world leader in commercialisation.

Thankfully, other paths into a career in quantum other than a PhD are starting to emerge. Research by the QED-C shows that a quantum-ready workforce requires a variety of technical and business skills at different educational levels. Crucially, except for the highly specific and technical jobs identified in this report, such as quantum algorithms developer or error correction specialist, companies that responded to the report are looking for a range of degree levels to fill these new positions, from bachelors to masters to PhDs.[26] With this information, industry can understand where lowering the barrier to entry could be possible with the expectation of on-site training during the graduate programme. These are starting to be offered in the UK, but more could be done to encourage this route into a quantum career.[27]

UK tech sector demand for skilled workers with expertise in quantum outstrips the supply from academia. It is key that the UK Government and the tech sector should collaborate on graduate programmes and internships to build connections between academia and industry, and lower barrier to entry. This could follow the UK Space Agency who operate a placement programme called SPIN (Space Placements in Industry) which co-funds paid work placements across the sector. This is already being explored internationally with quantum technologies, and shows best practice for developing a quantum-enabled workforce. The United States Government (through the National Science Foundation) helps fund graduate students to gain knowledge, skills and experiences for a successful long-term career through an internship in a non-academic setting and acquire core professional competencies and skills.[28] In the UK, this would help start-ups identify talent, build connections between industry and academia, without the huge upfront cost.

...it can be difficult for those without a PhD to find technical roles within quantum. Undeniably this creates a high barrier to entry for a career in quantum - a high barrier that the UK cannot shoulder when further compounded by intense international competition and the need to scale quickly for commercialisation

It is key that the UK Government and the tech sector should collaborate on graduate programmes and internships to build connections between academia and industry, and lower barrier to entry.

Upskilling the UK tech sector to unlock the quantum opportunity

Currently, there is a shortage of talent familiar with the technical skills needed for quantum, and even fewer candidates with business training that will be needed for quantum commercialisation. It will be rare for businesses to find a candidate competent in all key areas needed and businesses are increasingly recognising and preparing to offer necessary upskilling on the job to develop the right talent needed. Upskilling will be a key and fundamental part of the commercialisation process and is an area the UK tech sector and UK Government can work on together.

UK Government could help deliver training opportunities, working to develop post-graduate certificates to fill key missing gaps; and education programs that accelerate cross-disciplinary programs that bridge engineering, science, business, and social sciences to develop graduates with an understanding of the huge potential of quantum from a technological and business perspective. These programmes could also fund studies on the societal and ethical considerations of quantum technologies, where the UK could grow as a leader.

The UK has had success in the creation of AI Masters conversion courses which enable graduates to do further study courses in the field even if their undergraduate course is not directly related.[29] These courses have enabled 2,500 people to develop new digital skills or retrain to help find new employment in the UK's cutting-edge AI and data science sectors.

Upskilling will also open a greater understanding of the quantum opportunity across businesses who are empowered to use and utilise quantum technologies as part of a business solution. Those able to identify the quantum opportunity will not necessarily need all the technical skills to build a quantum computer, as an example, but how to access quantum technologies and build them into a business process. Equally, as the technology matures, the UK tech sector could help by utilising familiar development toolkits and software integration will make this upskilling more seamless.[30]

Developing the international talent pipeline

Ramping up the talent pipeline must happen immediately and rapidly. One of the biggest challenges of commercialisation is the development of a suitable talent pipeline and the UK will be in fierce competition with other nations that feature the development of skills as one of their core objectives and have already had considerable successes such as the United States and Germany closer to home. To remain competitive, we must ensure that the UK has access to the large international talent pool from overseas, and that, in turn, the UK remains an attractive place for international talent to develop a career in quantum.[31]

It is important, then, that the UK is considered an international leader in quantum which will help attract international talent; and through the work of the NQTP has developed a favourable quantum ecosystem that will offer opportunities to those looking to develop a career in quantum. Industry and Government should showcase UK successes, especially focussing on use cases to encourage more business interest. Quantum-based key national challenges will develop opportunities in the UK, providing business stability and attract businesses into the UK market.

Enhancing visa flexibility for quantum talent, including short-term access for academic-industry placements and internships, will also be crucial. techUK welcomes the number of steps Government has already taken on the immigration system to restate the UK's commitment to science, research and innovation. This includes the proposed Scale-Up Visa and work towards creating a Global Talent Network. This will make it quicker and easier for growing digital businesses to bring in highly skilled individuals, but tech employers have expressed difficulty attracting talent to the UK based off the difficulty to create international internships for PhD students, and in turn losing out to other nations. Increased openness will also motivate foreign companies to invest in the UK.

As the UK settles into the second year of the new points-based immigration system, techUK believes this is an opportunity to streamline the immigration system so it engenders public confidence and works for businesses of all sizes. The UK should not lose out on the key skills and talent needed due to difficulty in application processes. This is especially true for start-ups and SME's leading the way in quantum innovation but may not have the knowledge or capacity for an overly complex visa system.

Attracting international talent will also require collaboration between academia, industry, and government. Increased industry-academic collaborations are needed to pull research talent into innovation ecosystems and industry. Favourable international examples include Canada's NSERC's CREATE program, which is praised for being successful in developing next-generation talent. Equally, the Alberta Technical University of Munich School program between the University of Alberta and Germany is also an example which has developed international talent pipelines. These examples indicate international joint PhD programs and other mobility programs can help bring international students to the United Kingdom.

Business skills are needed for commercialisation

Identifying opportunities for commercialisation will require business development roles working in quantum. By focusing only on the technical skills needed, we risk limiting engagement with end users understanding the commercial opportunity. Upskilling should work both ways, and key interventions in training should also highlight the business skills needed for commercialisation.

Summary of recommendations

1. **Government and industry should work together to open access so that PhD's are not the only route into a career in quantum.** Changing this large barrier to entry will allow for more talented people to enter the sector, increase the sector's diversity, and fill industry job shortages.

2. **Government should encourage the move to industry by funding industry placements making the move from academia to industry more attainable.** These placements should also be available for international talent to mitigate difficulty in creating internships and industry placement for international PhD's.

3. **Digital skills for different technologies should not be viewed in isolation.** Quantum will align closely with other forms of technologies and cross-disciplinary programmes to bring technologies together should be encouraged.

4. **Support upskilling for a quantum literate workforce.** This can be done through training opportunities and education programs that accelerate cross-disciplinary programs that bridge engineering, science, business, and social sciences to develop people with an understanding of the huge potential of quantum from a technological and business perspective.

5. **Ensure the UK has access and remains attractive to large international talent.** Enhancing visa flexibility for quantum talent, including short-term access for academic-industry placements and internships, will be crucial so that we hire the best and brightest to progress the UK's quantum journey.

6. **Drive wider business skills and socio-ethical skills.** To create a successful quantum ecosystem, key interventions in training should include business skills that needed for commercialisation.

How do we develop a quantum ready workforce?

By Anuj Doshi, Quantum Computing Specialist at Data Reply UK

I like to draw parallels between Classical and Quantum computers to illustrate where we are on our Quantum Journey. In classical computing, it took 71 between the first computer, the Turing Machine being developed till the first iPhone came to market. Likewise, we are only 20 years into Quantum hardware, but it is rapidly improving. We need the UK to be Quantum Ready to reap the benefits as soon as the hardware becomes available.

To unlock the full potential of Quantum Computing in Industry we need the algorithm rich knowledge from Quantum Researchers to meet the specific computationally expensive challenges faced by the industry. The largest gap in the workforce is individuals with expertise in both these areas. One might suggest getting two people to work together, one with industry knowledge and the other with Quantum knowledge. Unfortunately, this is a lot harder to execute in practice since it isn't obvious which use cases and problems could be improved with Quantum Devices. Both industry experts and quantum specialists both struggle with identifying each other.

So, how can we solve this in the near term? There are two obvious solutions from my perspective. Firstly, we train members of the Industry with enough Quantum Computing knowledge, so they know to highlight potentially computationally expensive use cases for Quantum Computers. Secondly, a Quantum Specialist could be dropped into a company and rotated through different departments investigating the entire business and highlighting areas of interest. Both these approaches can lead to fruitful PoCs and the identification of near-term use cases. To this end, I expect there to be rapid growth in training pathways, certifications, and quantum education for non-scientists and experts alike. It is something that I and many others are working on today.

To unlock the full potential of Quantum Computing in Industry we need the algorithm rich knowledge from Quantum Researchers to meet the specific computationally expensive challenges faced by the industry.

In the longer term, I expect algorithms to be optimised and simplified, lowering the barrier to using gate computing. The day when Quantum Computing hardware becomes available easily accessible and cheap for the public to use, we will see applications that we can't even dream of today (much like the explosion of the Web and its applications). That day is a long way away but each PoC, each lesson taught, each webinar viewed brings us one step closer to that future.

Quantum and Emerging Technologies: Developing Access to Pioneering Commercialisation

Quantum technologies will not be used in isolation and commercialisation will rely on the convergence of other emerging technologies, including cloud, high-performance computing and AI. This is especially true for quantum computing, but also should be considered for other forms of quantum technologies such as quantum sensing and communications. This section of the report will explore how to support the development of infrastructure that will enable access to quantum, including the convergence of technologies with quantum in the coming years.

Many areas where quantum will be effective will not be quantum-niche, but will be incorporated into existing use cases, such as drug discovery or process optimisation, as a way to enhance efficiency, sustainability, or in novel solutions to potential data security threats from quantum. They will require convergence with other technologies as part of a wider technology toolkit available for businesses. There is a huge opportunity to bring the wider UK tech sector into the quantum ecosystem as these use cases begin to incorporate quantum.

To bring quantum into these use cases, investment into supporting infrastructure that will enable access to quantum and other technologies is required. The UK needs to prioritise building the infrastructure needed for quantum; as explored below, we may already be on the back-foot in terms of investment into key enabling technologies like high-performance computing.

To enable development of this infrastructure, we argue that the wider UK tech sector also has a crucial part to play in providing access to quantum technologies and emphasise the importance of building partnerships between Government, the quantum industry, the UK tech sector and end users to develop use cases.

What needs to happen?

For quantum access to happen, UK Government needs to play a crucial role. UK Government should think in particular about encouraging access to quantum for SME's and start-ups, to make sure quantum is accessible. This will include exploring different access models to quantum. International partnerships with those who can provide access to existing quantum capacity will be particularly valuable to support UK businesses adopting quantum, especially as other nations push forward in building HPC/quantum capacities.

Domestically, the UK has started to make headway with the development of the NQCC which will be crucial to give businesses the ability to experiment and scope out the use cases which will be most effective. As this develops, we need to think boldly about how to engage industry and end-users into developing commercially viable use cases with this technology as well as preparing organisations for broader implications for quantum technologies such as security. Here, UK Government could incentivise businesses to access quantum systems through Government Grants as seen in the United States.[32] The 'Quantum User Expansion for Science and Technology program' (QUEST) is an example of best practice in this space. This programme aims to encourage and facilitate access to United States quantum computing hardware and quantum computing clouds for research and development purposes, which will encourage use of quantum.[33]

Finally, the importance of UK Government, the wider tech sector and the quantum industry working together is paramount. Commercialisation of quantum technologies is a complex process that requires quantum leaders working together, an open network of knowledge sharing, and partnership is key to make quantum access and infrastructure a success.

The goal is to make quantum as accessible as possible to encourage adoption

As commercialisation becomes a tangible goal, it is imperative to give businesses the ability to experiment and scope out the use cases which will be most effective. Raising awareness that this is an opportunity that exists in the UK should be a priority. Government should think about access to quantum particularly for SME's and start-ups, to make sure quantum is accessible for smaller industry players and help foster innovation. Hybrid quantum systems will offer early users have access to quantum capability and have been recognised as foundational to the future of the adoption of quantum technology.[34] In quantum computing, the NQCC is an important development here. We will not switch to a brave new world of quantum overnight. It will be an incremental process that enables businesses the opportunity to scope out and experiment with use cases.

Bringing technologies together is fundamental for quantum success

Below we highlight some of the key technologies crucial for commercialisation. This multi-disciplinary approach towards convergence of quantum with other emerging technologies is fundamental to accelerating commercialisation in the UK. Afterall, there is a global race to harness the transformative power of quantum, and the UK should use its strengths with other emerging technologies to win this race. If we do not recognise the importance of these technologies working together, we will get left behind by other leading nations already facilitating convergence of these technologies in new use cases.

It should also be recognised that quantum can make other emerging technologies more powerful. For example, current approaches to AI are limited by classical ML algorithms and quantum could be used for the rapid training of machine learning models and to create optimised algorithms. It is a win-win situation for the UK if we get this right. Finding areas of overlap and complementing use cases at the stage of commercialisation will be key, and the UK tech sector can play a key role here.

One way to develop convergence is for Government to explore how emerging technologies can tackle key national challenges together. This frames quantum as a part of a wider technology toolkit available for businesses in the UK as a science and technology superpower. We are at serious risk of isolating technology supply chains, use cases and talent pipelines if each individual technologies are isolated and have competing strategies and goals. Furthermore, it should be noted that the success of future innovation and cyber-security strategies is likely to depend on our ability to integrate different technologies.

One way to develop convergence is for Government to explore how emerging technologies can tackle key national challenges together… [framing] quantum as a part of a wider technology toolkit available for businesses in the UK as a science and technology superpower.

Whilst this section has a focus on the access of quantum computing, we need to think inclusively to support the wide array of quantum technologies that have differing capabilities, strengths, timelines and maturity levels.

High performance computing

In 2023, 76% of HPC centres worldwide will be using quantum technologies — the majority with an on-premises infrastructure.[35] The main diver of integrating quantum into HPC infrastructure is staying ahead of the competition, with 52% of HPC centres worldwide stating this, meaning quantum is viewed as a key technology to achieve innovation. Furthermore, quantum is suited well to help tackle some of the leading challenges HPC is trying to solve, from weather forecasting to drug discovery, molecular dynamics, physical simulations, natural disasters, and artificial intelligence. This integration between HPC and noisy intermediate scale quantum (NISQ) is already being implemented for pharmaceutical drug development.[36] These align closely with the key national priorities the UK Government have identified for the UK, including becoming a science and technology superpower and achieving net-zero.

We must prioritise investment into HPC in the UK. The recent Government Office for Science review on HPC highlights that the UK's large-scale computing infrastructure lags behind other major global economies. With the prominent interconnection between HPC and other key emerging technologies where the UK is positioning itself as a leader, the lack of attention paid to HPC in the UK could also potentially hinder the UK's dominance in these areas too.[37]

We are not starting from zero, and the innovative work being driven at the Hartree Centre through public and private investment since 2021 is

worth highlighting. The Hartree Centre has started to apply AI, HPC, quantum computing and cloud technologies to boost discovery and develop innovative solutions to practical problems raised by UK industry.[38] The centre will work across sectors including materials, life sciences, environment and manufacturing. This will include collaboration with academic and industrial research communities, including start-ups and SMEs, public sector, and government.[39]

This is a great step for the UK, but other European countries such as France are starting to assert dominance in the intersection of these technologies. At the beginning of 2022, The French Government launched a new programme to link quantum machines and supercomputers, with the aim to make this technology accessible to as many people as possible, including the scientific community and French and EU start-ups. The platform has a total budget of €170 million and is part of the €1.8 billion national quantum strategy.[40] Alongside UK exclusion from EuroHPC, a joint initiative between the EU, European countries and private partners to develop a World Class Supercomputing Ecosystem in Europe, there is danger a gap is emerging between the UK and the rest of Europe on HPC capabilities, and this could potentially hinder UK use cases where quantum and HPC intersect.

Cloud

The global Quantum Computing-as-a-Service (QCaaS) market is expected to reach $4 billion by 2025 and $26 billion by 2030, delivered through the cloud.[41] Most customers are expected to access quantum computers in the cloud – either through public cloud services or private clouds linking directly though the underlying hardware providers. Currently, a variety of quantum computers are available through the cloud, including annealing and gate-model quantum systems as well as systems using superconducting chips, ion traps and photonics for their qubits. The tech sector is already offering cloud-based access to quantum computing, and in 2021 the UK announced its first commercially available Quantum Computing-as-a-Service through private cloud.[42]

techUK has explored with members the crucial role cloud will play in providing initial access to quantum computing to businesses where quantum was previously unattainable.[43] This 'democratisation' of quantum will boost investment and skills by giving many more companies access to quantum without the huge capital investment, accelerating adoption across the economy.

The global Quantum Computing-as-a-Service (QCaaS) market is expected to reach $4 billion by 2025 and $26 billion by 2030, delivered through the cloud.

It is understandable then that in the United States, the Center for Data Innovation called for investment into a national quantum computing cloud that provides affordable access to high-end quantum computing resources.[44] techUK believes affordable access through the cloud should be encouraged, and the UK Government could incentivise businesses to access quantum systems through Government incentive programmes that enable businesses to become quantum ready, and enable easier experimentation with quantum technologies for research and development.[45]

Artificial intelligence

Machine learning and artificial intelligence are increasingly becoming part of businesses technology toolkits used to innovate and solve business challenges. However, this technology can require huge computational resources and can be time-consuming. One new solution could be through the use of quantum machine learning (QML) techniques to enhance the performance of classical ML algorithms.[46] Here, quantum can be used for the rapid training of machine learning models and to create optimised algorithms. Equally, AI could help solve quantum calibration problems by automating much faster calibration routines and accelerating the delivery of quantum systems. In the coming years, the relationship between quantum and AI will be significant, with one report by EY stating that the top-ranked quantum computing use case across sectors will be to enhance to AI and machine learning.[47]

Summary of recommendations

1. **Investment into supporting infrastructure that will enable access to quantum is needed.** This includes encouraging key connections between quantum and high-performance computing, AI and cloud

2. **Encourage convergence between quantum and emerging technologies through key national priorities** and developing opportunities for this convergence to take place

3. **International partnerships with those who can provide access to existing quantum capacity** will be particularly valuable to support UK businesses adopting quantum, especially as other nations push forward in building HPC/quantum capacities.

4. **Government should think in particular about encouraging access to quantum for SME's and start-ups,** to make sure quantum is accessible. This will include exploring different access models to quantum through the cloud.

Commercialisation Opportunities at the Intersection of Quantum Computing and High Performance Computing

By Per Nyberg, Vice President, Quantum Machines

High performance computing (HPC) is commonly applied by organisations to use-cases of scientific, industrial, and societal importance in cases where the need for greater computational and data-driven capabilities are required. While there is a wide range in these capabilities, access to HPC is ubiquitous with systems located in private and public data centers, supercomputing centers, and the cloud. The HPC community has always been at the forefront of technology and continues to play a pivotal role in novel technology adoption where such technologies are often first adopted. Novel technologies not only speed up existing applications but also open the opportunity for the development of entirely new approaches. This is of course what we expect with quantum computing where HPC is already playing a key role in the deployment of quantum capabilities. Effective use of novel technologies requires tight integration across the hardware and software stack. As such today's HPC architectures are composed of multiple processing, memory, communication and storage technologies and this heterogeneity reflects the varied characteristics of algorithms, applications, and workflows.

Today's quantum world is still quite nascent and highly fragmented, with many quantum architecture modalities and an evolving technology stack. While much is unknown about how large scale quantum systems will be architected and about the requirements and characteristics of quantum algorithms and applications, it can be said with some certainty that quantum and HPC will drive the development and commercialisation of an entirely new set of technologies.

One parallel that has brought about fundamental changes to the HPC market is with data-driven approaches such as machine learning and deep learning. Traditionally HPC architectures were designed for simulation based approaches such as computational fluid dynamics. The different nature of machine learning, combined with its market demand, has driven innovation and given rise to AI specific processors, file systems, solid state storage technologies and vertical specific applications. The architectures of today's HPC systems have evolved to effectively support both simulation and data-intensive workloads. Much of this innovation and commercialisation was driven by startups who capitalised on new requirements and new markets created by the potential of machine learning.

We can expect a similar trajectory with quantum computing. In the context of today's stand-alone quantum computers, the technology stack is composed of the software development layer through to the quantum control layer and then to the QPUs. Integration into HPC requires a view that extends upwards through a broader traditional computing infrastructure. The challenge is that quantum computing has its own set of unique characteristics. Achieving effective integration into a heterogeneous HPC environment that will provide the necessary performance advantages, will require careful consideration across the entire stack and thus open entirely new areas of innovation and commercialisation. A final point is that experience has demonstrated that access to HPC and quantum testbeds are vital for technologists, developers and entrepreneurs to flourish.

Developing International Leadership and Collaboration in Quantum Technologies

Commercialisation will rely on the import and export of quantum products, technologies and services in the UK. Both new and existing international networks and markets will help broaden opportunities for UK successes, creating a shared knowledge base and opportunities to drive new discoveries.

The UK needs to think internationally from the start, both in terms of collaboration and regulation, for commercialisation in the UK. We need to highlight to other nations that the UK is the place for commercial success in quantum and access to the UK market is a route to success.

In this section, techUK outlines why partnerships will be crucial for access, talent, research and development, and ultimately achieving commercialisation. We are also aware of the need for innovation-friendly regulation that maintains public trust and safety around quantum especially as research moves towards application and deployment. Indeed, business and government communities should leverage trade agreements to establish cooperation on the development of regulation, standards and interoperable regimes around quantum.

Finally, it is important to underscore the areas in which the UK can also be a thought leader such as quantum ethics. There is a role that the wider industry can play in showcasing this, building the UK market into a thriving hub for quantum innovation.

Showcasing UK Success

The UK should be vocal about its success in quantum. We need to show to international leaders that the UK is a global leader and the place for commercialisation, and this should underpin any coordinated quantum initiatives between government, industry and academia in the UK. The establishment of the National Quantum Technologies Programme (NQTP) and the four technology hubs in 2014 have been crucial for bringing together industry and academia. Meanwhile, over 40 UK quantum startups generating £135m UK start-up investment by the end of 2021, and a steady increase in investments into quantum in the UK, ensures that the UK quantum ecosystem will be viewed favourably as a place for commercial viability.

Furthermore, the quantum ecosystem is supported in the UK by one of the greatest innovation heritages in the world, with an established legacy of turning research into development from Turing's computer to the recent COVID-19 vaccine rollout. We are also home to high-employment, high R&D investment sectors such as telecoms, automotive and aerospace, who are key players in new technology development, and this is equally as true for quantum. From an academic perspective, the UK has four out of the top 10 global universities, it also accounts for 4% of researchers, 7% of academic publications, and 14% of highly cited academic publications in the world despite having less than 1% of the world's population, and it has three of the most science and technology intensive clusters in the world in Cambridge, Oxford, and London.[48] These factors could be major pulls for global quantum talent, catalysts for partnerships, and key tools for international influence in this space.

techUK has been committed to showcasing the work of our members around quantum in the UK, bringing together networks and generating debates on how to build a successful ecosystem in the UK. The UK quantum ecosystem is eager to tell its story around the world and build a strong reputation for commercial success. In turn, the UK Government should use international collaboration and partnerships as an opportunity to showcase the weight of the UK quantum ecosystem, and match this with continued commitment to support the development of the UK quantum ecosystem through grants, opportunities and procurement.

Partnerships and collaboration

Commercialisation cannot be achieved alone. Sharing technologies, infrastructures, skills and knowledge with international partners are all key steps in achieving commercialisation. Partnerships will be crucial to provide access to international quantum capacity which will be particularly valuable with other nations who are pushing forward HPC/quantum capacities and infrastructure. Understanding the UK's limitations in how quickly we can scale infrastructure to become quantum ready means preparing for access to at least partially depend on international partnerships. This should not be viewed negatively, but rather as the opportunity to forge pathways for innovation to flourish and provide a new route to access international quantum talent.

Already, we are starting to see these pathways emerge in the UK and this should be celebrated. In 2021 the United Kingdom and the United States signed a new joint statement of intent to boost collaboration on quantum science and technologies.[49] Crucially, three of the 12 international research projects announced by UKRI at the end of 2021 is helping to forge this collaboration, with contributors ranging from NASA and the Massachusetts Institute of Technology (MIT) in the US to Australia's University of Sydney, Japan's Riken and the Max Planck Institute of Molecular Physiology in Germany.[50] These projects are especially useful for building best practice in the UK for research, but as we move towards commercialisation, the NQTP should use this model to encourage industry collaboration to make commercially viable breakthroughs that will drive success in the UK.

techUK sees international agreements as key to supporting quantum commercialisation, such as increasing the number of memoranda of understanding between UK and third countries that can promote shared principles of openness, transparency, and fair competition, whilst navigating potential security risks and safeguards together, such as through the role of international standards. We are starting to see the emergence of these important discussions, such as the recent international roundtable on pursuing quantum information together, which UK policy makers attended.[51] Agreements could also open avenues to explore bilateral sandboxes, as mentioned in the Innovation Strategy. These agreements should be flexible and have the ability to encompass the growth and evolution of quantum technologies.

Protecting UK Success

The protection of proprietary knowledge, to ensure creators of new products are duly rewarded, needs to be an important ongoing element in the UK's international regulatory policy around quantum technologies

It is important that quantum know-how created and developed by UK businesses and academia is protected, and the UK already has a robust IP framework. This can be underscored with any future UK trade deals keeping to the UK's high standard of IP protection.[52] Issues such as the protection of encryption keys should also be central elements of a UK's IP protection strategy. Again, this is an area where future trade agreements can be useful.

techUK has previously called for emerging tech taskforces aimed at breaking down barriers and streamlining regulatory processes to development and deployment of key emerging technologies where the UK is a leader, such as quantum technologies, artificial intelligence, autonomous vehicles, non-silicon based semiconductors and augmented and virtual reality technologies.[53] Modelled on the work of the Regulatory Horizon's Council, these taskforces should be a partnership between industry and government that seek to identify and tackle regulatory approvals, certifications and economic and cultural barriers to the commercialisation and deployment of key emerging tech. Creating these taskforces should complement the upcoming Quantum Strategy and existing initiatives such as the UK Government's AI and Innovation strategies.

In 2021 the United Kingdom and the United States signed a new joint statement of intent to boost collaboration on quantum science and technologies.

Summary of recommendations

1. **The UK should be vocal about its success in quantum.** the UK Government should use international collaboration and partnerships as an opportunity to showcase the weight of the UK quantum ecosystem, and match this with continued commitment to support the development of the UK quantum ecosystem through grants, opportunities and procurement.

2. **Increase partnerships, agreements and the number of memoranda of understanding between UK and third country regulators.** These agreements should be flexible and have the ability to encompass the growth and evolution of quantum technologies.

3. **Utilise emerging tech taskforces, framed on the Regulatory Horizons Council,** aimed at breaking down barriers and streamlining regulatory processes to development and deployment of key emerging technologies. These taskforces should be a partnership between industry and government that seek to identify and tackle regulatory approvals, certifications and economic and cultural barriers to the commercialisation and deployment of key emerging tech

International partnerships and secure access to key supply chain capabilities is integral for quantum commercialisation

By Jonathan Legh-Smith, Principal, Scientific Affairs, BT, and UKQuantum Executive Committee

Quantum technologies have the potential to transform the UK economy with applications for climate change, protecting the economy from cyber threats, drug discovery and providing advantage within the defence sector. Their significance is widely recognised and rightly identified as a UK strength in the UK Innovation Strategy and The Integrated Review. It is therefore imperative that the UK consolidates and builds upon its early successes and realises the potential of its investments so far, embedding capabilities, extending research and most importantly translating its science & technology excellence into economic growth.

In addition to the typical challenges of commercialising new technologies there are also national priorities to take into account: establishing the world's leading quantum-enabled economy i.e. the economy as a whole benefits from quantum technologies, and ensuring a resilient UK supply chain. A key challenge is that the UK's internal market is unlikely to be large enough to sustain a quantum supply chain and this is compounded by other countries having already established large, strategic programmes of their own. This means the UK's quantum strategy must support businesses products and services that compete in the global market from the outset. This goes beyond traditional collaborative R&D. It requires national-scale missions focused on clear societal and economic ambitions for the UK. Such missions should require businesses to deliver commercially-viable technologies and realise measurable value. In return they will allow businesses to prove the product-readiness of their technology and provide a showcase with which to compete globally. In particular such missions should enable UK Government to act not just as an enabler of innovation but as a customer for innovation; not just as a source of use-cases but as the lead for advanced trials.

International partnerships must also be a priority to create trade opportunities and secure access to key supply chain capabilities. We must promote the UK quantum strengths, successes, and our long-term ambitions if we are to attract investment, talent, and quantum companies to the UK. Including collaboration agreements on R&D and standards, and ministerial-led trade missions to key markets.

Over the last year, the UK seen the emergence of two quantum unicorns a level of success unheard of in the UK until now. We see the potential for a plethora of new and exciting, high potential and high growth companies emerging over the next few years, as well as new capabilities for existing companies. Now is the time to accelerate the growth of the UK quantum industry by driving scale up and developing user engagement that can fuel business cases for large scale commercialisation of quantum in the UK.

Building international success in quantum in the UK

By Rhianna Vulpio, Cybersecurity Analyst, KPMG

The quantum world is often considered to be a pipe dream; a futuristic, currently unattainable goal that belongs within the confines of academia. In reality, however, we are dealing with revolutionary first-generation quantum technology on a daily basis. We see it in fibre-optic networks, magnetic resonance imaging and satellite navigation systems (to name a few), but that's only the beginning. The last few decades have seen drastic developments in our understanding of quantum technology, and we're seeing an increasing amount of focus and investment into the development of quantum tech. The UK is in a strong position in terms of ecosystem, culture, and research, with successful start-ups and the largest venture capital in Europe. There has been little progress, however, in linking the astounding capabilities of quantum technology with real-world business problems.

Crises such as the COVID-19 pandemic and the current geopolitical situation have demonstrated the increasing complexity of business problems and have expanded the need for organisations to remain agile in an ever-changing environment. Harnessing the efficiency and vast capabilities of quantum technology would be an optimal approach to tackling these complex issues. An increasing number of organisations are beginning to explore the real-world benefits of quantum solutions, and we are seeing businesses start to identify potential use cases and benchmark them. Deriving real business value, however, lies with the selected use case - it is paramount that business leaders are able to identify the areas of their organisation that would be transformed by quantum technology, so that they are ready to reap the rewards of the quantum revolution.

The UK Government has outlined three objectives for the Quantum Strategy, one of which is "to grow and maintain the UK's capabilities and leading global position – to help the UK to have strategic advantage in and through quantum technologies". In a UK survey of business leaders, however, over 34% identified the digital skills gap as a future challenge.[54] If we are to grow and maintain our status as a strategic leader in the quantum space, we must invest in developing our people and our knowledge. It is critical that we encourage young people to pursue a range of STEM pathways to develop a spectrum of technical skills. We need pioneers who are aware of the real issues that companies face, and have a detailed understanding of quantum technology, that are able to bridge the gap between the research and business worlds.

The UK is one of the most established European countries at a quantum level, but building international success is not something we can achieve alone. Whether the solution is a partnership with the European Quantum Flagship, or a wider collaboration, we need to grow our skills and resources to develop concrete, real-world applications of quantum computing for businesses – because if we don't, someone else will.

"No individual country can master the challenge; it is not a race between nations but a challenge between human and nature." - Dr Tommaso

Public Procurement as a Catalyst for Quantum Commercialisation

techUK believes UK Government playing an active role as procurers of this technology will be crucial for commercialisation of quantum technologies. Private funding and investment to match business costs is still a core challenge for the quantum industry, and this is where Government procurement will be key. Quantum could offer UK Government the opportunity to boldly change the UK's approach to public procurement towards the intent set out in the Innovation Strategy that calls for UK Government to be a leading customer of innovation.

Why is public procurement key to success?

With over £292 billion spent on goods and services every year, public procurement accounts for a third of all government spending in the UK.[55] This level of public spending on goods and services is comparable to other major economies such as Germany (34%) and, to a lesser extent, France (26%) and the United States (25%).[56] In this context, governments around the world are exploring how to best leverage the weight of public sector spending by aligning it with long-term economic growth and strategic development goals. This has led to using public procurement as an instrument to develop the innovation ecosystem.

By procuring more innovative solutions, the public sector can be a driver of quantum commercialisation in the UK, providing businesses with the stability and consistency needed to showcase the real value of their quantum product and services, thereby facilitating wider adoption. This is especially true in the developing quantum ecosystem, where there may be reluctance for end users to be the first buyers. Indeed, UK Government can play a crucial and fundamental role through procurement in showing the efficacy of quantum and thereby encourage private sector investment.

Procurement of quantum technologies by government could build success on two fronts. First, it would empower the public sector to find efficient, innovative, and modern solutions through quantum to address their most pressing challenges; and second, procurement can be an effective tool in stimulating the innovation ecosystem, providing smaller firms what they need to succeed in the market, fuelling the scale-up ecosystem and facilitating wider adoption of new tech services, all of which enables structural change, increasing productivity, and stimulating long-term economic growth.

We are starting to see international successes with this model. For example, the Australian government have enlisted quantum computing to improve transportation system – and in turn is playing a key role in funding innovation, supporting their quantum industry, and finding real-world applications of this technology.[57] Other nations have also started scoping the role quantum applications could play in military and defense.[58]

quantum could offer UK Government the opportunity to boldly change the UK's approach to public procurement towards the intent set out in the Innovation Strategy that calls for UK Government to be a leading customer of innovation."

Other nations, such as Canada, have developed models similar to the UK industrial challenges.[59] These industrial challenges have a key role to play in developing applications of quantum but through procurement the UK can and should go further and encourage government departments to join together and actively procure quantum technologies to solve some of their key challenges. Here, procurement based on national

priorities could showcase how the UK intends to deliver on bold ambitions around quantum.

For this to happen in the UK, quantum applications should intersect with key national priorities identified by UK Government, such as developing low carbon solutions and levelling up UK regions, where departments are working together to find strategic solutions. Here, quantum should be embedded as part of the solution with other emerging technologies like cloud, HPC, AI and more. This approach frames quantum as a part of a wider technology toolkit available in the UK as a science and technology superpower. For example, if UK Government invests in battery research for net-zero, quantum should be considered as part of the solution for its role in materials discovery, or monitoring.

These mission-oriented programmes based on national priorities could underpin how the UK intends to deliver on bold ambitions around quantum. For example, UK Government can continue to accelerate adoption of quantum communications services and, in turn, showcase this as a viable product for UK companies – especially since initial quantum communications services are available now.[60]

Finally, it is important that public procurement is made to be as accessible as possible for quantum businesses, many who are in the early stages of commercialisation and will have less capacity, knowledge and resource for procurement practices. De-risking the process for start-ups and SME's will be crucial for increasing government demand in quantum, which in turn will allow lowering barriers to innovation and growth in these companies

Upskilling, education and awareness for strong UK Government procurement

In order to achieve this success with procurement, the UK should seek to address the barriers limiting public sector adoption of quantum. As explored in previous sections, upskilling will ensure a greater understanding on how the use cases for quantum will apply. Upskilling is part of developing a quantum-literate workforce within the UK who are empowered to use and utilise quantum and exploit the quantum opportunity. This does not necessarily require a technical background, but awareness and education on emerging technologies that are at the foundations of building the UK as a science and technology superpower.

Part of this education and awareness across UK Government means being able to reasonably address the risks posed by quantum technologies. This approach is being taken by other nations. For example, as part of the US commitment to advance quantum technologies in the United States, the White House recently announced two directives pushing for the overhaul of national cybersecurity systems to prepare for adoption of quantum technologies.[61]

Summary of recommendations

1. **Set ambitious plans for public procurement of quantum technologies** that will help find quantum-based solutions and drive forward commercialisation especially for SME's

2. **Frame procurement around intersect key national priorities** such as developing low carbon solutions and levelling up, where departments are working together to find strategic solutions. Here, quantum should be embedded as part of the solution with other emerging technologies like cloud, HPC, AI and more.

3. **Use procurement to frame quantum as a part of a wider technology toolkit available in the UK.** Again, achieving key national priorities will be crucial here

4. **Address the barriers limiting public sector adoption of quantum** such as skills and awareness, and accessibility for SMEs to the procurement process

How Can Governments Use Quantum Computing for Public Sector?

By Allison Schwartz, Vice President Global Government Relations and Public Affairs, D-Wave

Quantum computing technology is at a unique inflection point today. Through cloud access to systems and the availability of quantum-hybrid technologies, governments can now begin to build near-term applications for important public sector needs.

Quantum annealing is uniquely suited to tackle optimisation problems, many of which are at the heart of public sector needs. The simple answer to the question, can today's practical quantum computing technology play a role in these efforts is "yes", for many use cases and areas.

Transportation

Designing sophisticated transportation networks is an intractable problem for classical computing systems once the task reaches a certain size. Fortunately, quantum computers — with their ability to solve complex problems with various variables and constraints — can step in to fill the gap. Quantum computers can simultaneously map different modes of transportation in real time, updating routes and schedules to solve for disruptions. The Australian Department of Defense looked at quantum computing to optimise how autonomous vehicles resupply army forces from a central base. And Volkswagen has already solved a problem like this using annealing quantum computing technology: VW routed buses to optimise traffic flow in Lisbon, Portugal in 2019. Whether it be roadways, rails, airways, or waterways, today's quantum technology has the power to solve significant challenges for key infrastructure projects through intelligent design.

Emergency Response

There is a critical need to optimise emergency response. From vaccine distribution to humanitarian aid, finding a way to do things in a better and faster manner is critically important. Tokyo-based Sigma-i used D-Wave's quantum cloud to develop optimum tsunami evacuation routes and to increase the efficiency of automated robotic carts moving materials around within a factory. From March 2020-March 2021, D-Wave opened up access to our cloud-based quantum computing technology to anyone working on COVID-19 response to support innovation during a critical time. Sigma-i also worked on route planning for transporting large numbers of COVID-19 patients to and from a medical facility.

Supply Chain

In the maritime industry, global ports are looking at how quantum computing can assist with optimising the flow of goods. SavantX has built an application piloted by the Port of Los Angeles in the U.S. to ease backlogs by increasing the capacity and velocity of cargo movement. Today's manufacturers are also looking at quantum computing to build applications to speed up

their operations. Denso, a Japanese auto parts manufacturer, has piloted using quantum annealers to optimise the routes of automated guided vehicles (AGVs) and was able to reduce AGV traffic jams by 15 percent, thereby increasing productivity and reducing costs. GE Research has also been looking at how quantum computing applications can help with moving their parts through a repair shop floor more efficiently. Bin packing, packing goods into a number of bins of limited capacity, is a common problem for many manufacturers, one that can be difficult for classical computation but well-suited for quantum-hybrid applications. If goods were packed more efficiently, loaded onto trucks, trains, and ships in an optimal manner, and shipped via routes optimised for lower travel times, the collective impact could ease supply chain strains. From more efficient manufacturing practices, better bin packing for delivery, and optimisation of delivery networks and global ports, all of these have a use case which are possible today with annealing quantum computers.

Sustainability

Lowering carbon emissions is a global focus and one that the United Kingdom has been addressing head on. With a goal to slash emissions by 78% by 2035 and get to net zero by 2050, the UK should look to all available technologies, including quantum computing, to help achieve those objectives. Groovenauts, a Japan-based company, used quantum-powered machine learning to optimise garbage collection routes in Tokyo. Their pilot showed a significant uptick in efficiency using quantum technology, and even modeled a nearly 60% reduction in carbon emissions. There are a wide variety of public sector needs from waste collection, mail delivery and more that can benefit from quantum applications. And, if each one uses a quantum application aimed at lowering CO2 emissions for their specific area, it could provide a significant benefit in the sustainability objectives of government.

Broadband and 5G Access

The pandemic has highlighted the importance of equitable access to broadband internet and improved mobile connectivity, and quantum computers can help. For example, DCMS has been focusing on broadband and 5G roll outs for many years. Telecom Italia became the first telecommunications operator in Europe to implement quantum computing algorithms in planning its next-generation mobile networks. The company worked with D-Wave to optimise the implementation of telecom infrastructure, performing the task 10 times faster than traditional optimisation methods.

So What Should Governments Do?

UK Government can help by developing proof-of-concepts and testing near-term quantum applications provides a unique way to begin using today's technology. It could develop and deploy near-term quantum-hybrid applications for a variety of public sector areas in a rapid timeframe. The President's National Security Telecommunications Advisory Committee in the United States recommended a sandbox for communications resiliency. A similar programme in the U.K. can serve as a useful tool for not only educating on today's technology capabilities, but also with each application developed, it provides a feedback loop for additional innovation and

Responsible and Ethical Innovation should be part of Commercialisation

As with many new technologies, the development and emergence of quantum technologies is likely to raise legal, social and ethical questions that will need to be addressed as we move from research to deployment.

"Quantum technologies stand to transform our futures in many ways, but, as with all powerful innovations, this has the potential for challenging as well as desirable outcomes for society. A responsible innovation approach involves communicating with society about what quantum may mean, taking society's needs and views into account, and considering questions around equity, governance, and ethics, from the outset."

Dr. Philip Inglesant and Dr. Carolyn Ten Holter, University of Oxford, NQIT Project

"In a world increasingly defined by rapid advancements in AI, quantum, and other technologies, it is imperative that companies operate in a way which promotes trust with all social stakeholders, not just shareholders. Organisations should treat trust as the license by which they are permitted to operate, and that trust is now more important than ever before."

Richard Ward, Government and Regulatory Affairs, IBM

The predicted commercialisation of quantum technologies will make these concerns more immediate and increase debate around their deployment and use. This is especially true when compounded with concerns around cybersecurity and economic security. [62] Consequently, we need to transition responsible innovation practices at work in academia to the quantum ecosystem, enabling an ethics by design approach that ensures we get quantum commercialisation right for both the economy and society.

Both the development of quantum technologies, and the surrounding discussion on responsible innovation practices for quantum technologies, are still in the early stages. However, this gives us an exciting opportunity to prepare and build responsible innovation practices as the quantum ecosystem develops. In this section we explore how this could be done by building on the work and global leadership the UK has shown in the area of digital ethics, and how this is already starting to be applied through responsible innovation principles in quantum.

Responsible innovation in the Quantum ecosystem

Responsible innovation helps manage the risks associated with new technologies such as quantum, with the aim to take a proactive rather than reactive approach to preventing harm.[63] In the case of quantum, there are multiple directions this new technology could take. Therefore it is even more important to consider the ethical implications of quantum commercialisation and understand where practical tools and guidance may be helpful.

Responsible innovation is a well-established concept for businesses, with many companies having baseline principles designed to be applied across all technologies they work on. However, this can be a difficult process to operationalise, and for emerging technologies like quantum, it can be challenging to devote resource.

Recently techUK worked with members to host a joint Quantum and Digital Ethics Working Group workshop exploring the topic of Ethical quantum commercialisation: Applying principles of responsible innovation, as part of techUK's Quantum Commercialisation Campaign.[64] In this workshop, operationalising responsible innovation principles in the process of commercialisation was highlighted as an area where resources, knowledge and support were needed. While some attendees highlighted useful examples of how digital ethics principles have been operationalised, with one company for example deploying a chatbot to take employees through a consultative process to identify whether a project needed governance reviews, many are still unsure how to move from theory to practice. The discussion showed that businesses do not necessarily need more guidance on the establishment of responsible innovation or digital ethics principles, as these often already exist, either externally or within businesses. However guidance, resource and development of best practice on operationalising responsible innovation will be critical to industry in the process of commercialisation.

Responsible innovation is an iterative process, and the issues raised in this initial workshop will need to be discussed as quantum technologies continue to develop. techUK welcomes any further discussions on this topic, and will also continue to engage with industry through our work on the Digital Ethics programme.

Learning from a UK heritage of digital ethics

The existence of a well-established and respected digital ethics community in the UK places the country at an advantage when it comes to understanding and considering the ethical issues and questions that quantum innovation and the development and use of quantum products and services could raise.

This existing community has a strong legacy of leading the debate around the ethical adoption of other emerging technologies, such as AI, which can help shape the conversation around ethical commercialisation of quantum technologies with lessons learnt and best practice. Independent organisations like the Ada Lovelace Institute and the Alan Turing

Institute, government bodies like the Centre for Data Ethics and Innovation (CDEI) and the wealth of UK-based world-leading university researchers, can all offer expert insights into the implications of emerging technologies and help guide us in how to use responsible innovation to get quantum technologies right for people and society.

It is important that we start to leverage this already well established digital ethics community to prepare for a future potentially driven by quantum technologies. techUK recommends working with this community to help develop guidance, resource and best practice for operationalising responsible innovation in the quantum ecosystem.

The UK talent pipeline needs to include ethics and responsible innovation

For those working in quantum, it is not enough to just understand how the technology works. Instead, the talent pipeline needs to be sociotechnical to enable exploration of ethical issues during commercialisation

To recognise the importance of responsible innovation practices for quantum commercialisation, UK Government, industry and academia could partner to deliver training opportunities and education programmes on the societal and ethical considerations of quantum technologies, where the UK could grow as a leader.

Furthermore, the UK could be seen as a strategic leader by underscoring the importance of responsible and ethical commercialisation of quantum technologies through the National Quantum Technologies Programme and the Quantum Strategy. Whilst businesses may not necessarily need more guidance on the establishment of responsible innovation principles, as these often already exist, training, programmes and advice on how to turn principles into practice are needed.[65] This could be particularly useful for start-ups and SMEs with limited resource, especially if matched with grants as part of upskilling for projects, ensuring the UK is addressing responsible innovation at every stage. Government participation to encourage responsible innovation, through the National Quantum Technologies Programme and in other ways, will in turn create capacity, demonstrate confidence and maintain a public-sector interest.

Summary of recommendations

1. **UK Government, industry and academia should partner to deliver training opportunities and education programmes on the societal and ethical considerations of quantum technologies, to establish the UK's leadership position**

2. **Work with the UK digital ethics community to help develop guidance, resource and best practice for operationalising responsible innovation in the quantum ecosystem.**

3. **Ensure any strategy or approach to quantum skills includes the development of business, commercial and socio-ethical skills**

Why is responsible innovation in quantum so important?

By Mira Pijselman, Senior Consultant, Digital Ethics, EY

Responsible innovation (RI), also referred to as responsible research and innovation (RRI), is a methodology that can be used proactively to shape a technology's future in alignment with the values of society and the needs of the planet. RI recognises explicitly that multiple potential trajectories are possible with a disruptive technology, such as quantum. The trajectory that is realised is the result of cumulative choices that we – businesses, regulators, and broader society – make, starting today. RI rejects the idea that any one technological future is inevitable, or that it is too early to consider possible futures of a technology due to technical uncertainties. Quite the opposite, it asks us to engage in a "transparent, interactive process" that cuts across a variety of actors in the technology ecosystem and those it serves to evaluate and guide the "proper embedding of scientific and technical advances in our society". Importantly, RI is action oriented. Instead of focusing on principles or abstract ethical norms, as occurred with the rise of artificial intelligence (AI) ethics, RI is focused on enabling practical guidance for innovating in the public interest to help those designing, building, deploying and monitoring technological systems. Aptly stated by Inglesant et al. 2021, "the point [of RI] is not to predict or only interpret the future in various ways, but to explore, prepare, and respond to it".[66]

Responsible innovation (RI) is fundamental for quantum technologies because, when adopted, it provides a mechanism through which systems and their creators can earn trust. It does so through a reflective and pragmatic acknowledgement of innovation as being socially embedded – an acknowledgement that technology is not neutral or independent of society, but rather is fundamentally intertwined with social contexts. At this still-early stage in quantum's maturation, RI is an essential paradigm to help us think through the probable impacts of quantum technologies, as well as set out thoughtful guardrails and incentives to innovate for the betterment of communities and ecosystems.

Despite ongoing engineering challenges to move past noisy intermediate-scale quantum (NISQ)-era computing, we can already identify impacts, both positive and negative, that this paradigm-breaking technology presents. For example, because of quantum's augmented ability to simulate molecules, there is a concern that actors may develop materials that support unethical practices, such as the creation of cheaper, but more environmentally unfriendly chemicals. Further, while quantum sensing may provide us with richer data required to optimise traffic or detect diseases, it may also provide actors with even greater means to engage in covert surveillance. If applied unethically, quantum sensing technologies could be used to compromise individuals' privacy and – in more extreme cases – suppress dissent and degrade autonomy. If we can already foresee these types of risks today via RI, we can ensure our readiness against them, and, additionally, encourage the development of quantum

technologies that can service social and environmental good (for example, by helping to fight climate change).

In the past, practical opportunities were missed to operationalise ethics as new technologies were emerging. This has allowed significant issues to materialise, from racist facial recognition algorithms to discriminatory curriculum vitae-screening tools. Most recently, a great deal of societal harm, reputational damage and lost opportunity costs associated with big data and AI may have been mitigated had organisations embedded RI into their businesses earlier. Given the likely scale and scope of disruption posed by quantum technologies, innovators and regulators must adopt a more proactive position with quantum via RI, or else risk founding a quantum ecosystem that cannot be trusted.

Summary of recommendations

Ensuring access to quantum talent and developing quantum skills in the UK

1. **Government and industry should work together to open access so that PhD's are not the only route into a career in quantum.** . Changing this large barrier to entry will allow for more talented people to enter the sector, increase the sector's diversity, and fill industry job shortages.

2. **Government should encourage the move to industry by funding industry placements making the move from academia to industry more attainable.** These placements should also be available for international talent to mitigate difficulty in creating internships and industry placement for international PhD's.

3. **Digital skills for different technologies should not be viewed in isolation.** Quantum will align closely with other forms of technologies and cross-disciplinary programmes to bring technologies together should be encouraged.

4. **Support upskilling for a quantum literate workforce.** This can be done through training opportunities and education programs that accelerate cross-disciplinary programs that bridge engineering, science, business, and social sciences to develop people with an understanding of the huge potential of quantum from a technological and business perspective.

5. **Ensure the UK has access and remains attractive to large international talent.** Enhancing visa flexibility for quantum talent, including short-term access for academic-industry placements and internships, will be crucial so that we hire the best and brightest to progress the UK's quantum journey.

6. **Drive wider business skills and socio-ethical skills.** To create a successful quantum ecosystem, key interventions in training should include business skills that needed for commercialisation.

Working with the UK tech sector to develop models of easy access to quantum technologies, including building pathways with other critical emerging technologies such as Cloud, HPC and AI that will be key for commercialisation

7. **Investment into supporting infrastructure that will enable access to quantum.** This includes encouraging key connections between quantum and high-performance computing, AI and cloud

8. **Encourage convergence between quantum and emerging technologies through key national priorities and** developing opportunities for this convergence to take place

9. **International partnerships with those who can provide access to existing quantum capacity** will be particularly valuable to support UK businesses adopting quantum, especially as other nations push forward in building HPC/quantum capacities.

10. **Government should think in particular about encouraging access to quantum for SME's and start-ups**, to make sure quantum is accessible. This will include exploring different access models to quantum through the cloud.

Promote international collaboration globally to help grow and develop opportunities for the UK sector, and protect the UK's capabilities

11. **The UK should be vocal about its success in quantum.** the UK Government should use international collaboration and partnerships as an opportunity to showcase the weight of the UK quantum ecosystem, and match this with continued commitment to support the development of the UK quantum ecosystem through grants, opportunities and procurement.

12. **Increase partnerships, agreements and the number of memoranda of understanding between UK and third country regulators.** These agreements should be flexible and have the ability to encompass the growth and evolution of quantum technologies.

13. **Utilise emerging tech taskforces, framed on the Regulatory Horizons Council,** aimed at breaking down barriers and streamlining regulatory processes to development and deployment of key emerging technologies. These taskforces should be a partnership between industry and Government that seek to identify and tackle regulatory approvals, certifications and economic and cultural barriers to the commercialisation and deployment of key emerging tech

Encourage public sector procurement of quantum to grow the quantum market, offer stability, and enable commercialisation

14. **Set ambitious plans for public procurement of quantum technologies** that will help find quantum-based solutions and drive forward commercialisation especially for SME's

15. **Frame procurement around intersect key national priorities** such as developing low carbon solutions and levelling up, where departments are working together to find strategic solutions. Here, quantum should be embedded as part of the solution with other emerging technologies like cloud, HPC, AI and more.

16. **Use procurement to frame quantum as a part of a wider technology toolkit available in the UK.** Again, achieving key national priorities will be crucial here

17. **Address the barriers limiting public sector adoption of quantum** such as skills and awareness, and accessibility for SMEs to the procurement process

Ensure commercialisation and innovation is achieved in a responsible and ethical manner

18. **UK Government, industry and academia should partner to deliver training opportunities and education programmes on the societal and ethical considerations of quantum technologies, to establish the UK's leadership position**

19. **Work with the UK digital ethics community to help develop guidance, resource and best practice for operationalising responsible innovation in the quantum ecosystem.**

20. **Ensure any strategy or approach to quantum skills includes the development of business, commercial and socio-ethical skills**

References

1. https://www.nqcc.ac.uk/
2. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1054680/uk-quantum-strategy-call-for-evidence.pdf
3. https://www.techuk.org/resource/event-round-up-commercialising-quantum-positioning-the-uk-for-success.html
4. ey.com/en_uk/emerging-technologies/quantum-readiness-survey
5. https://itif.org/publications/2021/04/27/why-united-states-needs-support-near-term-quantum-computing-applications#:~:text=Investing%20in%20near%2Dterm%20applications,competitiveness%20and%20protect%20national%20security.
6. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1054680/uk-quantum-strategy-call-for-evidence.pdf
7. https://atarc.org/wp-content/uploads/2021/05/ATARC-Military-Paper-by-Quantum-Working-Group.pdf
8. This is on top of £93 million, which the Government has invested in the NQCC and forms part of a £1 billion, 10-year programme of investment in quantum technologies since 2014. https://www.hartree.stfc.ac.uk/Pages/New-%C2%A3210-million-centre-to-provide-industry-and-research-access-to-AI-and-quantum-computing.aspx
9. https://www.ukri.org/news/50-million-in-funding-for-uk-quantum-industrial-projects/
10. https://www.capgemini.com/wp-content/uploads/2022/03/Final-Web-Version-Quantum-Technologies.pdf
11. https://www.itpro.co.uk/business-strategy/startups/367235/uk-tech-sector-reaches-1-trillion-valuation
12. https://technation.io/report2021/
13. https://technation.io/news/new-tech-business-launched-every-half-an-hour-in-the-uk-in-2020/
14. https://quantumcomputingreport.com/venture-capital-trends-in-quantum-technologies/
15. https://www.ons.gov.uk/economy/governmentpublicsectorandtaxes/researchanddevelopmentexpenditure/bulletins/ukgrossdomesticexpenditureonresearchanddevelopment/2018#:~:text=The%20UK's%20gross%20domestic%20expenditure,up%20from%201.67%25%20in%202017.
16. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1009577/uk-innovation-strategy.pdf
17. https://www.wipo.int/edocs/pubdocs/en/wipo_pub_gii_2021/gb.pdf
18. https://technation.io/report2020/#13-unicorns
19. https://newsroom.bt.com/bt-and-toshiba-launch-first-commercial-trial-of-quantum-secured-communication-services/
20. UKNQTP-Strategic-Intent-2020.pdf (ukri.org)
21. https://quantumcomputingreport.com/quantum-salaries-in-the-u-s/
22. https://www.techuk.org/resource/the-future-is-bright-for-quantum-in-the-uk.html
23. https://www.techuk.org/shaping-policy/fast-forward-for-digital-jobs-report.html
24. https://newsroom.accenture.co.uk/english-uk/news/uk-tech-job-openings-declined-in-2020-uk-tech-talent-tracker.htm
25. https://www.nqcc.ac.uk/online-courses/
26. 2109.03601.pdf (https://arxiv.org/abs/2109.03601)

27. https://www.riverlane.com/vacancy/graduate-recruitment-scheme/
28. Dear Colleague Letter: Non-Academic Research Internships for Graduate Students (INTERN) Supplemental Funding Opportunity (nsf21013) | NSF - National Science Foundation
29. https://www.gov.uk/government/news/23-million-to-boost-skills-and-diversity-in-ai-jobs
30. https://azure.microsoft.com/en-us/resources/development-kit/quantum-computing/?msclkid=32aec716c70211ecb6d8f55dfbcd216d
31. https://www.ic.gc.ca/eic/site/154.nsf/eng/h_00002.html
32. https://www.aip.org/fyi/federal-science-bill-tracker/116th/quantum-user-expansion-science-and-technology-act
33. America Competes Act includes programs for data center energy efficiency, post-exascale supercomputing & AI, and $400m quantum networking push - DCD (datacenterdynamics.com)
34. https://www.forbes.com/sites/arthurherman/2022/04/29/the-quantum-revolution-is-here-its-name-is-hybrid/
35. https://www.meetiqm.com/technology/iqm-atos-state-of-quantum-research-2021/
36. https://www.nqcc.ac.uk/updates-article/announcing-the-qupharma-project-for-drug-development-using-quantum-computing/
37. https://www.techuk.org/resource/new-government-office-for-science-review-outlines-why-the-uk-needs-to-invest-in-supercomputing.html
38. https://www.hartree.stfc.ac.uk/Pages/New-%C2%A3210-million-centre-to-provide-industry-and-research-access-to-AI-and-quantum-computing.aspx
39. https://www.hartree.stfc.ac.uk/Pages/New-%C2%A3210-million-centre-to-provide-industry-and-research-access-to-AI-and-quantum-computing.aspx
40. https://www.euractiv.com/section/digital/news/france-opens-access-to-quantum-computing-to-researchers-start-ups/
41. https://thequantuminsider.com/2021/08/12/report-quantum-computing-as-a-service-market-to-hit-26-billion-by-end-of-decade/
42. https://www.hpcwire.com/off-the-wire/oqc-delivers-the-uks-first-quantum-computing-as-a-service/
43. https://www.techuk.org/resource/event-round-up-is-the-future-of-quantum-commercialisation-in-the-cloud.html
44. https://datainnovation.org/2021/04/why-the-united-states-needs-to-support-near-term-quantum-computing-applications/
45. nsf20073 Dear Colleague Letter: Enabling Quantum Computing Platform Access for National Science Foundation Researchers with Amazon Web Services, IBM, and Microsoft Quantum | NSF - National Science Foundation
46. https://www.capgemini.com/wp-content/uploads/2022/03/Final-Web-Version-Quantum-Technologies.pdf
47. ey.com/en_uk/emerging-technologies/quantum-readiness-survey
48. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1009577/uk-innovation-strategy.pdf
49. https://www.gov.uk/government/news/new-joint-statement-between-uk-and-us-to-strengthen-quantum-collaboration

50. https://www.ukri.org/news/international-collaborations-to-develop-technologies-of-tomorrow/
51. Readout: International Roundtable on Pursuing Quantum Information Together | The White House
52. https://www.techuk.org/resource/a-blueprint-for-uk-digital-trade-a-techuk-report.html
53. Seizing the opportunity for tech led growth in 2022 (techuk.org)
54. https://www.telegraph.co.uk/business/emerging-technology/skills-gap-in-uk-market/
55. Public Expenditure Statistical Analyses 2019 (publishing.service.gov.uk)
56. Government at a Glance - 2017 edition: Public procurement (oecd.org)
57. https://www.hpcwire.com/off-the-wire/australian-government-enlists-quantum-computing-to-improve-transportation-system/
58. https://crsreports.congress.gov/product/pdf/IF/IF11836#:~:text=Quantum%20sensors%20could%20also%20enable,detect%20electromagnetic%20emissions%2C%20thus%20enhancing
59. Applied Quantum Computing Challenge program - National Research Council Canada
60. BT and Toshiba launch first commercial trial of quantum secured communication services | EY UK
61. FACT SHEET: President Biden Announces Two Presidential Directives Advancing Quantum Technologies | The White House
62. https://cifar.ca/wp-content/uploads/2021/04/quantum-report-EN-10-accessible.pdf
63. Creating a Responsible Quantum Future - 18-Nov-21.pdf
64. For the full write up of this roundtable: https://www.techuk.org/resource/event-round-up-ethical-quantum-commercialisation-applying-principles-of-responsible-innovation.html
65. One example of existing governance is the publication of Quantum Computing Governance Principles by the World Economic Forum January 2022. https://www3.weforum.org/docs/WEF_Quantum_Computing_2022.pdf
66. https://ora.ox.ac.uk/objects/uuid:9faf3a72-d68d-44a4-b29e-ff4ef34c372f/download_file?safe_filename=Inglesant_et_al_2021_Asleep_at_wheel.pdf&type_of_work=Journal+article

techUK
FOR WHAT COMES NEXT

About techUK

techUK is a membership organisation that brings together people, companies and organisations to realise the positive outcomes of what digital technology can achieve. We collaborate across business, Government and stakeholders to fulfil the potential of technology to deliver a stronger society and more sustainable future. By providing expertise and insight, we support our members, partners and stakeholders as they prepare the UK for what comes next in a constantly changing world.


linkedin.com/company/techUK


@techUK


youtube.com/user/techUKViews


info@techuk.org