Quantum technologies – the state of the art

There is widespread agreement across academia, industry, and policymaking that the pace of development in quantum technologies (QTs) has accelerated in recent years. This is largely due to significant policy interest around the globe, as quantum has become a technology-set considered to be an important component of the future economy. The discovery of Shor's algorithm, which would enable a cryptographically relevant quantum computer[1] to breach current internet security protocols, led to an international rise in interest in quantum computing, and concomitant support for other QTs. In the wake of this policy attention has come investment and enablement, with the UK's commitment reaching £2.5bn over the next decade (in addition to the £1bn of previous investment). Other countries have also allocated significant sums to research and development (see Figure 1).

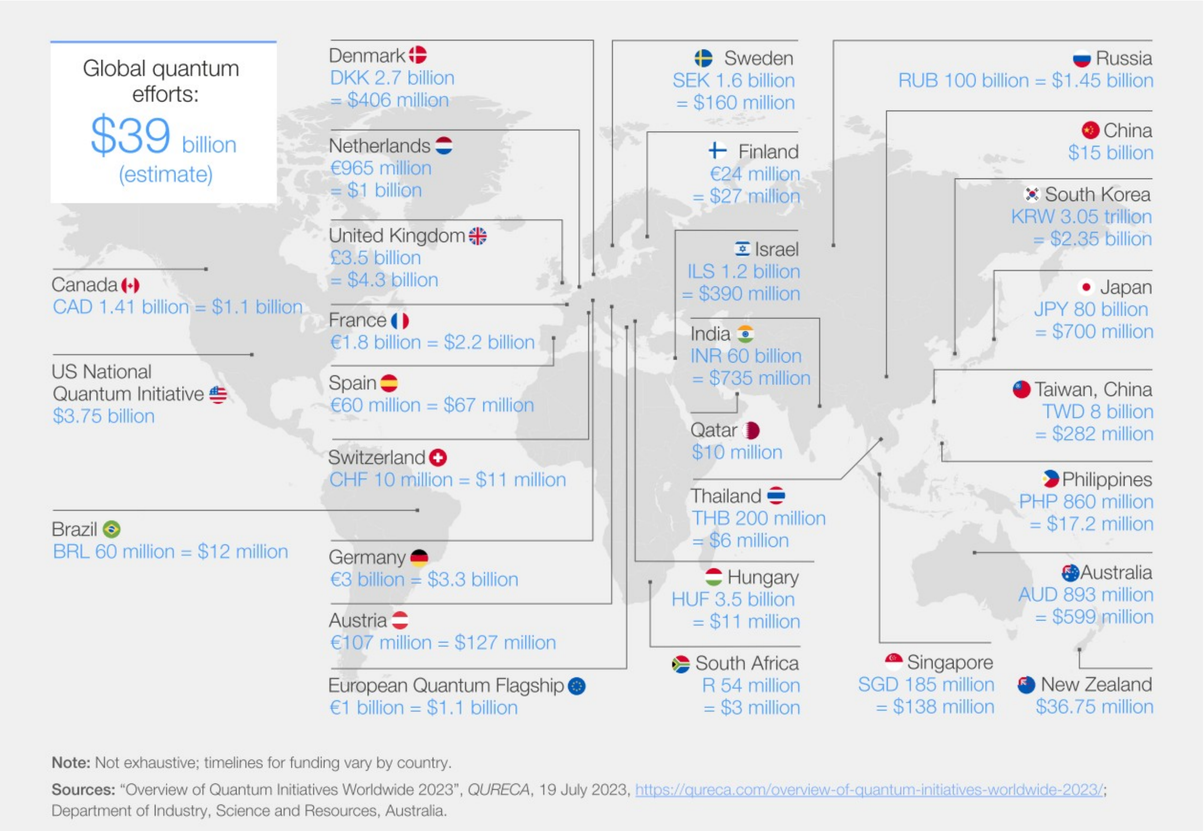

Figure 1: QURECA map of quantum technology investment 2023

[1] https://www.ncsc.gov.uk/whitepaper/next-steps-preparing-for-post-quantum-cryptography

What are these quantum technologies?

QTs fall into broad domains – sensing and timing, imaging, communications and computing – all of which may transform current capabilities. The 20th century enabled quantum-based technologies such as MRI scanners and fibre-optic cable, but the next phase – quantum 2.0 – may represent a groundbreaking increase in capabilities.

- **Quantum computation** is built around the development of novel quantum 'bits' – these may deliver not just faster, more powerful, or more efficient computers, but computers that afford different *types* of computation. They are predicted to tackle challenges that are known to be NP-hard for a classical computer such as modelling new molecules and materials; the 'travelling salesman' problem; and large number factoring. Although robust large-scale quantum computers are still considered to be some distance off (estimates vary from 3 to 10 years), there is a growing body of work on obtaining useful results from current devices, while companies such as IBM and AWS have provided access to their models to support experimentation. It is considered possible that there may not be one single best architecture for a quantum computer but that different physical qubits may offer different variants of capability.
- **Quantum sensing** hugely improves the accuracy of measurement in the physical world using atomic properties – this has applications in multiple domains including navigation (allowing for more accurate and reliable geolocation), healthcare (improving the accuracy and robustness of medical devices), and detection (for example to map pipes and track leaks). Quantum sensing works by detecting changes in motion, and electrical and magnetic fields – hence devices that use quantum sensing are in some ways more robust than conventional systems as they are not susceptible to signal jamming or other electromagnetic interference. Quantum timing is included within this set of technologies, as it utilises the measurement of atoms to provide a timing signal with far greater accuracy than is possible with non-quantum devices.
- **Quantum imaging** is also related to quantum sensing. Quantum imaging can provide resolutions beyond classical optics and can also provide imagery much more efficiently (using less data, or less power). The utilisation of quantum mechanical properties also provides affordances for quantum imaging such as seeing through smoke and foliage, and around corners.
- **Quantum communications** is centred on the development of completely secure communications networks, and potentially in the future could provide the basis for a 'quantum internet' that would

operate in tandem with current technologies to provide communications that cannot be hacked or surveilled. The applications for this are clear, but this technology may also be linked together with networks of quantum computers to provide 'blind' quantum computing – using remote quantum computers over a secure network to perform computation in an entirely secure manner.

Given that these capabilities may collectively redefine numerous sectors of any country's economy, the increased attention and investment across policy and commercial domains is straightforward to understand. The 2023 Quantum Technology Monitor from McKinsey reported that the global quantum computing market alone was predicted to reach £70bn by 2040.

Perceived risks and challenges

Although QTs are at an early stage of development (with some, such as sensing and imaging, closer to commercialisation than others), there are already concerns that their development and deployment should be conducted responsibly and in accordance with societal need. These 'responsible' innovation principles were built into the very earliest investments in the UK's quantum programme, and other national programmes have followed suit. There is now a growing community of researchers worldwide focused on policy and research aimed at ensuring that downstream and broader impacts are considered and mitigated where possible. Some of the key challenges and risks include:

1. *Uncertainty around standards and governance*. There is little clarity on the exact meaning of terms such as 'quantum advantage', with standards bodies around the world assessing different possibilities including energy efficiency, speed, or simply novel capabilities. There is a balance to be struck between developing standards too early, which may limit innovation, and developing them late, when path-dependencies may be locked in. Uncertainty naturally represents risk for investors and companies, so discussion on co-operative standards development represents a key international conversation.
2. *Perceptions of hype*. The development pathway for most QTs remains uneven as they transition from the lab to the marketplace. Ongoing investment and long-term horizons for returns are therefore critical and there is a need to sustain interest and commitment from venture capital sources. However, this must be balanced against the necessity of managing expectations and avoiding overpromising, amid warnings of a 'quantum winter'.

3. *Uneven access*. Many commentators have discussed the inequitable distribution of quantum knowledge and resources across the globe, with majority-world countries facing language and access barriers that present ongoing challenges to their participation in quantum technology development. There is a significant risk that existing digital divides will be exacerbated by the concentration of investment and effort in Global North countries.
4. *A quantum 'race'.* The perceived importance of QTs at the nation-state level has generated its own momentum along geopolitical lines, with multiple sources concerned about the risks inherent in treating quantum (particularly quantum computation) as a race. Not only does this approach favour deep-pocketed nations and companies, it creates intense competition for both human and material resources and throws up barriers to collaboration in fields that continue to present foundational challenges.
5. *Governance and regulation.* Although it is widely agreed to be too early to consider specific legislation around QTs, it is useful to note that a lack of clarity around regulation – both in terms of timing and scope – can itself be an impediment to investment and long-term planning. The incorporation of self-governance processes such as responsible innovation and societal dialogue is seen as one way to retain some guardrails on the development of these technologies and seek to manage risk using non-legislative means.

Next steps

The UK is currently in a strong leadership position on QTs, but to retain this position it is important to support both specialist training pipelines and the UK's thriving startup community. Risks such as those presented by Shor's algorithm need to be understood and managed, with much broader awareness among business communities. There is also a need for greater quantum literacy that can build cross-domain opportunities and develop use-cases. Finally, there needs to be an ongoing conversation about pro-innovation regulation that can both support and guide the UK's quantum ecosystem and ensure its participation in the world conversation on quantum futures.