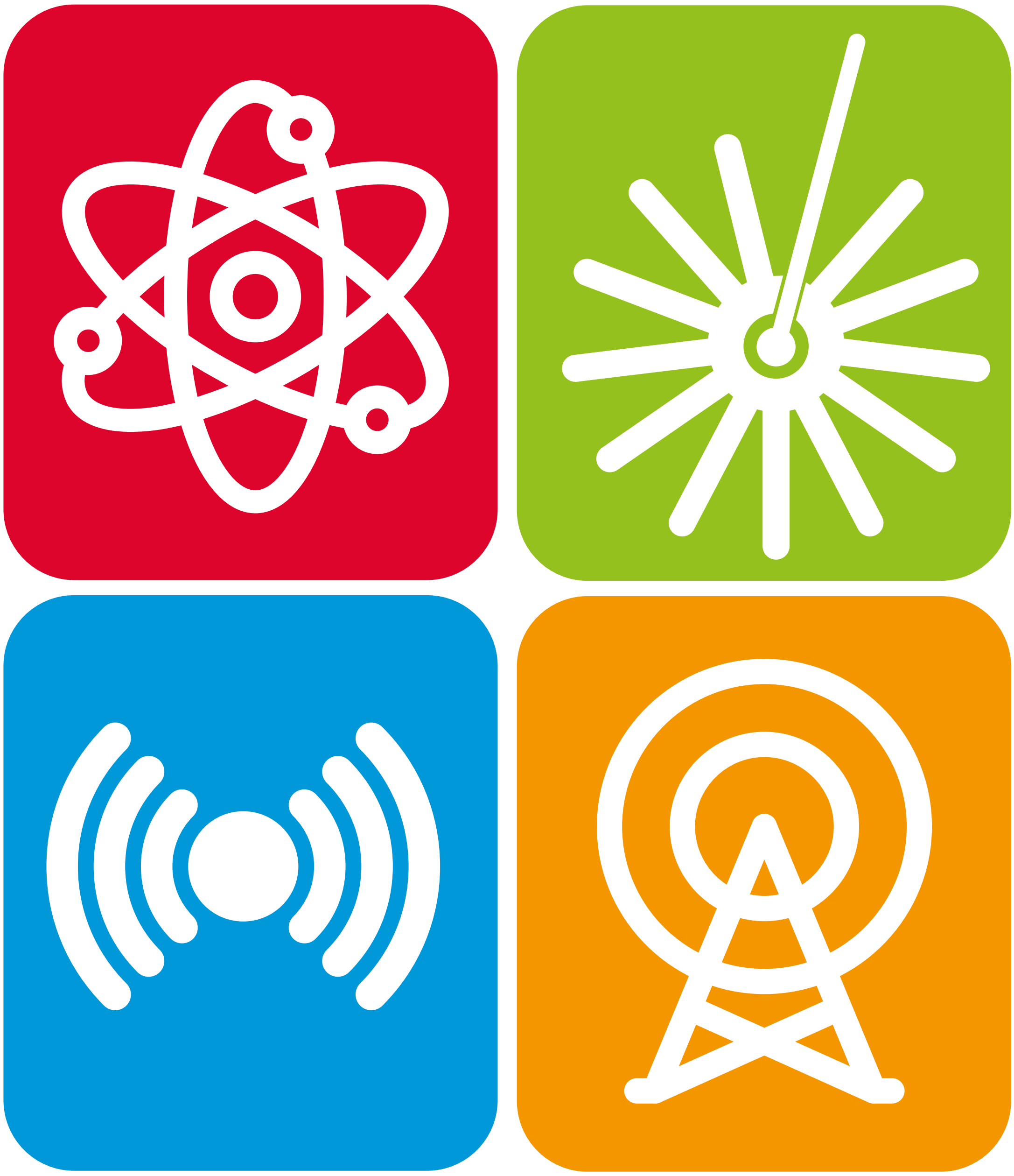
Scottish Science Advisory Council

Quantum Technology: Opportunities for Scotland



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Executive Summary

Emerging knowledge in quantum physics is globally recognised as leading towards the delivery of transformative technologies expected to deliver a step change in computing, communications, sensing and imaging, with the potential to bring economic and social opportunities for Scotland, but also risks.

The UK Government has invested more than £1bn in quantum research since 2014 with Scottish universities and businesses strongly represented and new investment promised. Scottish success in winning competitive UK funding demonstrates strength in our universities which supports a growing technology industry, notably in photonics. In addition, the Scottish Government (SG) has provided financial support for activities associated with quantum technologies, for example via Scottish Enterprise and the Scottish National Investment Bank to businesses and via the Scottish Funding Council to universities.

The photonics industry already contributes to the Scottish economy but recent scientific advances, outlined in Appendix 1, suggest the potential for quantum technologies to make very significant contributions in the long-term in sectors important to the SG's National Strategy for Economic Transformation. With a supportive environment, applying these technologies in the medium term could accelerate progress in the Scottish Climate Change Action Plan and also benefit the health sector.

As with all transformative technologies, potential risks need to be recognised and the development of quantum computing poses widespread cybersecurity risks, unless preventative action is taken in the near future.

This report was requested by the Scottish Government's UK Industrial Strategy and Technology Team and led by the independent Scottish Science Advisory Council (SSAC) which sought views from experts and stakeholders in a 'roundtable' on Scotland's strengths, opportunities and on actions to capture the opportunities and manage the risks.

The recommendations are that the Scottish Government should:

1. **Appoint a part-time independent Chief Technology Adviser** to join the cadre of CSAs within SG, with the remit of regularly reviewing emerging technologies with respect to opportunities and risks for Scotland and bringing these to the attention of relevant CSAs, the SG and relevant agencies;
2. **Catalyse the creation of a quantum focus group** with a remit to ensure that all relevant sectors, industries and businesses are aware of the risks and opportunities associated with the adoption of emerging quantum technology;
3. **Ensure formal Scottish representation on relevant UK bodies** setting standards and developing policy relating to the development and adoption of quantum technologies is strengthened or initiated to ensure engagement to enable realisation of quantum technology opportunities;
4. **Request organisations responsible for education and skills training in Scotland** to provide appropriate support for the development of career opportunities in quantum technologies in Scotland;
5. **Review current early-stage business support** for sufficiency to stimulate new company formation and establishment to take advantage of quantum technology opportunities.

1. Introduction

This report was prepared by the Scottish Science Advisory Council (SSAC) who engaged with the UK quantum technologies community. An important input was a roundtable event in January 2022 with about 50 participants, from universities, industry/business, government agencies and policy bodies, primarily from Scotland with relevant UK organisations represented. Appendix 2 provides a summary of the roundtable.

Many existing technologies, such as electronics and photonics (e.g. lasers and their applications) are based on quantum physics, and are often described as *Quantum 1.0*. However, current international interest is in the potential to exploit the quantum phenomena of *superposition* and *entanglement* to achieve transformational technological change. The exploitation of those phenomena is generally called *Quantum 2.0*, which forms the primary subject of this paper. For an explanation of quantum physics and these concepts see Appendix 1 which outlines the principal areas of application of 'quantum 2.0' technologies currently envisaged, in computing, communications, and sensing and imaging.

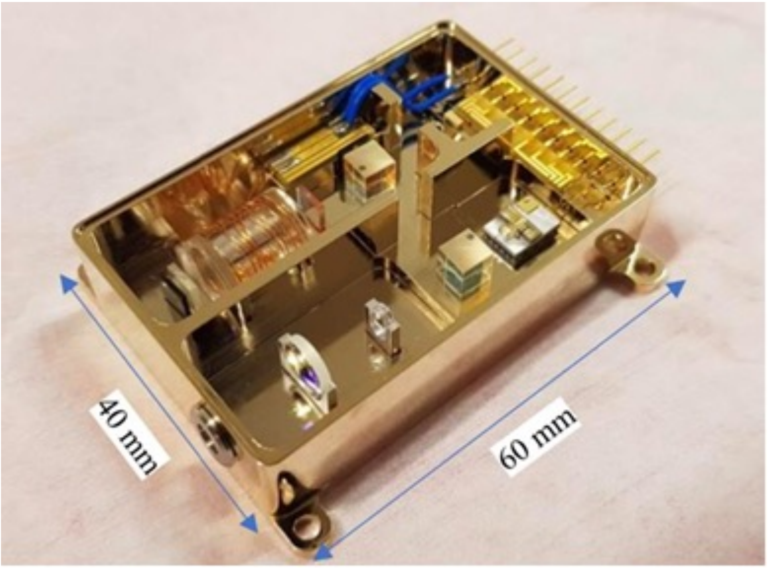
The agreed aim of the study was to review the status of quantum technologies worldwide and in Scotland and offer recommendations to highlight future opportunities and challenges, signposting how Scotland could capitalise on its own quantum capabilities.

2. Applications and Markets for Quantum Technology

2.1 Quantum Computing

Of all applications, computing probably receives the greatest current attention and investment, but is furthest from technical maturity. The dominant challenge is instability caused by unwanted interactions between the 'quantum bits' containing the computing data (called *qubits*) and the environment. Therefore, the first phase of development and applications will be based on 'noisy intermediate scale quantum computing' (NISQ, see Appendix 3), with applications limited and specialised. Maturity is generally considered to be a decade away and operating systems and software all continue to be under development.

However, government needs to be aware of the risks associated with **quantum computing which have the potential to render most current data security techniques redundant, with immediate consequences for cyber security and defence**, but in due course for all organisations reliant on or responsible for data security,



Alter Technologies 'FLAME' Stabilised Laser Module: highly stable laser sources are an essential component in many quantum technology applications, including computing and sensing. FLAME was developed in a research collaboration between Alter Technology UK and the Fraunhofer Centre and is an example of the contribution made by the Scottish photonics community to quantum technology.

whether public or private (the 'crypto-apocalypse' in which public key encryption ceases to be effective).

The suitability of quantum computing for unstructured data searches has wide applicability, for example for logistical operations. Further applications will arise and are developing in fields where the ability to handle large data sets is important, with examples in the finance and health sectors.

Quantum computing may also enable modelling of atomic and molecular systems thus accelerating e.g. drug discovery and advances in material science. There is also considerable potential in improving machine learning. Early applications are being investigated in the defence sector, with potentially much wider use, e.g. in manufacturing, especially when combined with technology advances in sensing, metrology, and robotics. **Quantum computing artificial intelligence will pose ethical and public understanding issues** when applied to decision-making processes which would then be difficult to explain in conventional terms.

2.2 Quantum communications

The most highly developed and urgent area is quantum key distribution (QKD) to enable secure communications. QKD is explained in Appendix 1 and has already been demonstrated in many projects world-wide (see Section 3.3). Data/communications security are fundamental to many sectors: defence; national infrastructure (energy, transport, communications and finance); and data storage and computer networks. Ensuring future security to compensate for threats posed by quantum computing is imperative, requiring extensive engagement with infrastructure providers and the development of international standards.

2.3 Sensing and Imaging

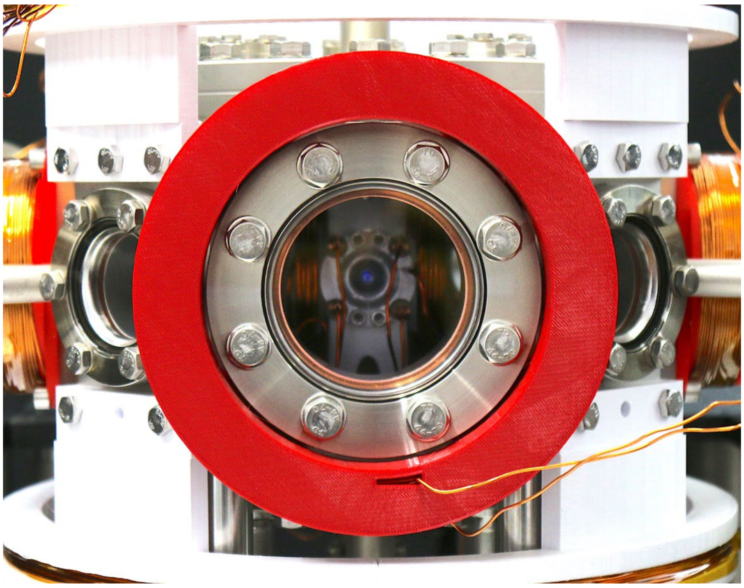
Quantum Clocks

Telling the time with atomic clock precision is essential, e.g. in communications systems (including the internet), navigation and financial transactions. Currently there is reliance on distributing time information via the satellite Global Positioning System (GPS), the Global Navigation Satellite System (GNSS), thus posing a critical failure risk, whether from natural phenomena or otherwise. **Quantum technology can produce atomic clocks practical for widespread and even portable use, providing increased resilience, reliability and independence**.

Atom Interferometers

Atom interferometers enable measurement of acceleration and rotation with extreme sensitivity and accuracy and can enable navigation without GNSS. GNSS is vulnerable to failure, e.g. by attack, so that navigation without it offers security and reliability in aerospace, marine and land-based applications.

Atom interferometers enable gravitational sensing with extreme sensitivity and accuracy. Development was initially directed at enabling navigation by strategic defence submarines without the need to receive radio signals and hence potentially reveal



M-Squared Laser's **'Maxwell' Neutral Atom Quantum Processor.** The image shows the vacuum chamber used to generate the core element of a quantum computing processor formed from an array of caesium atoms. The processor is based on neutral atoms that are excited into 'Rydberg states' and is suited both to digital computing and analogue simulations.

their position, by instead comparing local gravity with a world-map of gravitational force. There are also extensive civil applications. **Examples include geological measurements and geo-engineering, enabling mapping of subterranean rock structures, e.g. revealing natural resources, managing oil and gas reservoirs, and enabling carbon capture and storage. There are also applications in civil engineering, for example for the non-invasive and mapping of buried infrastructure, and surveying.**

Atom interferometers enable magnetic sensing: for defence (including submarine location), geoscience, and for battery research/development. An example includes investigating lithium-ion battery ageing. They could also be used for medical applications (e.g. brain imaging) and animal welfare and agriculture.

Imaging

A key advantage of quantum imaging is that it is possible (for example) to 'see' through turbid media and thus to image through fog, cloudy water, or even to build images through and within the human body. It is also feasible to produce images even if there is no direct line-of-sight to the target, and hence to 'see round corners'. Because the optical signals used are so faint, then from the position of the object being imaged it would be difficult to detect that imaging was taking place—i.e., it is also possible to 'see without being seen'.

Quantum imaging has immediate defence applications. Other applications include autonomous vehicles, e.g. for underwater applications (including offshore renewables, oil and gas), and more generally, such as for 'self-driving' cars and other vehicles (which already employ non-quantum optical radar, '*Lidar*').

Quantum-enabled spectroscopic techniques are already developed for environmental monitoring, e.g. remote detection of methane emissions from oil/gas operations or leakage from carbon capture and storage, and in supporting the development of hydrogen technologies. Demand for such instrumentation will inevitably increase in enabling progress towards Net Zero.

3. Scale and Maturity of each of the Principal Areas of Technology

3.1 World-wide Ecosystem

Since 2010, there has been major world-wide investment in quantum technologies, mostly by public funding, with over £1bn committed since then by each of the USA, China, India, France, Germany and the UK, and with further European Union programmes. In addition, there have been substantial investments by large and multinational companies and some commercial sales of products.

The ecosystem comprises:

- **research groups** (universities and research institutes);
- **large system-integrator commercial companies** (primarily computing and defence); and
- **small technology companies** participating in research projects and as lower-tier suppliers of components/subsystems for projects and products, primarily photonics (lasers and other devices) and cryogenics (to achieve low temperatures needed to achieve environmental isolation); and also electronics.

3.2 UK and the National Quantum Technologies Programme

In the UK, a major support to the ecosystem is provided by the UK National Quantum Technologies Programme, (NQTP) founded in 2014. Its strategic vision is to create a 'quantum enabled economy' and to stimulate market growth and security. The first phase provided £400M and involved over 150 partner companies. The second phase is in progress, with a commitment to fund a total of about £1bn. The initiative includes four Quantum Technology Hubs with Scottish companies and universities being active participants across all four. The activities are summarised in Appendix 3. Associated with the NQTP are the National Quantum Computing Centre and the Quantum Metrology Institute, also described in Appendix 3. A general overview of the UK quantum technologies landscape is provided in Appendix 4.

In January 2022, the UK Government announced the intention to publish a new UK Quantum Strategy later in the year (see page 38 of the 'Benefits of Brexit' report) and issued a Call for Evidence (closed in March). The proposed objectives for the strategy were: grow and maintain a sustainable quantum sector, deliver societal and economic benefits to the UK; grow and maintain the UK's capabilities and leading global position; and enable the wider economy and society to realise the opportunities and mitigate risks.

3.3 World Ecosystem for each Quantum Technology Application

Quantum Computing

Quantum computing is the largest single area of quantum technology activity. Examples of industry and government initiatives are summarised in Appendix 2. The primary technology platform remains unclear and a key decision to be made is whether preferred systems will operate at room temperature (e.g. based on trapped ions) or will be cryogenic. The most important practical problem to be tackled is environmental noise and its effect on the qubits. **The applications being pursued by the commercial companies are primarily in the finance, oil and gas, automotive, medical and healthcare, and aerospace sectors**.

Quantum Communications

The most developed quantum application in communications is for generating truly random numbers for public-key encryption, with commercial products available and early engagement by UK companies.

Quantum computing could render current public-key cryptography ineffective. The primary candidate to defend against that is Quantum Key Distribution (QKD). QKD is best developed for 'free space' communication, notably for satellites, with many demonstration projects world-wide. QKD for optical fibre systems, which dominate the world's communications infrastructure, are more challenging because of the attenuation of the optical signal as it propagates through the fibre. China has demonstrated the most advanced trial in fibres, establishing a QKD network between four cities. Toshiba Europe and BT have collaborated in a demonstration of a QKD-based secure network using Openreach infrastructure between the National Composites Centre and the Centre for Modelling and Simulation (see also the 'AQuaSec' project, Appendix 3). The European Quantum Communication Initiative intends to provide a full 27-country QKD network to be operational by 2027 and QKD features significantly in the current portfolio of UKRI projects.

Sensing and Imaging

Using quantum technologies in sensing and imaging has potentially fewer barriers to widespread application than computing and dedicated communications infrastructure is not required. In many situations, from the user's perspective, whilst the device performance would be revolutionary, in other respects the experience would be evolutionary, and thus markets would potentially be easier to develop. It is feasible for relatively small companies to become system integrators and suppliers-to-end-users for quantum sensing and imaging products, potentially providing agility in bringing the technology to market.

Quantum clocks and quantum atom interferometer sensors for gravity, acceleration, rotation and magnetic field are beginning to be commercially available. Quantum imaging systems (to see 'round corners' and through turbid media) and for spectroscopy (e.g. by '*Lidar*') are also commercially available.

4. Quantum Technology in Scotland

Scotland has relevant strengths in its university research groups and industry, perhaps most extensively in photonics, and has won 32% of the Innovate UK funding in the field (see Appendix 4). University groups have extensive engagement in the Quantum Hubs (in the NQTP) and other publicly funded initiatives including contributions to training. Fraunhofer UK collaborates extensively in quantum technologies projects involving industry/business partners, and has received Scottish Government financial support, for example from the Scottish Funding Council and Scottish Enterprise. Scottish companies and universities are active participants across all four of the UK Quantum Technology Hubs. The table below summarises Scottish involvement in the Quantum Technology Hubs and other quantum activities in Scottish universities and companies.

AMTE Power's cell-ageing facility (Thurso), which will employ quantum technological magnetometers (inset) developed in a UK Quantum Technologies Challenge project to optimise ageing protocols for their high-power batteries.

The UK Quantum Technologies Challenge was launched in 2018 with £173M of funding from the Industrial Strategy Challenge Fund. It is part of the NQTP with the primary objective of achieving commercial development. As of Summer 2021, there were 49 projects, 31 involving Scottish collaborators, with 91 businesses (18 in Scotland) and £25.6M funding in Scotland. Appendix 5 summarises the projects involving Scottish participants. Predominant applications are in sensing and atomic clocks. The principal area of technology in projects with Scottish participants is photonics, where there is exceptional strength in both universities and industry, particularly in the central belt. In its 2021 report, Photonics Scotland notes that over 50% of its members are active in quantum technologies.

UK National Quantum Technologies Programme, Quantum Hubs	Other academic/Industry Centres (examples)	Industry, from Appendix 5
Quantic: the imaging hub, led by Glasgow with Heriot-Watt and Strathclyde universities and other rest-of-UK universities **Sensors and Timing Hub:** led by Birmingham, with Glasgow, Strathclyde and others **Quantum Communications Hub:** led by the University of York, with Glasgow, Heriot-Watt, Strathclyde and others **Quantum Computing and Simulation Hub:** led by Oxford and with Edinburgh, Glasgow, Strathclyde and others.	University of Glasgow Centre for Quantum Technology, launched in September 2021. Centre for Designer Quantum Materials at the University of St Andrews. University of Strathclyde and M-squared lasers quantum technology research centre Fraunhofer UK also has extensive engagement in quantum technology projects	Alter Technology Caledonian Photonics Helia Photonics Kelvin Nanotechnology Leonardo UK M-Squared Lasers Photon Force Power Photonics Thales TopGAN Quantum Technologies UniKLasers

Scottish companies involved in quantum technology projects are dominated by the photonics sector, including for example Alter Technology, Caledonian Photonics, Helia Photonics, M-Squared Lasers, Photon Force, Power Photonics, TopGAN and UniKLasers, but also from the nanotechnology sector, including Kelvin Nanotechnology, many of whom have received financial support from Scottish Enterprise and from the Scottish Government more generally. M-Squared Lasers have the most extensive participation, for sensing applications (timing, gravity and magnetic field sensing), and for computing. They were the first relevant recipient of funding from the Scottish National Investment Bank. M-Squared Lasers has also established a quantum technology research centre in collaboration with the University of Strathclyde. The dominant area of application for Scottish photonics companies is in sensing, timing and imaging applications.

An example of a Scottish-based company whose primary interest is in the application of quantum technology rather than its manufacture is AMTE Power, whose interest is in magnetic field sensing for testing in lithium ion battery manufacture.

University collaborators in these projects include Edinburgh, Glasgow, Heriot-Watt and Strathclyde, and cover the full range of primary applications of sensing, timing, imaging, communications (QKD) and computing. Fraunhofer UK and Strathclyde are extensively represented in photonics and nanotechnology projects, including for sensing (gravity and rotation) and communications (QKD) and in developing quantum technologies for space applications.

The Glasgow Economic Leadership report in the Science and Innovation audit, mentioned in Appendix 3, expressed the vision for the Central Belt of the ‘creation and application of photonic and quantum enabled devices’ to create ‘an internationally recognised cluster of enabling technology growth companies’. It noted engineering and physics-based research excellence in measurement science, and opportunities for development of quantum technology sensing and imaging products.

5. Future Opportunities and Challenges

Quantum technologies provide a key opportunity for Scotland to implement its National Strategy for Economic Transformation, whilst contributing to the transition to Net Zero.

5.1 Opportunities

Scotland's National Strategy for Economic Transformation emphasises Scotland's role as an entrepreneurial nation with ambition to lead in chosen areas of research and development, and establishing new markets and industries whilst implementing existing strategic imperatives. Quantum technologies are potentially an important contributor to **Net Zero**, for example in:

- **Sensing/imaging for environmental monitoring:** remote gas sensing and imaging, e.g. methane emissions; improving performance of renewable energy generation, e.g. in wind and water turbines; and in energy storage (e.g. battery manufacture); and
- **Computing:** e.g. improving efficiency of **logistics** (transport, manufacturing etc) and in modelling for new materials (e.g. **battery technologies**) and chemical simulation.

Scottish universities and companies are recognised for photonics expertise, e.g. with UKRI project engagement well above the UK average. Opportunities continue for leveraging funding, from public sources and from industry. Industry is predominantly SMEs and components suppliers, dominated by photonics with some Scottish-based large company/system integrator involvement, mainly defence, with principal participants Thales and Leonardo.

Imaging, Sensing and Timing

The combination of research groups and industries in Scotland provides particular strengths in quantum technologies for imaging, sensing and timing, for which there are important emerging applications.

Quantum imaging enables new environmental monitoring techniques, important in the transition to **Net Zero**. Imaging through obscuration provides a new capability for the **energy industry**. In the **longer term**, quantum technology may provide opportunities for **medical imaging** including early-stage diagnosis and non-invasive examination. Imaging through obscuration is also important for autonomous vehicle control.

Quantum sensing techniques have particular advantages for geoscience and engineering in gravitational and magnetic field sensing, including for **civil engineering and for the mineral and hydrocarbon sectors**. Quantum magnetometers may also be developed for **medical and veterinary/ agricultural applications**.

Quantum sensing and timing avoid current critical dependence on GPS/GNSS for **internet communications** and navigation. Sensing and timing also have applications in **industrial testing and metrology**. There is a potentially significant opportunity for Scotland because of the planned establishment of a 'National Timing Centre' to be operated by the National Physical Laboratory (NPL), with an 'Innovation Node' at the University of Strathclyde.

Communications

A special opportunity potentially exists in secure **satellite communications** (for example in Cubesats, and see also 'A Strategy for Space in Scotland'), and in the manufacture of photonics components for Quantum Key Distribution (QKD).

Computing

Major economic benefits from quantum technologies will potentially derive from the manufacturing of quantum technology equipment, and from the competitive advantage that will be achieved by the application of quantum technologies in relevant market sectors. Scotland has industry and business sectors that could benefit significantly from quantum computing, e.g. **pharmaceutical and fintech**. More widely, quantum computing potentially offers new capabilities in **artificial intelligence and machine learning**, for which applications would be extensive.

Scotland has strength in quantum computing hardware (e.g. neutral atom technologies, superconducting qubits and nanofabrication) and software, and for example in the Quantum Computing Application Cluster (in the universities of Edinburgh, Glasgow and Strathclyde). There is significant engagement with the Quantum Computing Hubs. However, it would be useful to assess the extent of involvement of potential quantum computing users with the Scottish quantum technologies ecosystem for comparison with the evident strength of engagement e.g. between research groups and manufacturers of quantum technology components.

5.2 Challenges

Importance of leveraging research funding: there is substantial quantum technologies research funding, but funding for Scottish research generally comes from public sources (rather than industry) and from UK (rather than Scottish) agencies. For Scottish universities, relevant current research funding is primarily from UKRI.

Continuing to stimulate SME formation and their support: although Scotland has strengths in its SME sector relevant to quantum technologies (and especially in photonics), the rate of formation of such companies has fallen over the last few years and is now lower than that in some other parts of the UK.

Engaging larger companies: substantial growth will require involvement of large, often multinational companies, which are generally not based in Scotland, especially for system integrators in computing and from infrastructure providers in communications. Attracting companies with quantum technology ambitions would be desirable and their engagement, whether or not they are based in Scotland, will be essential for computing and communications applications.

Influencing international standards: as quantum technologies become established, there will be a requirement for international standards and for products and services to be consistent with them. **Scotland needs to ensure that it is involved in developing the standards** (perhaps through the NPL) and to ensure it is in a position to influence policy. For example, given the global nature of communications, the components and operating methodologies employed must be agreed internationally, and the standards established then favour or disfavour particular types of products. Similarly, standards for timing and fundamental measurements must always be agreed internationally, again influencing opportunities for market development.

Developing international relationships: post Brexit there is a risk of reduced participation by UK institutions in EU research programmes, which will impact existing partnerships and potentially inhibit new ones. Continued engagement will be needed with other major international quantum initiatives, e.g. in Canada, Germany and France.

Involving infrastructure companies: applying quantum technologies in communications requires close involvement of infrastructure companies, again not generally based in Scotland. Decisions on implementation will be made at the international level and require development of formal standards. Until then it will be difficult to precisely specify the opportunities for the manufacture of the components and subsystems that will be employed. Similar issues may also arise as quantum technologies are employed e.g. in the electricity and energy infrastructure and in transport systems.

Engaging potential users: Scotland has sectors that will potentially be major users of quantum technologies, e.g. **fintech**, and their level of engagement in the quantum technologies ecosystem should be assessed. End-user engagement is at an early stage, perhaps because further development is required before the full capabilities of quantum computing will be readily understood and realised. Some large corporations may benefit from their own quantum consultant/research divisions but smaller and local businesses will not, thus creating challenges.

Developing and retaining talent: Scotland has strength in the expertise of its quantum technologies research groups, including the education and training of PhD students; as the sector grows, it will be important to continue both to **grow the skills pipeline and to retain talent**. Growing the sector in Scotland will require training to provide the supply of suitably qualified individuals at all levels, perhaps especially of technicians. With the growing importance of the field world-wide there will be an increasing need to act to attract (both locally and internationally) and retain the workforce that will be required to realise the opportunities that the technology offers.

5.3 Risks

Risks to communications and data security: quantum computing challenges current techniques for encryption of data and communications. Without secure communications and data storage, industry, government and society generally would face intolerable threats including to basic infrastructure. Quantum technology (e.g. QKD) represents the only currently realistic solution. It is critical for Scotland to have security for its energy systems, transport, health data, computer networks and communications infrastructure. There will be **opportunities for Scottish SMEs, for example in manufacture of components to enable QKD**. However, engagement of major computing systems integrators and communications network providers will also be essential to address and mitigate the potential threats.

6. Conclusion and Recommendations

6.1 Conclusions

Quantum technology is recognised globally but its transformational potential is still in most respects nascent. Hence planning must continue to accommodate uncertainty and be agile. The Scottish community has UK and international recognition for its strengths, but action will be required to achieve the full economic and societal benefits that the technologies can bring, and to defend against the threats that it poses.

Implementation of the recommendations proposed by this report will support the following objectives:

- **Next 5 years:** enable Scotland to leverage increased research funding from the UK and internationally and build on the strengths of the developing ecosystem - Scottish technology ecosystem: review (reviewed by Mark Logan for the Scottish Government in 2020):
    - *universities* and the *education/training sector;*
    - *policymakers* (including for the development of international standards);
    - new and existing *SMEs and larger companies* for the manufacture of quantum technology products to provide a strong and resilient supply chain within Scotland;
    - *infrastructure providers;* and
    - *public and business future users* of quantum technologies.

  The existing Scottish ecosystem has significant strengths, notably in research groups and the photonics sector. Opportunities are emerging to develop it to increasingly include potential users of quantum technology and infrastructure providers. External engagement, leveraging funding and influencing policy, will continue to be important. Supporting an innovative environment to develop, attract and retain talent will also be required. Another key challenge is in the effective integration of the various components of the ecosystem.

- **5–10 years:** maximise economic benefit to Scotland from products primarily for sensing (including timing) and imaging; continue to strengthen the ecosystem with increasing emphasis on using quantum technologies for societal benefit; advanced preparation for secure communications and data and adoption of quantum computing e.g. for fintech. Maintaining a healthy research community as technologies develop will also continue to be critical.
- **>10 years:** quantum communications and computing begin to mature, with opportunity for economic contribution from associated industries and societal benefit from its applications with potential disruption to existing technologies. Benefits will be gained through manufacture of quantum technology-based components and equipment, but probably the major benefits will be derived from the applications of the new technologies, the new capabilities that they deliver and services that they provide.

6.2 Recommendations

1. Appoint an independent Chief Technology Adviser

It is recommended that the Scottish Government appoints a part-time (2-3 days per week), independent Chief Technology Adviser, to work with the existing team of CSAs, Chief Social Policy Adviser and Chief Economist.

Given the transformative nature of quantum (and potentially other technologies) and its associated opportunities and risks across multiple sectors, rapid access by government to expert advice could bring multiple benefits. Appointing an independent adviser with experience in both academia and industry to work with SG to give early notice of both opportunities and risks could significantly support the delivery of the current Programme for Government and the development of future strategies, such as those associated with combatting climate change. The remit should include a regular review of potential opportunities and risks for Scotland from the application of new and emerging technologies, and bringing these to the attention of relevant CSAs. the Scottish Government and relevant agencies.

2. Establish an independent, interdisciplinary, inter-sectoral advisory group

It is recommended that the Scottish Government catalyses the creation of a 'Quantum focus' group with a remit to ensure that all relevant sectors, industries and businesses are aware of the risks and opportunities associated with the adoption of emerging quantum technology, with regular review of priorities.

Quantum technologies offer opportunities for Scotland in leveraging research funding, economic benefit from manufacturing, and social and economic benefit in their application. However, whilst there is universal recognition of their transformative potential there is no consensus or certainty on key issues, e.g. which technology will be predominant for quantum computing, or the speed with which the threat to conventional cryptography will crystallise. Therefore, despite the urgency to act, plans must be dynamic and agile.

The expertise required to develop quantum technologies is quite different from the specialisms of the potential users and in many situations, the technology cannot be implemented without agreed standards and engagement of infrastructure providers, nationally and internationally. A forum where these issues can be discussed collectively by stakeholders could help to identify risks and opportunities and prioritise and accelerate mitigation of risks and delivery of benefits.

Scotland already has a few leadership groups and industry associations (e.g. Photonics Scotland) with relevant experience but not specific to quantum technologies. There are also policy bodies and enterprise agencies with an interest in quantum technologies (e.g. Scottish Enterprise, the Scottish Funding Council, Scottish Development International). Creating a group, focused initially on quantum technologies could help to ensure that there is a common understanding across these bodies of the possible levers and barriers to delivering the potential benefits highlighted in this report. A Chief Technology Adviser working with such a group would in turn ensure inter-sectoral awareness of risks and opportunities and instigation of relevant actions.

3. Ensure liaison with UK bodies

It is recommended that formal channels for liaison with UK bodies, including BEIS/UKRI, are strengthened or initiated and those involved are appropriately briefed, that involvement with relevant UK policy is reviewed, and actions implemented to ensure engagement to enable realisation of quantum technology opportunities.

Maintaining the vitality of the Scottish quantum technologies research base is fundamental to realising the opportunities, but is dependent on leveraging research funding, primarily from UKRI sources. UKRI policy is increasingly concentrated on challenge-led research (rather than investigator-led), and quantum technologies are certainly recognised as a priority challenge. However, challenge-led policies tend to favour larger universities, research institutes and research-focused industrial partners. Ensuring that relevant bodies are aware of the ability of Scottish organisations to work synergistically and to respond with agility is therefore essential. It is important to ensure that Scottish expertise is appropriately and sufficiently represented in relevant UK bodies including those for international standard-setting for quantum technologies.

4. Training and Skills

It is recommended that current provision of relevant education and training is reviewed and that organisations such as SFC, Skills Development Scotland and those responsible for the school curriculum are requested to provide appropriate support for the development of career opportunities in quantum technologies in Scotland.

There is currently significant investment in postgraduate (mostly research postgraduate) activities in the universities involved in the Quantum Hubs. However, implementation of the technologies, both in manufacturing components and systems, and their use, will require physical science and technology skills with investment in interdisciplinary education and training at an advanced level, and progressively in continuous professional development (CPD) activities and technician training, needing to involve Further as well as Higher Education providers. Learned societies also have relevant experience and their advice could usefully be sought.

5. Business Support

It is recommended that current early-stage business support is reviewed to consider its sufficiency to stimulate company formation and establishment to take advantage of quantum technology opportunities.

Current engagement is primarily from existing businesses, mainly in photonics. To take full advantage of intellectual property from current research, new companies will need early-stage support, with proof-of-concept funding, support for patenting etc, perhaps complementing Innovate UK support. Continuing support is also important as the sector develops internationally, to reduce risk of loss of talented individuals and to attract new talent to Scotland. As an example, financial and policy support to stimulate exploitation of the outcomes from Scottish involvement in the UK Quantum Technology Hubs would be appropriate.

Acknowledgments

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