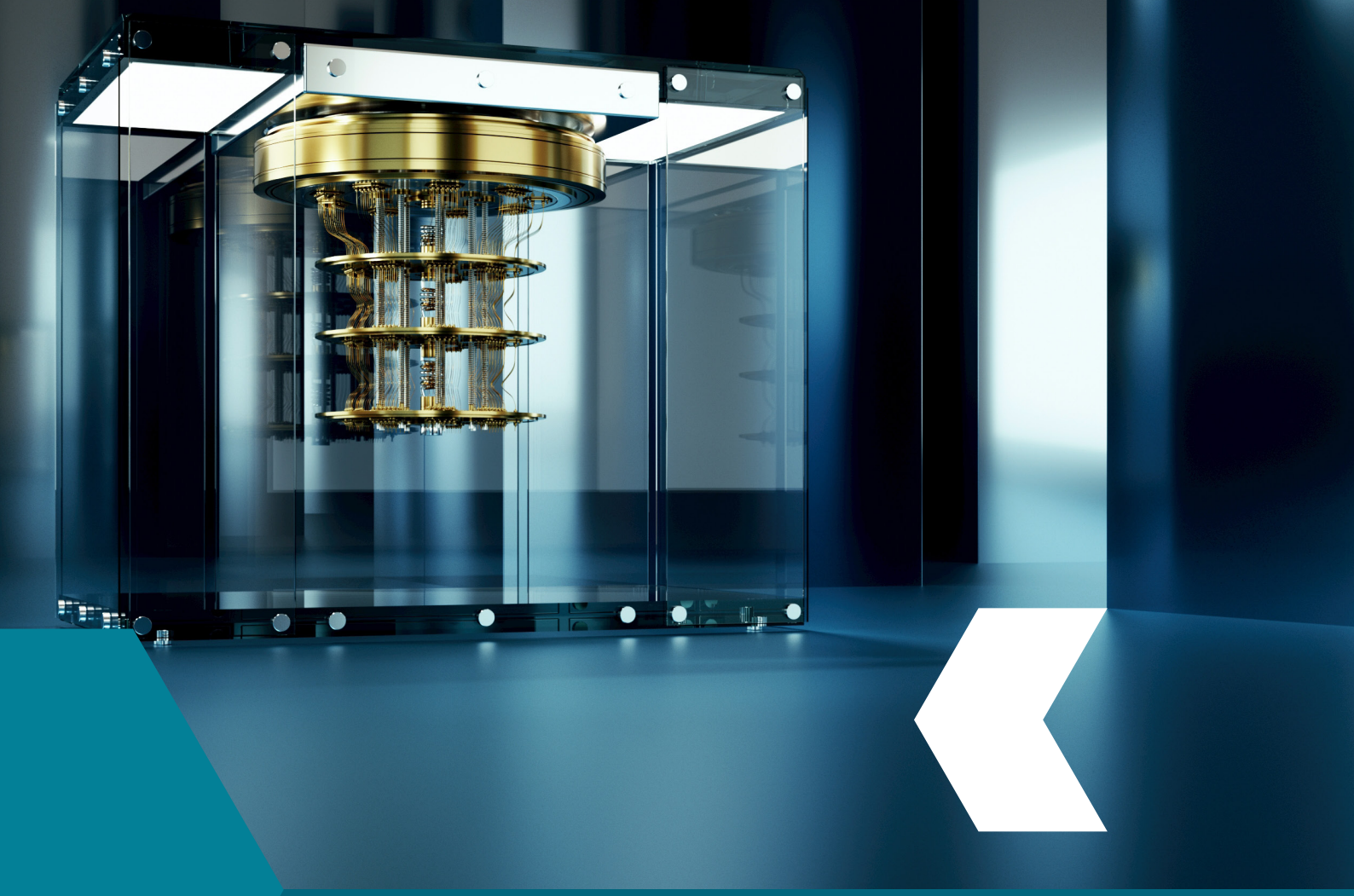

NQCC QUANTUM COMPUTING TESTBED PILOT STUDY

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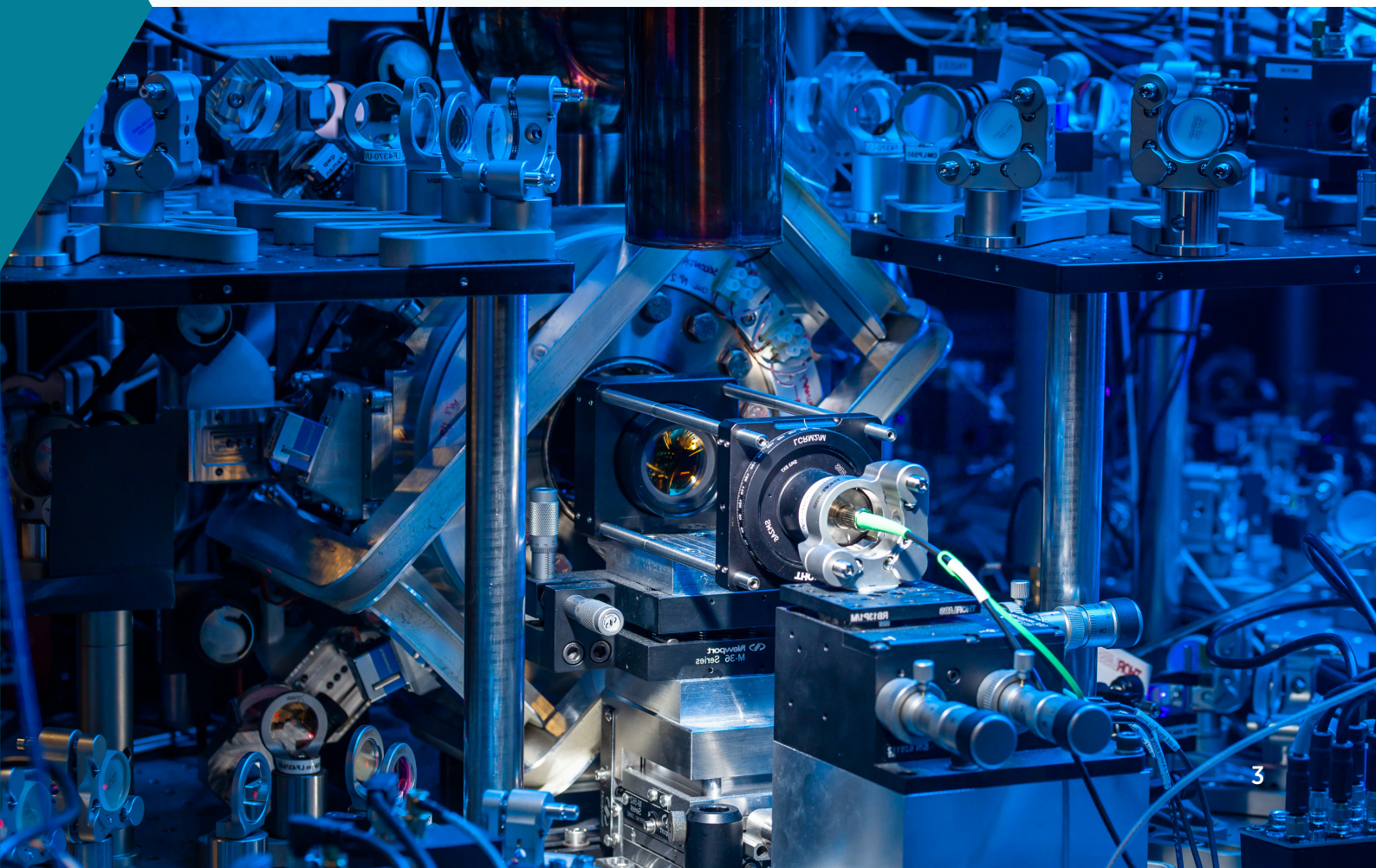


EXECUTIVE SUMMARY

In 2023, the National Quantum Computing Centre (NQCC), in partnership with Innovate UK, launched the Testbed programme, with contract delivery commencing January 2024. As the testbeds began their installations at Harwell, we conducted a pilot study with the testbed providers, observers of the programme and policymakers, including Riverlane, QuIC, UK Quantum, Quantum Industry Canada, Q-Star, QEDC and the UK Quantum Office. Our aim is to better understand the key issues surrounding commercialisation and how to foster the business ecosystem related to the testbed rollout. The testbed programme is a "living lab", enabling socio-economic development, with the potential to enhance UK productivity and economic growth.

Key strengths of the programme

Our study identified several important strengths of the testbed programme. First, the testbed community really appreciate the innovation model, where the NQCC acts as a "lead customer", with full engagement and the provision of critical support infrastructure. It is a key attraction of the UK quantum computing (QC) landscape for external observers. Second, the funding for technical development and the forum for testing ideas in state-of-the-art facilities are truly valued. Third, the technical skills of the NQCC team, and the potential to work with partners from the wider ecosystem, are seen as key strengths. Finally, vendors see significant benefits in the potential access to users by building on Phase 1 of the programme's focus on hardware implementation.

Findings and suggested initiatives

The NQCC is already deeply involved in several use-case and ecosystem-development programmes, such as the SparQ user-engagement programme and the Quantum Computing Access Programme (QCAP) and other related programmes. There are significant NQCC initiatives that support firms and the UK user community to develop the capabilities to adopt quantum computing by building knowledge and expertise in applications discovery. The study findings and recommendations, we hope, will build on the success of the NQCC's major quantum computing readiness initiatives. Through the lenses of technological framing, business and economic incentives and capabilities, our key findings and suggested initiatives are as follows:

1. Technological framing

a. Findings

The testbed providers understood the importance of timely delivery of their proposed hardware to the agreed specifications, to enable the NQCC to conduct the planned technology benchmarking and characterisation activities. The NQCC plans to build on the technology benchmarking initiative to user application benchmarking. Some testbeds are technologically more mature, and application benchmarking, including feedback from users, will be key to their development plans. These testbed firms will significantly benefit from guidance on where to focus their technology development attention through having closer links with potential user applications.

Suggested initiative

Technology benchmarking will need to be closely linked to the SparQ use-case development programme to identify key areas for reducing tech-development uncertainty, and to identify knowledge gaps in potential use-case testing opportunities. We recommend developing deep-dive pilot case studies across the end-to-end demand and supply chains in selected industries to develop the methodology for seamlessly designing user benchmarks from the technical benchmarks and to build links between end users and testbed vendors.

b. Findings

Some participants are struggling to access packaging capabilities, electronics testing and cloud provision, and they are keen to explore whether there could be better solutions for accessing these enabling technologies and other elements of the supply chain (both within the UK and Europe and elsewhere). There was also a general theme of firms wanting to position themselves with end customers, although not all firms want to engage early.

Suggested initiative

The NQCC has convening power as a neutral party with national credentials, which could be leveraged to provide credibility to access users (e.g. between primes and start-ups) and suppliers, and boost interaction and collaboration initiatives. The aim would be to develop a directory of key suppliers for the enabling technology and potential end users to better understand how to unblock disincentives and create opportunities for testbeds to develop their capabilities. In addition, the NQCC can act as a filter between testbeds and potential customers.

2. Business models and economic incentives

a. Findings

“Anchor tenants”, or key firms that attract participation among testbed firms (e.g. Riverlane, Phasecraft, academic groups in the Quantum Software Lab and Quantum Technology Hubs (QSL)), have an important role to play in helping to develop the ecosystem.

Suggested initiative

Identify key anchor tenants and develop plans to help them build their ecosystem to enable building of the wider quantum computing ecosystem. Such a programme should focus on helping to nurture the anchor firms in shaping the business ecosystem by understanding the value-creation and value-capture approaches of anchor tenant firms.

b. Findings

Some testbed vendors have “steps on the road” products on the way to building a full quantum computing platform. These interim products and their associated ecosystems are key for both the business and technical development of the testbeds.

Suggested initiative

The NQCC should help to enable testbeds to test emerging business models for interim products and to build the business ecosystems without compromising its neutral stance.

c. Findings

The NQCC could consider providing support for quantum-inspired computing capabilities, to enable business-case development within potential user organisations.

Suggested initiative

Build a programme of quantum-inspired computing applications to help firms and users build the business and economic case early. Such a quantum-inspired application development needs to be tied closely to the SparQ programme to help potential user firms get ready – from a skills and technical capabilities perspective – and be prepared for when the testbeds are ready for deployment.

3. Capabilities

a. Findings

The development of middleware to better understand the costs of testing and development will be important when it comes to reducing the costs of integration into existing legacy systems and increasing the benefits for users.

Suggested initiative

Continue to identify the key middleware needed and develop a plan to facilitate this by working closely with the testbeds.

b. Findings

Talent development needs to consider leadership and business skills to complement technical skills, which are essential for the success of the programme.

Suggested initiative

Identify a programme building quantum leadership talent by working with industry, academia and other related institutions to complement the related skills development.

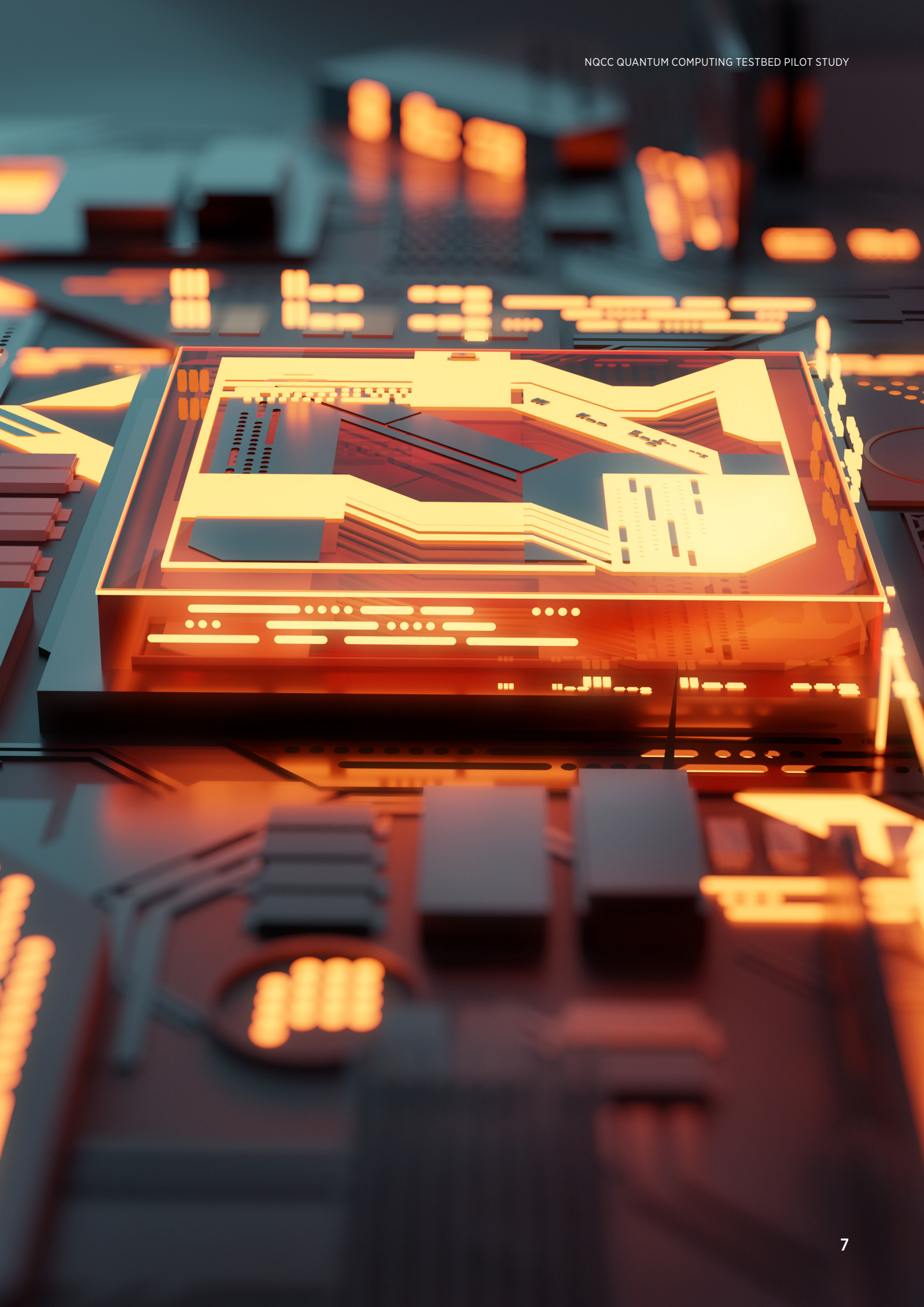
c. Findings

The testbed programme should be highlighted as a way for the UK to identify the key capabilities to provide critical components and expertise for quantum computing, and to identify where it wants to "play" in the supply chain. This is particularly important given the open and collaborative nature of the NQCC programme to help build national capability.

Suggested initiative

Develop a programme of supply-chain mapping and technology roadmapping to identify key capabilities for the UK to build key component supplies.

We recommend developing a mission-driven approach, aligned with the National Strategy Missions, as the basis for helping to create and shape the market for quantum computers (Mazzucato, 2021). The aim of this approach is to solve a grand societal challenge that has characteristics of public goods whereby no firm will invest individually because of the limited private benefit, but where such an investment will benefit society more broadly (such as improving the resilience of financial systems, supporting the development of low-carbon technologies to address climate change, or improving hybrid classical–quantum forecasting of the weather). Such an approach would help to align business models and economic incentives among users and suppliers of the technology to demonstrate the proof of concept, which could stimulate private-sector investment to help scale the quantum computing testbeds.



BACKGROUND

In 2023 the National Quantum Computing Centre (NQCC) launched a competition through Innovate UK, part of UK Research and Innovation (UKRI), to deliver quantum computing testbeds for characterisation, benchmarking, verification and exploratory application development. The £30M programme is funded through the UKRI Technology Missions Fund and the UK's NQCC. The seven winners were announced in February 2024 (NQCC, 2024), and through to April 2025 they will develop and deliver quantum computing testbeds that represent cutting-edge quantum computing solutions, implemented in a range of technology platforms.

The winning companies are:

- Aegiq (photonic qubits)
- Infleqtion (neutral atoms)
- ORCA Computing (photonic qubits)
- Oxford Ionics (trapped ions)
- Quantum Motion (silicon spin qubits)
- QuEra Computing (neutral atoms)
- Rigetti (superconducting qubits)

In establishing these quantum testbeds, the NQCC is aiming to showcase, demonstrate and evaluate the capabilities of different hardware solutions. The successful firms are undertaking development, build and commissioning activities to deploy operationally ready quantum computing testbeds at the NQCC.

RESEARCH OBJECTIVES

The testbeds provide exemplary live cases – a "living lab" to study the development of socio-economic systems, to complement the technical development, and to enhance productivity and UK economic growth (Engels et al., 2019). The IfM and NQCC proposed a pilot study to explore the business and economic aspects of the testbeds.

The aim of this pilot study is to explore the barriers and enablers in building a business ecosystem that will facilitate the scale-up of QC technology, spur economic growth and ensure that the benefit of QC accrues fairly in society. Previous work has developed the idea that adopting quantum computing could result in lower productivity growth before the economic benefits accrue fully (Velu & Putra, 2023). It is therefore important to understand the key factors that encourage users and suppliers to engage with the testbeds, and to be able to identify and explain what success means in this context.

The research questions for the pilot study are as follows:

1. What are the key enablers and barriers for the QC testbeds to build a UK QC ecosystem?
2. How can the QC testbed firms develop appropriate business and economic incentives for users and enabling technology suppliers to work with them to build the UK QC ecosystem?

The research is carried out through three "lenses":

1. Technological framing. There must be a common conceptual understanding of the value of QC among the various stakeholders in the industry, and a willingness to engage with the QC testbeds to achieve their desired goals (Cortada 2004; Kaplan & Tripsas, 2008). Key to this is the way the technology is "framed" by the language used and the corresponding meaning attributed to that language by the stakeholders (Bingham & Kahl 2013).
2. Business models and economic incentives. Often the stakeholders' business model design influences the development of a new technology (Tongur & Engwall 2014). Stakeholders need to have their economic incentives and business models aligned to want to participate and develop the market and the corresponding ecosystem (Velu, 2024).
3. Critical resources and capabilities. To develop the ecosystem, it is important to be able to build the relevant capabilities, on both the demand and supply sides. Even when the business and economic incentives are present, the ability to develop critical resources and capabilities could constrain development of the new technological ecosystems. It is imperative for key stakeholders to encourage effective cooperation in building complementary assets (Tolonen et al., 2017).

The framework for the pilot study is summarised in Figure 1.

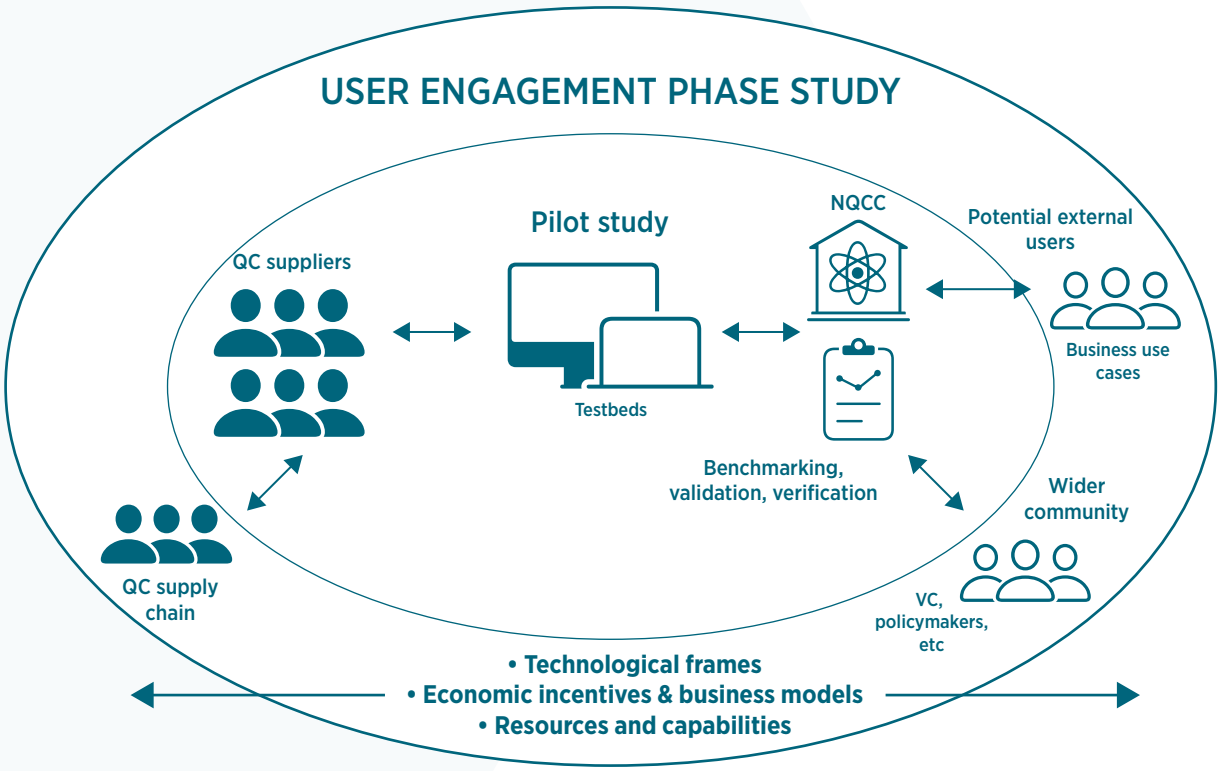


Figure 1: Key stakeholders for the pilot study

METHODOLOGY

The pilot study comprised interviews with the testbed firms and representatives from quantum computing industrial communities. The interviews took place during July–December 2024.

The interviews broadly covered the following questions:

- How do you perceive the key benefits of QC and the engagement with the QC testbeds to achieve them?
- What are the main factors acting as barriers to engage with the QC testbeds, and what are the alternative solutions?
- How does the business model design affect your decisions?
- What are the initiatives that need to be taken by the QC testbeds, NQCC and other relevant stakeholders to help build the UK QC ecosystem?
- What are the resources and capabilities that are needed to help the QC testbeds build the UK QC ecosystem?

A more detailed interview protocol is given in Appendix 1: Protocol for testbed interviews.

KEY STRENGTHS OF THE TESTBED PROGRAMME

Next, we examine some of the key strengths that the interview participants felt the testbed programme exemplifies.

The NCCC as the lead customer

First, the testbed community really appreciate the innovation model, where the NQCC acts as a "lead customer", with full engagement and the provision of critical support infrastructure. It is a key attraction of the UK quantum computing (QC) landscape for external observers. In general, there was a view of the NQCC as a "sympathetic customer", interested in the state of the art and what the machines can do. Comments included *"…it feels like we are doing research together…helping us find the dragons…"* and *"…more like working for mutual benefit…".* Participants made comparisons with industrial customers, who tend to focus on service levels around stability, reliability, guaranteed uptime, regular maintenance and potentially "business-class" access to expertise. Interviewees felt one of the key benefits is that there is currently no real commercial market for industrial customers of quantum computing, so the NQCC is providing a valuable first step in trying these machines in a customer-like setting, without being too focused on commercial arrangements.

"…By having a physical centre and a physical presence there, you actually create a type of community connection that you can't so well create otherwise…"

For firms based in the USA, the UK was seen as a "good bet" because of the language, culture, travel, lack of certain EU regulations, and access to scientists and "anchor tenants" such as Riverlane and photonics firms. Comments included: *"[This is] a good way to become a global company without leaving home…"* It is clearly different to non-quantum testbeds (e.g. 5G, autonomous vehicles), where the demand side is more evolved – hence, the key stakeholders are relatively well

defined. The wider ecosystem perceived the programme as different to other countries, and possibly unique in its attitude to IP, its openness to non-UK players, and its willingness to help develop the ecosystem. Favourable comparisons of the NQCC testbed programme were made with other national programmes in the EU, such as the French and German programmes where sovereign ownership of intellectual property is a key factor.[1]

From the perspective of the testbed providers, the programme as a pathway to the talent pool in the UK ecosystem was seen as very important. The physical location of the NQCC at the Harwell site was described as *"...a pipeline for people...a springboard"*. Several of the testbed providers commented on how the programme helps them build partnerships in the ecosystem, particularly for non-UK native firms; but some also noted there is a need to consider parts of the ecosystem that are not represented at the NQCC or in the UK (e.g. semiconductors).

Funding for technical development and testing ideas

The interviewees commented that the programme allows the community to test the state of the current technology, providing hands-on experience with deployed systems, and improved understanding of operational aspects (i.e. What does it mean to be/engage as an end user?).

"...We can start to do stuff...we can learn about these devices...and see how applications scale between different types of qubit hardware, and benchmark against traditional GPUs..."

Several participants said the programme is helpful for testing small-scale proof of concepts across multiple environments, and it is seen as an accelerator for internal development, being particularly useful for finding mitigation strategies for potential modes of hardware failure and helping to assess risks in technology investments. It also encourages thinking on strategic direction for the testbed providers. Comments included: *"...it helps us firm up our technical roadmap... it helps us discover the unknowns..."*; and *"...There is a huge difference between making machines and selling them ... it's easy to build a product; it's harder to build a product that someone wants to use..."*.

There were several comments about the differences between building in the lab versus building in an industrial environment. One participant commented that *"... the NQCC testbed forces us to think about putting the whole machine together..."* One firm described the value of having parallel testbeds in different locations (e.g. the USA and UK) to accelerate learning between labs in different geographical locations.

Technical skills of the NQCC team

Overall, there was broad interest in the NQCC's vision as a centre of technical excellence for quantum computing (e.g. providing technical training), as an access point for end users, and its vision for building the business ecosystem. In particular, NQCC plans to connect firms with other technology areas, potential end users and the supply chain, and to build business excellence around the technologies – potentially collaborating with other agencies, including academia – are particularly attractive.

For the NQCC and UK's own benefit, several interviewees commented that the testbed programme is a significant economic benefit to the UK – the total cost, including all support-related costs to develop the testbeds, is much higher than the

[1] We note also that Germany recently announced it will host the IBM's first European Quantum Data Centre (Shaw, 2024), in contrast to the UK approach of a state resource in the NQCC.

£30M that the NQCC have invested, with the potential economic benefit being multiple times the investment outlay. Furthermore, the testbed programme will help to guide the NQCC's strategic thinking and roadmap: *"...The testbeds provide the 20% view, but the UK needs a 5–10-year plan..."*) and *"... [this programme helps develop] a vision of NQCC as a Centre for Computer..."*

Access to users and ability to work with partners/collaborations

The programme offers a better understanding of the integration costs as well as transformative costs of business models, which would make the UK ecosystem attractive and eventually help to drive the thinking around a coherent policy for user access. For example, participants noted it will cost a lot to run the testbed hardware "as a service", and they were interested in exploring whether there will be free access for research use, and what industry would be charged for access.

A big draw for several vendors was building relationships with key supply-chain elements in the UK (e.g. Phasecraft or the academic research community). Potential partnerships with "anchor tenants", such as Riverlane, offer an avenue to strengthen the learning opportunities and business cases of the testbed firms.

FINDINGS AND SUGGESTED INITIATIVES

The NQCC is already deeply involved in several use-case and ecosystem-development programmes, such as SparQ. Significant NQCC initiatives support firms and the UK user community to develop the capabilities to adopt quantum computing by building knowledge and expertise in applications discovery. The study findings and suggested initiatives aim to build on the success of the NQCC's quantum computing readiness initiatives. We carried out this pilot study through the perspective of three "lenses": (1) the technological framing, (2) the economic incentives and business model design, and (3) critical resources and capabilities. These findings are subject to some of the testbeds being able to deliver on the planned technical development goals.

The testbeds are at different stages of maturity in terms of technical development and business model design. Therefore, a range of development strategies are being pursued by the respective testbeds, depending on their vision and goals, resulting in a range of initial business models:

- Technology platform providers to enable various quantum technologies, versus dedicated full-stack quantum computers (there is a spectrum from platform to dedicated machine).
- Some are developing initial demonstrators/accelerators, with the ultimate aim of producing full-stack, universal quantum computers.
- Some will develop quantum computers that live in the data centre with cloud access, while others will develop locally hosted machines.
- Some primarily want to provide machines, and some also want to be involved with systems integration.
- There was a spectrum of views between being guided by improving the technology and being guided by "What can we do with these systems that is of interest to industry?"
- There are also various viewpoints on how much firms currently want to engage with end users. Some want close relationships with customers now, some are doing this via partners, and others are less keen to develop very close relationships at this stage, preferring to wait to develop a more mature working prototype before doing so.

We outline below the key findings and suggested initiatives.

1. Technological framing

Findings

(a) Evolve technology benchmarking to user application benchmarking through SparQ and related initiatives (need to calibrate the technology and use cases to ensure an efficient and effective feedback loop between them).

The testbed providers understood the importance of timely delivery of their proposed hardware to the agreed specifications, to enable the NQCC to conduct the planned technology benchmarking and characterisation activities. Participants broadly understood the importance of delivery to the agreed criteria: *"…we said we will deliver a quantum computer with a certain number of qubits, and there are a number of criteria that define the performance – those [are the] things we will have to verify and measure … the NQCC will verify before the end of the project, and that is the acceptance."* The NQCC plans to build on the technology benchmarking initiative to user application benchmarking. Some testbeds are technologically more mature, where user application benchmarking will be key to their development plans to enhance the feedback loop with users.

"…The feedback loop is very important. There is a potential disconnect between system testing and the development cycle. But start-ups cannot wait very long! We can't just go to a component provider and say we want this spec instead of another spec, because items take 6 months or a year to procure…"

The interviewees also emphasised the need to calibrate the rate of development of the technology with the use cases. One interviewee said: *"It is important that at this stage of the development of quantum computing that the respective progress between the technology and the use cases is synchronised appropriately, and acts as a positive feedback loop, as otherwise we risk losing momentum if one accelerates compared to the other."* Participants saw the potential of technical benchmarking as a positive, even if one technology doesn't perform as well as another – one participant noted, "In that case, we want to know!" Several participants were interested in how the technical benchmarks could be further developed (e.g., benchmarks across platforms or modalities) to complement the use cases (e.g., developed via the NQCC SparQ programme) to enhance the seamless feedback between them. These discussions around use cases prompted some participants to make comparisons with other types of testbed, for example 5G or autonomous vehicles, where the demand is relatively well identified and already exists; this is less true for quantum computing.

Suggested initiative

Develop tools and methods to connect the technology benchmarking with user application benchmarking via SparQ and related initiatives. Consider deep dives into one or two pilot studies based on the SparQ programme in selected industries to develop the methodology. Identify the right "stakeholders" and build connections early, particularly with other stakeholders in the ecosystem, for example, Quantum Software Lab (QSL), Quantum Technologies Hubs and global quantum industry consortia among others. These stakeholders are likely to have complementary programmes that will help the NQCC to move from technology benchmarking in Phase 1 of the testbeds to business-case benchmarking in later phases. For example, some interesting trial problems might have emerged from the work of the QSL. Building closer links between the SparQ programme and some of the other initiatives would provide the basis for the deep-dive study to develop the methodology to bridge the technical benchmarking and use-case benchmarking. Moreover, discussions with the DARPA quantum computing benchmarking initiative might provide useful lessons and shared learning opportunities (DARPA 2025).

Findings

(b) Need to provide access to suppliers and end users. Several testbeds are sourcing parts from Europe or other areas; and while the UK has some supply-chain strengths in this context (e.g. photonics), it is likely to need to continue sourcing from outside the UK. Furthermore, some participants are struggling to access packaging capabilities, electronics testing and cloud provision, and interviewees were keen to explore whether there could be better solutions for accessing these enabling technologies and other elements of the supply chain. One interviewee said: *"…there are some core competencies that will definitely be within [our organisation] … but then of course there are many other layers. There is the whole thinking about packaging. Then there is thinking about the signal chain, and the control electronics. There's a level of testing capabilities that is expensive for smaller companies to put in place themselves."* It may be helpful for the NQCC and other UK institutions to help these firms lower the search, transaction and negotiation costs (and provide incentives for the suppliers) to continue supplying new components, potentially by contributing to a supply-chain directory, and acting as a convenor to unblock the barriers to developing special components.

In addition, there was a general theme of firms wanting to position themselves in the market distinct from their competitors, and making sure people know who they are. All participants felt that relationships with end customers were important, but not all firms wanted to engage early. Specifically, interviewees said that too much engagement with potential end users at this stage risks leading to being *"… pulled into the wrong feedback loops, and spending time polishing stuff that isn't important…"*. Conversely, participants felt they currently have limited ways to position themselves in some sectors that are dominated by Tier 1 contractors (e.g. defence). Participants asked whether the NQCC could help with building credibility for large bids, and potentially act as a filter for academics, for small firms who want to try things out, or through connections via a systems integrator or similar consultancy. The NQCC may need to consider how it can help to build industrial consortia to bring the technology into industrial use cases.

"It takes a lot of time to collaborate with everyone … so don't!"

Suggested initiative

Develop a directory of key suppliers for the enabling technology and act as a proactive convenor. The NQCC has convening power as a neutral party with national credentials that could be leveraged to act as a source of credibility to access users (e.g. between primes and start-ups) and suppliers, and facilitate interaction and collaboration initiatives. Also, it should develop a directory of key suppliers for the enabling technology and potential end users to better understand how to unblock disincentives and create opportunities for testbeds to develop their capabilities. It could consider areas where the UK has strengths (e.g. photonics) and less clear capabilities (e.g. semiconductors) to better understand how to unblock disincentives, and open more avenues for testbeds to develop their capabilities. Ideally, this should go beyond the core "quantum components" of the hardware technologies, and include, for example, packaging capabilities, electronics testing and cloud provision. The NQCC would need to consider acting as a convenor to give users access to the supply chain. It can act as a filter between the testbeds and potential customers (e.g. signpost smaller customers to academic research groups or QSL, or act as a credible partner for Tier 1 suppliers).

2) Business and economic incentives

Findings

(a) "Anchor tenants" have an important role (e.g. Riverlane, Phasecraft, academic groups in the Quantum Software Lab and Quantum Technology Hubs). Several interviewees commented on the importance of a few key players, or "anchor tenants", in the UK ecosystem. These anchor tenants are a key national asset, acting as one of the main attractions for some of the testbeds and related stakeholders to invest in developing the quantum computing ecosystem in the UK. One participant said: *"Riverlane's partnership will be instrumental to getting to build error correction in our system, so having a system at the NQCC, considering that Riverlane is a partner in the project and a British company, makes it likely that we will have some of those activities that we need to do around error correction happen in the UK."*

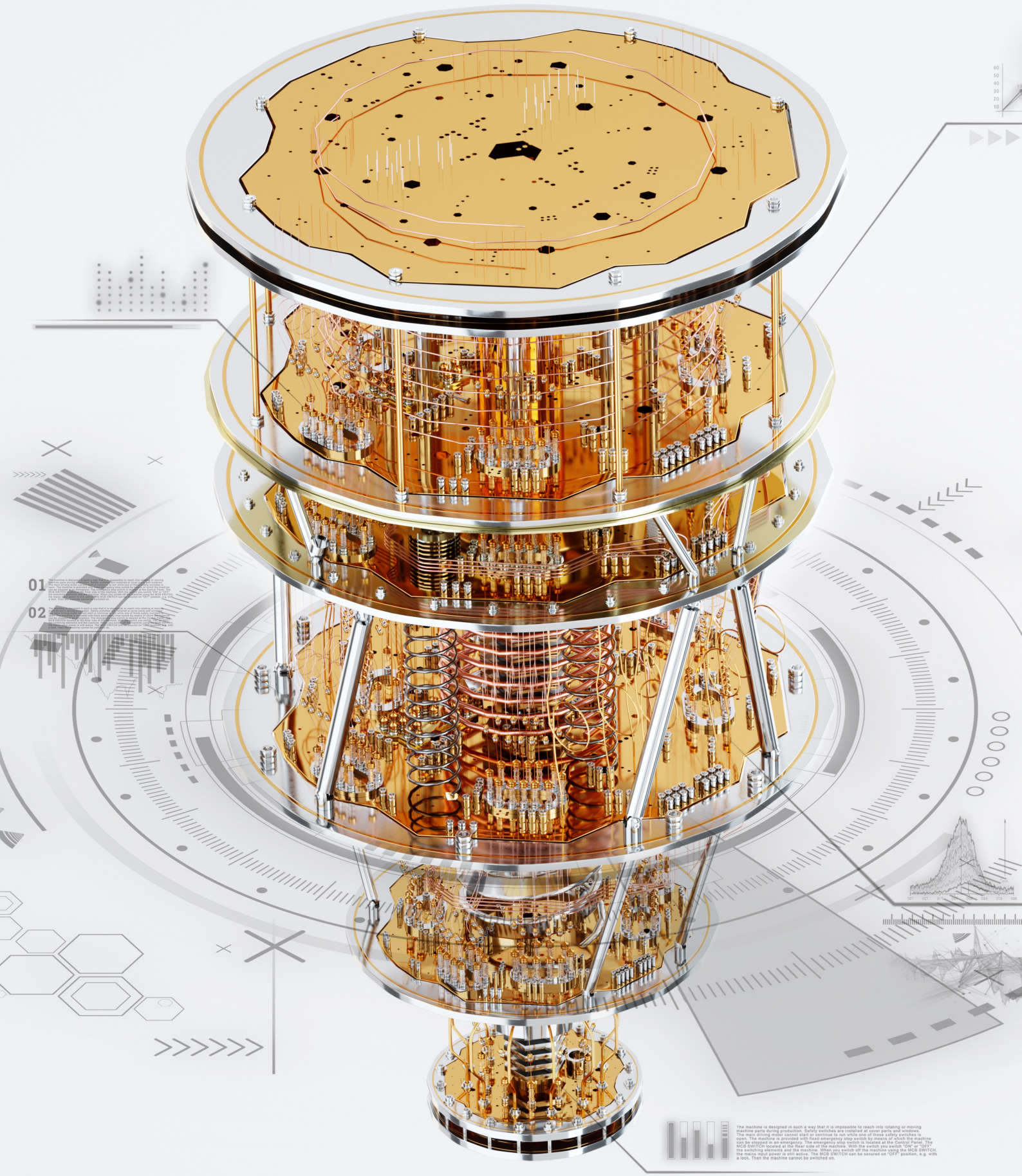
Cultivating these anchor tenants and helping to develop their business models and ecosystems may be critical to the success of the NQCC programme. Moreover, there were concerns about what would happen if these key players were less accessible (e.g. through acquisition). One participant said: *"Is it too fragile? What if Riverlane just stopped? What if they got acquired? Would we need to go to government for cash flow or for technical issues? If it's technical issues, could we help them crack the problems? How could we ensure that they honour their commitments to the testbeds, and hence the missions?"* Until there is a real commercial market, the views shared suggested that government will be buying research rather than products, with the implication that this will not in itself drive the question of what the real customer use cases will be. Hence, access to these organisations becomes even more critical. Participants emphasised the need for the NQCC and the national programme to establish deeper relationships with, for example, Riverlane, Phasecraft and business consultancies who understand the wider business transformation.

Suggested initiative

Identify key anchor tenants and develop plans to help them build their ecosystem. There should be a programme that works with the key anchor tenant firms, both to help build their business and foster partnerships with the testbed and wider ecosystem. This needs to be a targeted programme of development, identifying the critical assets and capabilities needed by the key players to enhance and develop their technology and business models. It should consider ways to reduce the risks of losing one of these key players (e.g. through acquisition by a large organisation), and what can be done to support them equitably for the UK ecosystem's benefit. And it should explore the relationship with business consultancies, who will understand the wider business transformation required as quantum hardware becomes a reality. This will help with derisking the software side in parallel with derisking the hardware currently underway.

Findings

(b) Enabling and testing interim business models for intermediate products is key for successfully developing a roadmap for future business models for completed QC systems. Some testbeds are developing "interim technologies" (e.g. harsh environment multiplexers) or "steps in the road" as part of their overall roadmap to develop a fully fault-tolerant system. These testbeds are looking to monetise these interim technologies and test different business models. Participants were keen to explore how the NQCC could provide an avenue to test these business models, for example by enabling more interaction between players in the ecosystem, enabling sharing of non-competitive IP between testbed providers, or connecting testbed



providers to other organisations that might be interested in the "by-products" of quantum system development. One interviewee said: "*...if we just talked to the other testbed providers about whether they'd be willing to test our systems in their setups, because we would like to just know what performance they can get with our system compared to the commercial solutions that they are using at the moment ... if we said, oh, could you do us a favour and just test the system for us? They would probably not be ready to do that, but if there were a framework around it, where we are all the testbed providers or anyone interacting with the NQCC partners with the others to help them advance their own roadmap, that could be very valuable.*"

Suggested initiative

Build the capability to enable testbeds to test and evaluate their interim and evolving business models. There should be a programme for the testbeds to test and develop business models for their interim technologies. It should consider how to encourage more interaction between players in the ecosystem, enabling sharing of non-competitive intellectual property (IP) between testbed providers, or connecting testbed providers to other organisations that might be interested in the "by-products" of quantum system development (e.g. other quantum technology firms, or other high-tech firms such as space satellites, or deep-sea equipment associated with Harwell or the wider STFC).

Findings

(c) Quantum-inspired computing capabilities can be helpful to enable business-case development within potential user organisations. There are a number of countries (e.g., Japan) that are developing use cases that will ultimately have a quantum solution but also a classical solution that user organisations can learn from now. The aim is to *"...transfer the skills later, when quantum computing has evolved enough to have business benefit..."*. The UK needs to emphasise use cases in end-user organisations to familiarise organisations with quantum algorithms and related data management methods. Participants suggested that the programme could build on existing NQCC programmes (e.g. SparQ) to contribute to thinking about "quantum-inspired" computing. This could incentivise end users to learn about quantum now, while the machines are being built. For example, one participant said: *"... [in our programme] we use quantum inspired for small optimisation problems as part of our message to government – there is no need to wait until the hardware is mature; we can train customers now, get them familiar with optimisation issues by using the existing technology, and then they can transfer the know-how to quantum computing when the hardware is ready."*

Suggested initiative

Build a programme of quantum-inspired computing applications to help firms and users build the business and economic cases early. It should consider how quantum-inspired applications can help build the business case. This requires identifying computer-intensive business problems and formulating them using thinking based on the principles of quantum mechanics to solve that problem. This approach to quantum-inspired computing could help to prepare firms for when fault-tolerant quantum computers are realised (Sodhi & Tayur, 2022). For example, in Japan, under the Q-Star programme, such quantum-inspired computing (e.g. using digital computers such as Fujitsu's Digital Annealer and Toshiba's Simulated Bifurcation Machine (SBM)) is being developed and used to enable training, and to learn about wider business process changes as fault-tolerant quantum computing becomes a reality. This may boost interest from the industrial community and lower the barrier to entry for non-quantum firms.

3) Capabilities

Findings

(a) Building middleware can help reduce costs of testing and development and reduce barriers to entry. Participants expressed a desire to make it easy for people to gain access without having to rewrite their workflows, using middleware that can work across devices, stating *"…it's no good providing a machine that nobody knows how to programme…"*. However, particularly for the research community, the idea is to develop such middleware as open source, which needs to happen in parallel with developing the hardware. Participants made comparisons with the slow development of the use of GPUs, pointing out that *"… [they were] useless until Nvidia released CUDA … the first paper that said you could use a GPU for science came out in 2002, but the first supercomputer to hit #1 with GPUs wasn't until 2012…"*). In addition to middleware, this is likely to include cloud provision, remote access for vendors, job scheduling/queuing tools, access cost models, tools to request access in grant applications, and technical training for users.

Suggested initiative

Continue to identify the key middleware and other enablers of access, and develop a plan to facilitate this. There should be help building the middleware, or enabling access to third-party middleware to reduce the costs of integration with existing workflows. In particular, they should investigate whether the middleware needs to be different for different hardware technologies. The NQCC's plans to build middleware and information sessions to further integrate these with the testbeds would enhance the programme and its adoption. Furthermore, the NQCC should consider the broader access enablers that will be required to provide quantum computing as a service, such as cloud provision, remote access for sellers, job scheduling/queuing tools, and technical training for users. It may also be useful to start considering charging models for industrial users, and ways of providing access to academic researchers (e.g. planning for how academics will request time on testbed hardware in grant applications).

Findings

(b) Building talent (technical and software skills, but also quantum leadership skills) will be key to capability development. Interviewees felt that a systematic programme needs to be developed to build broad business skills to help cultivate the UK quantum ecosystem. For example, they outlined the vision for a hub for digital leadership to contribute to building "T-shaped people" with deep technical knowledge and broad business skills (e.g. the ability to sell the vision of quantum computing to C-suite in industry). One participant noted, *"the conversation to be having right now with boards and with the C-suite around quantum so that they understand the ROI … they've got to justify to the shareholders what this investment looks like, and that requires innovation leaders [to communicate that message]…".* The UK is already investing in relevant technical training (e.g. via Centres for Doctoral Training), but to ensure the success of the UK quantum ecosystem, it is essential that the community build people with wider business insight.

Suggested initiative

Identify a programme of building quantum leadership talent by working with industry, academia and other related institutions to complement the related skills development. The NQCC should consider facilitating building partnerships with centres of business excellence to contribute to building "T-shaped people"

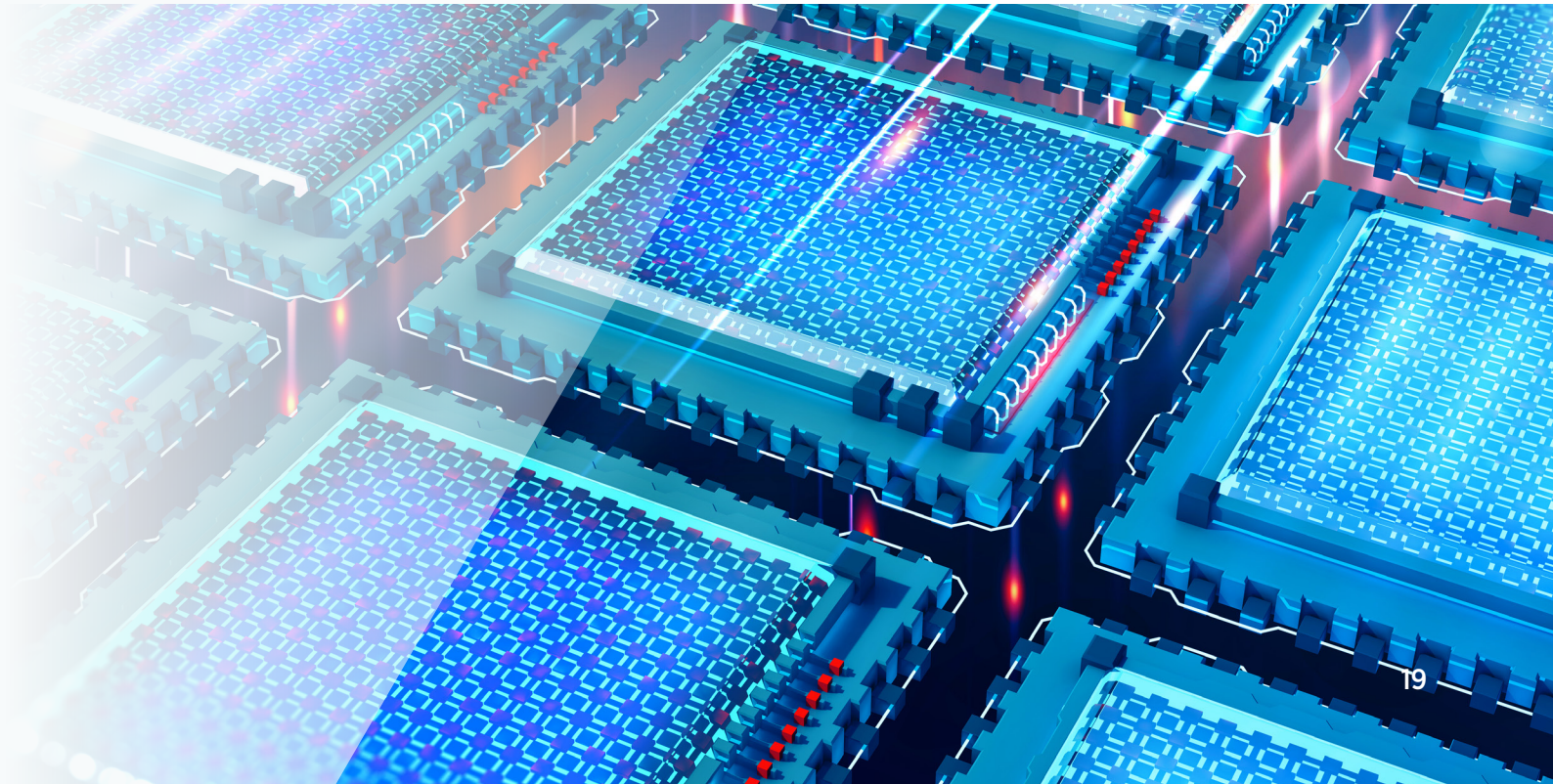
with deep technical knowledge and the business leadership skills required to ensure the UK ecosystem thrives in the market. This activity should look at what partnerships will be required to address this, and with whom. For example, there is academic expertise at business schools, and legal and IP expertise in various UK institutions. The NQCC could help to convene relationships and signpost potential centres of excellence by leveraging Harwell's reputation as a "pipeline for people" to build a more coherent offering around these wider business, management and entrepreneurship skills.

Findings

(c) The UK needs to identify the key capabilities to provide critical components and expertise for quantum computing. Participants felt that, while the strengths of the UK supply chain are well known (e.g. photonics), the NQCC needs to play its part in identifying where in the global quantum ecosystem the UK wants to specialise. For example, participants asked if the UK wants to be seen as a supplier of full-stack quantum machines, or as a key part of the supply chain for certain hardware modalities. This is particularly important because of the NQCC's open and transparent innovation model compared to some countries (e.g. the EU, where sovereign capability is emphasised as a key consideration). One interviewee noted that *"even though the components are off the shelf, they are specialised, so there's only one or two companies on the planet to make them."* Sellers were interested in whether they could help the UK government identify the technologies they want to be manufactured in the UK.

Suggested initiative

Contribute to developing supply-chain maps and technology roadmaps. This will be key to identifying the required capabilities for the UK to build component supplies. Several contributors suggested that the UK needs to do more to identify where it wants to play in the quantum space – as a supplier of complete systems or of key components in the supply chain. The NQCC has a key role to play in this discussion and will be able to offer a view on manufacturing scale-up in relevant technologies to enable the UK to capture more value in the quantum sector.



CONCLUSIONS

The aim of the study findings and suggested initiatives is to build on the success of a number of NQCC use-case and ecosystem-development programmes to build a major quantum computing capability in the UK.

This pilot study has demonstrated how the testbed providers value the programme and are keen to contribute to its continued success. It is interesting to note how the national innovation model, particularly its openness to non-UK participants, is seen to be important in driving both the UK's interests and the global interests of the quantum computing community. It has also been interesting to begin to explore the role of "anchor tenants" in attracting firms to the programme, and contributing to both the success of individual firms and the wider ecosystem.

The key findings of this pilot study are as follows: the importance of connecting technology benchmarking to use cases; uncertainties around the supply chain (in the sense of both providing hardware elements and access to "anchor tenants"); the role the NQCC may be able to play as a filter for smaller potential customers, and as a convenor and trusted partner with larger customers; and testing interim business models and building confidence in the wider community via "quantum-inspired" computing. We observed how middleware in the widest sense is important – beyond programming APIs, this includes reducing barriers to access in a variety of ways, such as cloud provision and costing models. And we saw the importance of building talent, which, critically, needs to include the wider business and entrepreneurship skills that will be vital to ensuring the success of the UK ecosystem. Finally, helping to build a deep understanding of the UK supply-chain capabilities is key to success.

The NQCC has a major role to play in enhancing its current initiatives in:

1. formulating a common vision of quantum computing and materialising new value propositions
2. helping to form the ecosystem community, by defining and aligning business and economic incentives, and
3. helping to develop capabilities by orchestrating the resources of the ecosystem.

One way to support this is by developing a mission-driven approach, aligned with the National Strategy Missions, as the basis for helping to create and shape the market for quantum computers (Mazzucato, 2021). The aim of this approach is to potentially solve a grand societal challenge; this would help to prove the concept and deliver on the points above. In particular, there are significant uncertainties on the user-driven demand side, and the technology-providers supply side, in terms of enabling the scale-up of quantum computing testbeds. The government acting as a customer via the NQCC programme offers a unique opportunity to derisk the technology development through a mission-driven programme that could facilitate coordination and align incentives among firms and other stakeholders to develop quantum computer applications that benefit wider society. Such a proof of concept should be demonstrated as a societal grand challenge that has public-good benefits. It will not necessarily be funded by the private sector, because of the limited private benefits, but such an investment will benefit society more broadly. These include improving the resilience of the financial system, supporting the development of low-carbon technologies to address climate change, or developing hybrid classical–quantum methods to improve weather forecasting. Once such a proof of concept is demonstrated, it is likely to encourage private-sector investments to help scale the development of quantum computing.

We hope this study has provided value to the NQCC and the testbed providers, and that it can be used as the basis for further research as the programme develops in 2025 and beyond.

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APPENDIX 1: PROTOCOL FOR TESTBED INTERVIEWS

A. Company's profile and quantum computing initiatives

1. Could you tell us your background (i.e. roles and responsibilities) and share the history of the company?
2. How the quantum initiatives in the company are organised? And how do you describe the commitment of the leadership team towards the quantum initiatives?
3. How is the progress of the QC initiatives and what has been done so far (use cases and challenges from a hardware and software perspective)?
4. How do you perceive the challenges of building the demand as well as supply sides?

B. NQCC testbed initiative

5. What was the reason for joining the NQCC testbed initiative?
6. How do you perceive the key benefits of QC and the engagement with the QC testbeds to achieve them?
7. What are the main factors acting as barriers to engage with the QC testbeds, and what are the alternative solutions?
8. How does the business model design affect your decisions?
9. What are the initiatives that need to be taken by the QC testbeds, NQCC and other relevant stakeholders to help build the UK QC ecosystem?
10. What are the resources and capabilities that are needed in order to help the QC testbeds build the UK QC ecosystem?
11. What are the benefits and challenges of the funding model for the national innovation system where the government acts as the initial customer to the testbeds?
12. What are the additional initiatives needed or could be improved to enable the building of the quantum computing ecosystem?

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