7th November 2024

Hardware for Educating Quantum Engineers

Joint NL-UK opportunities for fostering further cooperation on key technologies

Purpose

Quantum Technologies is a key area of innovation that unlocks disruptive capabilities not achievable by other means. Developing these as well as knowing how to apply it effectively will become a key differentiator in the economy of the future in a manner similar to the benefits provided by Computers, Internet of Things and Artificial Intelligence. To achieve this, significant resources in terms of time, materials, financing and in particular talent are required. This whitepaper explores the opportunities for utilising the strengths of the United Kingdom and the Netherlands in the context of cold atom quantum technology for education and accelerating research.

Summary

The Netherlands and the United Kingdom are both leaders in the quantum technology space, with deep understanding and expertise across its many platforms and application areas. The importance of skilled labour to achieving national strategies as well as key technology development is a major key factor to both. Initiatives and opportunities to address this is at an early stage and market potential found is in the hundreds of millions for the single application of hardware for educating quantum engineers. A set of recommendations that focus on enabling immediate and direct collaboration between the UK and NL is made, in line with the recently signed memorandum of understanding, with outcomes that will benefit both economies, delivery of their quantum strategies and technology development.

Introduction

The quantum technology market is nascent, but it is already a multibillion-euro industry today and is expected to grow over 15-fold by 2040 (McKinsey, 2023). Parallels are often drawn with the semiconductor industry and the advent of the transistor. Accurate numbers predicting the exact market vary significantly from study to study due to the high uncertainty and potential offered by quantum technology. The impact of performing previously impossible calculations, 1000x improvements in sensing sensitivity and unbreakable communication are some of the tantalising prospects offered and currently being explored in the sector.

Estimates put the potential economic impact to industries such as automotive, chemical, finance and life sciences at a value of $1.3tn by 2035. According to the latest McKinsey report in quantum technology, the respective markets for computing, communications and sensing is expected to be $93bn, $7bn and $6bn by 2040.

Technical University Eindhoven

The technical university of Eindhoven is a leading university in the development of quantum secure communication, and quantum computing using cold atom technology.

Aquark Technologies (cont.)

The quantum efforts have strong industrial goals: The TU Eindhoven is looking for the connection with the high-tech industry to create manufacturable, commercial quantum systems. To achieve this an infrastructure route is followed, with a quantum computer being developed which is externally accessible, a testing network for quantum communication accessible by industry and extensive connections to enable high-tech custom component manufacturing in the region for industrial partners and to enable national and international collaborative design/engineering, which has grown into a national activity called the quantum manufacturing alliance.

The university works with the higher vocational institute Fontys to provide master level education in quantum at both levels and provides re-education and specialist training for engineers through a talent and learning centre.

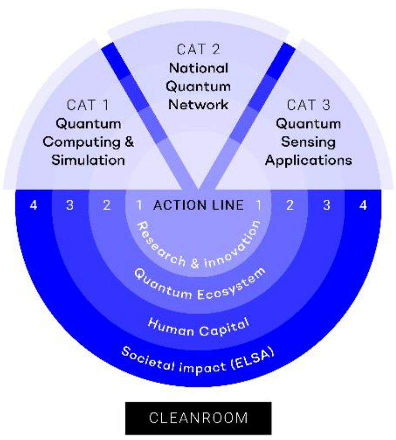
Aquark Technologies

Spun-out in 2021, Aquark Technologies looks to enable the future of quantum innovation by addressing the miniaturisation, robustness and scalability of cold matter-based technology. Based in Southampton, United Kingdom, the company has specialist knowledge in microfabrication and vacuum together with a unique and simplified method for trapping and cooling atoms. Dubbed a Supermolasses trap by the company, Aquark works to enable cold matter technology that can offer cutting edge precision for a device the size of a credit card.

Recognising the nascent, but disruptive nature that quantum technology offers, Aquark Technologies is embracing a holistic approach with a quantum system integration and ease access of hardware to support the growing ecosystem and missing talent pipeline.

Regions and Technology

The quantum landscape in the Netherlands



In the Netherlands, a significant portion of the funding for quantum developments is arranged through the Quantum Delta ecosystem, which is itself funded through the Dutch national growth fund mechanism for long-term economic development (Quantum Delta, 2024) (Quantum Delta, 2021). The Quantum Delta ecosystem contains 5 regions (**D**elft, **E**indhoven, **L**eiden, **T**wente and **A**msterdam - **DELTA**). Each region specializes in different technologies and industrial capabilities. A total of 615 million € has been dedicated to research, development and education of quantum systems as well as for the generation of collaborations with business, spin-off, collaboration and more through 3 catalyst programs funding quantum system development:

- CAT1: Quantum Computing,
- CAT2: Quantum Networking,
- CAT3: Quantum communication

and 4 action lines:

- AL1 (fundamental) research,

- AL2 national ecosystem development,
- AL3 workforce and education,
- AL4 ethics and society.

All activities in the quantum delta program are designed to be non-competitive and to support the activities in other CAT's, action lines and regions where possible. Each catalyst and action line has its own roadmap with dedicated goals and objectives.

Regionally the differences are large: Delft focuses on cryogenic systems with superconducting and spin qubits, with a startup base largely focused on quantum components such as chips, electronics, quantum links with several full stack system suppliers. In Eindhoven the focus is full stack systems, with efforts on commercialization focusing on cold atoms and quantum secure equipment/software as well as supporting industrialization and mass production through the local high-tech manufacturing and integrated photonics ecosystems. Leiden has a focus on theory and has several interesting quantum sensing startups. In Twente the focus lies on photonic quantum computing with a world-leading startup. In Amsterdam a more software and algorithm focus has generated a growing series of startups. Each region is therefore significantly different than the others, utilizing different technologies and strategies for the development and eventual commercialization of quantum technologies.

Significant support is offered from the Dutch ecosystem through education to engineering new quantum technologies: The Quantum Delta action lines support talent and learning centers in each hub across the Netherlands (in AL3), which utilize hands-on experimental education to educate the next generation of quantum researchers and to educate existing engineers that find themselves in a quantum context, working for a quantum company or their supply chain. This is increasingly relevant due to a new activity (in AL2): The quantum manufacturing alliance aims to connect the High-Tech Systems, Micro, Nano and photonic ecosystems to develop equipment and components for the quantum industry. Additional educational activity is needed to educate these companies to the subtleties of quantum technology.

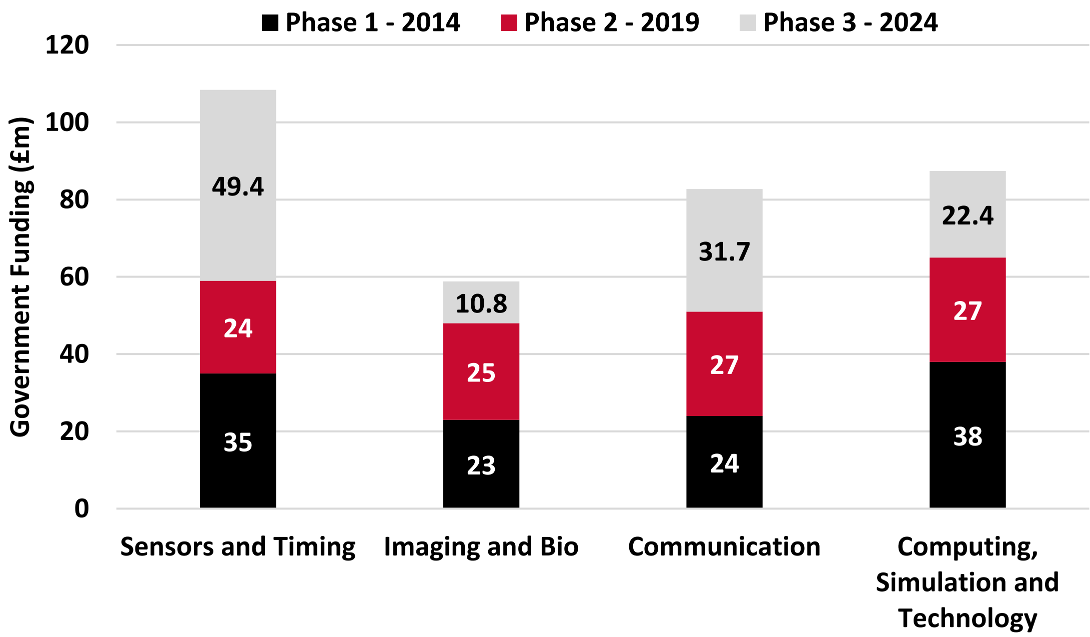
The quantum landscape in the United Kingdom

In 2023 the UK announced its updated National Quantum Strategy, that looks to build on the over £1bn investment it has made into Quantum Technology since 2014 (Department for Science, Innovation & Technology, 2023). Highlighted as an area of key and strategic importance to the UK economy, Quantum Technologies has a great disruptive potential for the economy of the future. It is strongly recognised as an enabler for vast economic opportunities, jobs creation and bringing key differentiating factors into the industries of the future. Development of new hardware and technology is widely recognised as difficult and long-term and hence the UK committed a further £2.5bn to support a confluence of Industry, Academia and Government to create a sustainable and growing quantum ecosystem. At this date of this publication, only a fraction (approximately a fifth) has been deployed or committed to date. The strategy outlines 4 key goals that builds on the world leading expertise and reputation in science and commerce in the areas of; technology leadership, high tech supply chain, quantum utilisation and regulatory framework.

Table 1, Targets for the United Kingdom National Quantum Strategy to reach in priority.

Priority Areas	2033 Target
Technology Leadership	• Maintain top 3 position in quality and impact of quantum science, • Train +1000 postgraduate researchers • Bilateral agreements with 5 further leading quantum nations
High Tech Supply Chain	• Obtain a 15% share of global private equity in quantum technology companies • Obtain a 15% of global quantum technology market
Quantum Utilisation	• All key sector business be quantum aware • 75% of key businesses have taken steps to implement quantum technology
Regulatory Framework	• Be a global leader in establishing global standards for quantum technology

These targets are confidently achievable by the UK as it was one of the first countries in the world to implement a dedicated and impactful national quantum technology programme. As a result of this early action more than 10 years ago, the UK has a thriving ecosystem that today already has the second largest number of quantum companies in the world, a complete coverage of expertise in quantum technology areas, world class testing capabilities and key user sector strength only second the United States. To date, the government via Innovate UK has funded £227m over 189 projects involving 182 companies for commercialising quantum challenges alone and these companies have raised £610m in private investments (Innovate UK, 2024). This industry has also been supported by a series of national quantum technology hubs to the tune of £343m since 2014 (table of funding in appendix) that cover the areas of:



With phase 2 of the existing quantum technology hubs having come to a close in 2024, a new portfolio of 5 hubs and centres have taken with 5 years £106m of funded programs and £54m from industrial contributions. The 5 hubs selected now are:

- The UK Quantum Biomedical Sensing Research Hub (Q-BIOMED)
  Led by: Professor Rachel McKendry, UCL and Professor Mete Atatüre, University of Cambridge

- UK Quantum Technology Hub in Sensing, Imaging and Timing (QuSIT)
  Led by: Professor Michael Holynski, University of Birmingham

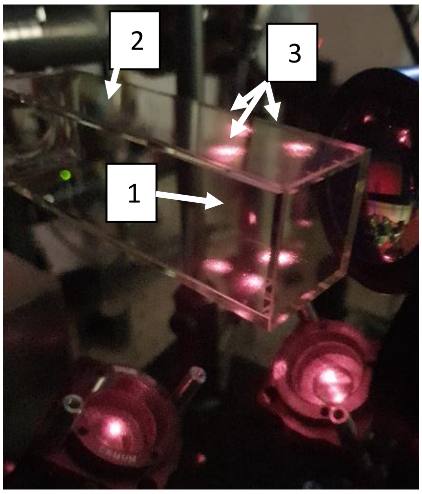
- Integrated Quantum Networks (IQN) Quantum Technology Research Hub
  Led by: Professor Gerald Buller, Heriot-Watt University

- QCI3: Hub for Quantum Computing via Integrated and Interconnected Implementations
  Led by: Professor Dominic O’Brien, University of Oxford

- The UK Hub for Quantum Enabled Position, Navigation and Timing (QEPNT)
  Led by: Professor Douglas Paul, University of Glasgow

These hubs will be applications-focussed quantum technology research as the developments in the UK has now considered to have matured sufficient to leave the laboratory. The UK is in a fortunate position with a dynamic ecosystem with companies operating at all levels from start-up to established primes as well as exploring all current areas of quantum, from single photon to ion based to cold atoms. A full consideration of this would be beyond the scope of the whitepaper and thus, the following will concentrate of the area of cold atoms based quantum technology.

Cold atom technology



The technology advocated by the Technical University of Eindhoven and Aquark Technologies has some distinct advantages over other methods for creating quantum systems. It works by trapping atoms (1) in a vacuum (2) by using light (3) and typically other electromagnetic fields. Traditionally this is done by capturing a cloud of atoms using an MOT (magneto-optical trap, frequency stabilised lasers in a quadruple magnetic field). Aquark has a proprietary trap method (pictured left), which doesn't require such a magnetic field, referred to as a Supermolasses trap and is therefore simpler, smaller and more durable. In the quantum technology fields, cold atoms occupy a unique position in that they are able to address all of the 3 pillars of development, computing, sensing and communication.

Quantum computers with cold atoms can be created from laser cooled atom clouds by using optical tweezers to capture individual atoms, which can then be used for quantum computing by manipulating them with several other lasers.

Atoms are all identical, which means that there are no manufacturing challenges in creating perfectly identical qubits. This decreases manufacturing development costs as well as allowing the build of useful quantum systems with (customized) commercially available components.

This method has tremendous advantages in scaling as it does not required the immediate extremely high investment costs that wafer manufacturing lines require. Developing integrated circuits is also very much an iterative process, that must be largely repeated when new materials are used. This slows down development and keeps the yield of effective qubits low as has been seen: Some superconducting qubit chips have hundreds of qubits, but only a small fraction are usable for quantum computing. Miniaturization and wafer manufacturing for scaling will still accelerate cold atom quantum computers in mid to long term through integrated photonics. This will enable scalable manufacturing, but after quantum advantage and effective computing use cases will already have been established. Lastly, cold atoms have the advantage of not needing cryogenic cooling. An effective quantum sensor or quantum computer based on cold atoms can cost as little as just the cryogenic system around other quantum technologies. Companies that work on this globally are: Atom Computing (US), Atom Quantum Labs(US), Infleqtion (previously Coldquanta) (US), Pasqal (FR), PlanQC (DE) and QUEra (US).

As quantum computing grows in power, it on one hands opens new opportunities in areas such as quantum memories and repeaters, while on the other it also creates concerns over potential threats such as the ability of existing encryption methods to withstand decryption by a quantum computer.

Quantum Communication looks to address the exchange of information using quantum methods. This can be "quantum internet", the exchange of qubits between quantum computers or “Quantum Key Distribution (QKD) the exchange of cryptography keys over a quantum channel. QKD encoded information fundamentally cannot be intercepted without notice, enabling security in a world where quantum computers might endanger information security. It is typically used in combination with post-quantum encryption algorithms. To enable the exchange of qubits over longer distances, a so-called quantum repeater is needed. A quantum repeater consists of quantum memory that stores the qubit and a transceiver. The repeater can then forward the qubit from node to node over fibre optic networks until it reaches the quantum computer on the other side for shared calculation.

Some types of QKD, but not all, use qubit exchange, which has the advantage that with a quantum repeater no special requirements are needed on the node. It does not see the data, so an attack on the node will not endanger information security.

It is, however, the view of the authors that greater technical challenges exist for qubit exchange than only those solved by a cold matter memory.

These issues include transmission distance limitations for qubit exchange since the data is encoded in single photons, and integration questions into traditional telecommunication. Typical transceivers have more or less the size and shape of a USB stick, and miniaturization to that point is far away for qubit exchange. The authors view this topic should therefore be revisited once greater progress has been made (at least 2-5 years in the future).

This is a topic for some commercial companies despite this challenges: WeLinkQ(FR) is a company utilizing cold atoms for this application. Hot vapour technology, which utilizes very similar principles, and requires a similar skillset to develop, is used by a variety of companies to develop quantum repeaters such as Qunnect Inc(US).

Quantum Sensors represent the most readily available and established market compared to computing and networking. Contesting with well-established technologies that have been pushing the boundaries of performance for decades, quantum looks to start where classical approaches peak performance. The two greatest challenges for quantum sensing is by far the environment in which sensing is required and the double edge sword that is high sensitivity. Often located outside the confines of controlled environments, sensors are required to work where data needs to be gathered or used and this mean instrumentation that keeps precision to a fraction of an atomic transition must be robust enough to allow the distinction between signals of interest and background noise. These challenges represent more engineering problems than limitations of science and will be solved by the application of robust development. The sensors produced are expected to provide new capabilities as well as direct improvements in:

- **Time keeping:** Greater resilience in time infrastructure such as GNSS, telecoms, financial transactions, electrical grids and navigation.
- **Inertial Guidance:** Reduced noise thereby limiting drift when navigating underground or in GNSS denied environments, using accelerometers, gyroscopes and clocks for dead-reckoning navigation.
- **Magnetometry:** More accurate data and mapping for brain imaging, material characterisation, process optimisation and multi-vector navigation.
- **Gravitometry:** Civil, geological and environmental infrastructures can be probed to get better insight into their condition. Monitoring of carbon captured, resource exploration, water and coastal monitoring.

It is worth noting that in quantum sensor, cold atoms are not the only platform available with devices based on trapped ions, trapped lattices, quantum dots, nitrogen vacancies or single photons also competing. Each are worthy of consideration, offering a different set of opportunities and challenges, but relative to cold matter, it is the universality of cold matter application and consistent high performance across them that are the key differentiating features. Companies that work on cold atom sensing and timing is: AOSense (US), Aquark Technologies (UK), Delta G (UK), Exail (FR), Infleqtion/Coldquanta (US), M Squared (UK), Spectra Dynamics (US), Teledyne (US) and Vector Atomics (US).

Accessibility to quantum technology has improved considerably in recent years, but it remains a challenge for all its use cases as hardware is often large, heavy, expensive and typically custom made. This slows progress and the development of impactful uses as not only is usage limited to experts in the technology, but also limits the development of a workforce surrounding it due to limited exposure. To address this, technology needs to be developed with a primary focus on the cost and ease of use instead of pushing for excess performance. By building robust hardware that researchers, engineers and students can rely upon, not only will quantum utilisation increase, but the gradual up-skilling of the workforce towards a quantum-enabled economy begin to be prepared.

Both the Netherlands and United Kingdom recognises the importance of quantum technology for the economy and the need for increasing the talent pipeline within their national strategies. The lack of talent in quantum is although, no means unique as the Science, Technology, Engineering and Mathematics sector has been lacking for several years with the UK alone recognising a shortage of 173,000 STEM majors estimated to cost the economy £1.5bn a year (IET, 2022), while in the Netherlands, 80% of technical organizations are expecting shortages in personnel (Engineers Online, 1999), with over 100.000 open vacancies in technology and ICT in 2023 leading to governmental action plans to increase education (Rijksoverheid, 2023). This means that a threefold problem exists with addressing the quantum talent pipeline:

- Challenges around approaching quantum without a STEM degree due to its high level of technical complexity
- high levels of competition within STEM degree holders from competing non quantum industries.
- Nascency of technology with limited time for knowledge to make it to the non-quantum use and its addressing affordability

Educational Initiatives and Workforce Development

The activities in the Netherlands and United Kingdom are largely centred around the national program for quantum technologies. One of the core components of the Dutch national program is the 3rd action line, which is dedicated to human capital. This action results in the activities on quantum education in the Netherlands being coordinated to synergise the different regions and connect with a variety of education levels and outreach at all age groups, from young children through students and even re-educating existing engineers.

In the United Kingdom, the training of human capital is addressed by a mixture of the Quantum Hubs (+£100m), industry partners like QURECA and Centres of Doctoral Training in Quantum (£14m) spread out all across the UK with some areas of overlap. This will primarily focus PhD level courses and research although dedicated quantum masters are also being setup. Little to no direct training occurs at undergraduate level or below.

In the Netherlands, efforts are to set up quantum dedicated masters in a coordinate way across universities with each having a different focus. Quantum information science and technology master are in the University of Delft and Leiden, a scientific master in quantum computing at Amsterdam and the University of Eindhoven has a master certificate program in quantum technology as an engineering discipline.

Besides the education of new masters/PhD level scientists in quantum technologies, a viable industry requires that other engineering is present and has the knowledge to work with quantum systems. Re-educating engineers in fields such as electronics, mechanics and software is therefore a key activity within the Dutch Quantum Delta program. This is implemented through a series of Training and Learning Centres (TLC's). The TLC's offer courses, which are partially implemented through challenge-based learning labs (CBL's) with a lot of hands-on quantum training. CBL's are also being implemented for Master and Bachelor quantum education.

From the University of Eindhoven, a lot of exchange with other universities is also happening, exchanging PhD's and master students.

For each of these educational activities it's important that the student can use educational grade equipment. A quantum lab setup is easily several hundred thousand if not millions of Euro/Pounds worth in value and requires a lot of finesse to use. The educational activities will therefore acquire their own equipment, with important requirements on cost, very clear and easy to access limited capabilities and a reasonable lifetime even when (mis)handled by many users.

Opportunities

Worldwide billions of investment is happening in quantum technologies sector with activity in both industry and academic environments. With quantum equipment being generally expensive, a very significant amount of investment is made to enable quantum capabilities and upcoming commercial systems.

In 2023 private investment in companies has decreased somewhat compared to the previous year, but remains high and in particular in education growth has continued (Leprince-Ringuet, 2024). With existing investment being expended and commercial sales prepared for the next few years, moving to development of quantum systems that can be produced at scale and a very significant and robust worldwide quantum research community, the demand for capable quantum professionals and engineers will only increase for the foreseeable future.

This requires investments in education from national programs such as the UK and Dutch ones described here. Other countries in the EU also have some sort of stimulus programs, with Denmark (1Bn DKK/134 m€, (Denmark, 2023)), France (1.8Bn€, (Invest in France, 2023)), Germany (2.65Bn€, (The Quantum Insider, 2023) and Italy (1.6Bn€ for 7 key technologies including quantum, (Rossi, 2021)). The EU itself also has programs on quantum, this includes the EuroQCI secure quantum networking infrastructure and its transnational Central European Facility counterpart, as well as the quantum flagship program (1 Bn€, (Quantum Flagship, 2018)). Also needed to be mentioned here is the EuRyQa project (EuRyQa, 2022), which is a 5m€ European collaboration under horizon, which offers collaboration on cold atom technology for quantum computing.

These programs require a large group of highly educated people, so the opportunity to provide educational equipment for this industry is therefore already large and will expand with more commercialization. Arguably due to the development status of most current quantum technologies and consumer acceptance at time of writing the educational market is the most mature market currently in existence for quantum equipment[1].

We are identifying several markets in this field for quantum systems:

- Undergraduate and graduate studies
- Hardware for vocational training
- Quantum re-education and upskilling of existing engineers

These inexpensive systems can also have third party uses, such as for startups to perform experiments or demonstrate proof of principles. Ruggedized and simplified systems can also be adapted into components for higher end commercial systems.

The requirements on systems such as these are relatively simple:

- They need to demonstrate a specific quantum feature and be flexible enough to perform experiments around this principle. A few examples:
  - Noisy 1 or 2 qubit quantum computers, spin-qubit systems are currently available at this level for this use case.
  - Breadboard quantum key distribution or quantum internet setups

[1] An exception can be made for atomic clocks and certain quantum sensors, which have been in commercial sales for some time.

- The topical miniaturized cold atom trapping and control system
- They are required to be small such that they can be stored away in a cupboard when not in use, to enable efficient use of scarce educational space and protect any sensitive components.
- They need to be inexpensive, at most in the several 10's of thousands of Euro/GBP.
- They need to be very robust as they need to able to withstand a large group of students, each of which has the potential to misuse the technology due to a lack of knowledge.

According to the latest McKinsey monitoring report on Quantum there is approximately 350,000 graduates in quantum technology and relevant fields per year (McKinsey, 2023). Training of the ones working with hardware is likely to be a fraction of this and take place in established physics departments around the world. Using the 1370 counted by The Times Higher Education as a baseline together with the assumption that only 1 in 3 departments will work directly with cold atoms and graduate 50, this leaves 22,600 people a year with needing access to such teaching equipment (Times Higher Education, 2024). Using the median salary of these quantum educated professionals at $80,000 a year (SPIE, 2023), this represents a societal economic value of $1.8bn. This leaves a market for this equipment in the hundreds of millions.

As a target of strategic importance to both the United Kingdom and Netherlands, the development of hardware for educating quantum engineers represents a prime opportunity for UK/NL collaboration. Offering a global market economic opportunity and addressing key priorities, such a collaboration would become a cornerstone of the growing global quantum ecosystem and leverages the best of world class expertise and reputation of both nations.

To enable such opportunities the UK and NL should consider supporting collaborative initiatives between the nations in a manner similar to those recently pursued with Canada and German as well as those between NL and DE/FR:

- Canada UK Commercialising Quantum Technology Programme: CR&D (Innovate Uk, 2022)
- UK - Germany Bilateral: Collaborative R&D Round 3 (Innovate UK, 2024)
- Trilateral program between NL and DE/FR for quantum technology (Quantum Delta, 2022)

Future Roadmap and Milestones

The memorandum of understanding signed between the UK and the Netherlands signed on the 7th November 2023 expressly anticipates and supports the creation of funded collaborations. Partaking in the trillion euro/pound economy that quantum technology is expected to become, drawing parallels with the semiconductor industry, will require not only bold initiatives, but also the traditional factors of production, land, labour and capital. The high cost in capital and specialised labour that quantum requires mean we are likely to see a coalescing of activity into single locations. With many places with sufficient land to carry out quantum activity and ease of moving capital in the modern world, the establishment of a skilled workforce will likely be the greatest factor in determining the epicentre of the growing quantum ecosystem.

The United Kingdom and Netherlands occupy a unique position in this regard with excellent access to the world's talent pool as well as world renown teaching, commerce and research facilities. Netherlands and in particular Eindhoven is host to one of the world's biggest technology companies, ASML and with that has established a strong local ecosystem for carrying out deep tech at scale that quantum companies looking to scale should look to utilise. The authors therefore strongly recommend that bilateral funding and knowledge exchange opportunities for Dutch and UK companies, academia and industry be created to enable more close collaboration together and leveraging of individual strength areas. These should be implement both at the level of the research funding bodies, but also at the level of the Dutch catalyst program and UK Quantum Hubs with focus to achieve specific goals relevant to both national programs. For example, from the CAT3 Sensing Catalyst Program paired to the Quantum Sensing Hub, aiming to extend capabilities developed in both. This would benefit both ecosystems at large as the best of both can be brought forward, activity coordinated and resources best allocated to enable exploitation sooner in rapidly developing globally competitive market.

For the development of hardware for educating quantum engineers, the authors propose a 3 stage process for closer UK/NL collaboration:

- **Stage 1 – Foundational capabilities, gaps analysis and solution building**. This would be a 12 month period of joint exploration of each sides capabilities, needs and demonstrations to gather feedback and validate strategies. TRL target 1-3.
- **Stage 2 – Creating disruptive capabilities and initial implementation**. This would be a follow-up period of 12-18 months dedicated to serious efforts in maturing concepts and ironing any technical creases so seamless adoption of the technology can be obtained. TRL target 4-7
- **Stage 3 – Rollout, growing consortiums and applications**. For projects with clear value add, economic sustainability and established growing demand, the early adopters may still struggle with accessing the technology due to upfront costs. TRL target 8-9.

Each stage would see a shift in funding support from solution provider to end users with stage 1 primarily focusing on the solution provider and stage 3 focusing on the end users.

In deploying such a program, hardware for educating quantum engineers could be developed with a shared risk and return between SMEs, Academia and Countries. Developing these inceptional capabilities, skilled talent and supply chain to support on global stage will be pivotal in bringing the epicentre of quantum development closer to both ecosystems and fulfilling the national quantum strategies.

Conclusion

The United Kingdom and Netherlands are both leading in the field of quantum technology with ambitious national strategies for quantum technology and a mutually beneficial opportunity exists for joint-collaboration and co-development. Deploying programs similar to those established by the UK and NL with Germany, France and Canada would create a foundation for immediate direct engagement with route to economic benefits in the hundreds of million euros in size. Development of projects such as hardware for educating quantum engineers will leverage UK expertise in building compact cold matter technology with NL expertise in challenged base learning, teaching and quantum education. Such a project would not be unique as many other similar opportunities could be established through the interface between the Dutch catalyst and UK Quantum Hub programs giving way to even greater economic development and delivery of national strategies.

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Acknowledgements

This whitepaper was written with the support of the Netherlands Innovation Network UK, based at the Embassy of the Netherlands in London and is part of the Dutch Ministry of Economic Affairs and the Netherlands Enterprise Agency (RVO).

The author's would like to extend their thanks to and acknowledgement of their colleagues for their support in preparing, drafting and reviewing this whitepaper.

Appendix

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UK Quantum Hub Funding

The original 4 hubs have now concluded after 10 years and a new set of 5 hubs have been established in 2024. While not explicitly referred to as phase 3, the author's have adopted this terminology as the hubs builds on the previous learning and in some cases are superseeding previous hubs at the same institution.

Hub	Lead	Funding
UK National Quantum Technology Hub in Sensing (Imaging) and Timing	University of Birmingham	Total £91.5m Phase 1 £35,513,855 (EPSRC, 2014) Phase 2 £28,537,607 (EPSRC, 2019) Phase 3 27.5m (2024)
The UK Quantum Technology Hub in Quantum Imaging superseded by The UK Hub for Quantum Enabled Position, Navigation and Timing (QEPNT)	University of Glasgow	Total £69.9m Phase 1 £23,061,154 (EPSRC, 2014) Phase 2 £24,961,172 (EPSRC, 2019) Phase 3 £21.9m (2024)
The EPSRC Quantum Communications Hub	University of York	Total £51.4m Phase 1 £24,093,966 (EPSRC, 2014) Phase 2 £27,348,141 (EPSRC, 2019)
EPSRC Hub in Quantum Computing and Simulation Superseded by QCI3: Hub for Quantum Computing via Integrated and Interconnected Implementations	University of Oxford	Total £87.8m Phase 1 £38,029,961 (EPSRC, 2014) Phase 2 £27,338,781 (EPSRC, 2019) Phase 3 £22.4m (2024)
The UK Quantum Biomedical Sensing Research Hub (Q-BIOMED)	University of Cambridge	Total £10.8m Phase 3 £10.8m (2024)
Integrated Quantum Networks (IQN) Quantum Technology Research Hub	Heriott-Watt University	Total £31.7m Phase 3 £31.7m (2024)

Comparison of cold atoms to other technologies

Note: Information indicated here is illustrative. The take-away here is that each of these technology types has specific advantages, disadvantages and uses. We have specific expertise in cold atoms so information while focus on being objective is at risk of bias and knowledge on other qubits may be somewhat out of date.
The authors express no opinion on one qubit being better than any other, other than on our own type, cold atoms, which is obviously the best.

For more specific background information we recommend the excellent book of Olivier Ezratty, Understanding Quantum Technologies. The current version is the 7th edition and is available for free from https://www.oezratty.net/.

The core technology for most quantum technology is the qubit. Qubits are a 2 state system, where it is possible to create a superposition between these two states. Beyond this they need to be able to be maintained for a sufficient time, interacted between and read out. Fundamentally any 2 state system that complies with this can be used to create a quantum computer, which has led to a wide range of candidates.

For quantum sensing and networking other requirements are needed, such as interaction with light for communication and sensitivity to specific factors for sensing.

Roughly speaking qubits fall under three separate types: Integrated qubits, Photonic qubits and matter qubits, which includes trapped ions and neutral atoms. Below we will compare our neutral atom qubits with the other qubits.

Integrated qubits

The currently most common type of qubits are the integrated qubits (creating a qubit through a structure on a chip, just like a traditional chip). By far the most well-known at the moment is the superconducting qubit (Included in IBM quantum computers for example), with spin-qubits, spin-SiGe qubits and topological qubits with many variants also under development.

The famous pictures of a quantum computer looking like a chandelier comes from this type of qubit: This is the wiring coming in from the top, into the restricted space of a cryostat that maintains the low temperatures needed.

These technologies have obvious advantages in scalability for computing. Creating a wafer, then producing devices on it for computation is a scaling methodology that we have developed over the last 50 years. Issues in fidelity and manufacturing problems still have to be overcome. Limitations in device density per chip due to heat generation in very cold cryogenic requirements is another challenge.

Compared to neutral atom qubits, the core differences are in the interfaces. Since there is no material interface to the neutral atom qubits (they are held in space by lasers) there is less interaction damaging the quantum state and the temperature can be further reduced with laser cooling (mK to µK) which helps stabilize the quantum state further and ensures no cryostat is needed. Neutral atoms can be produced in unlimited numbers (if enough light beams are created) and are perfect qubits: each atom behaves exactly as its neighbour. While scaling limitations do exist (see below), much larger quantum computers are available currently with thousands of qubits per system versus several hundred integrated qubits per system.

For communication there is also an advantage to the neutral atom platform, and these are being developed as quantum memory (especially variations using atom cloud methods). The interface being optical makes interfacing with a fibre network significantly simpler as the quantum signal does not need to be converted from electronic to light. Significant work has however been done to convert quantum signals from integrated qubit systems like superconducting to allow for scaling.

In the sensing field, the technologies have different applications on what they measure. The lack of required cryogenics and ability to withstand vibration makes miniaturized sensing systems for neutral atoms very applicable in the field with commercial applications being developed for markets such as aerospace applications. Superconducting quantum sensors are also well established and used in scientific applications but remain high cost.

Photonics

Using the properties of light itself to create a qubit is a logical step. Light is by its nature polarized, which has multiple states, can be relatively easily put in a superposition and light interferes with other light, making interaction possible. Light is however also fleeting, since it is always moving at the speed of light. Integrated photonics methods to create quantum computers are relatively mature and are used for example in the LIGO detector that detected gravitational waves for the first time.

Photonic techniques are used in many of the other quantum methodologies to allow for scaling. This includes the neutral atoms, trapped ion and diamond NV-centers (see below) as well as to enable quantum communication between all other types of quantum computers.

Integrated photonic quantum systems are also the default technology to develop secure quantum communications systems (quantum key distribution).

Compared to neutral atom systems, the clear advantage is in the ability to create chips, which has similar advantages in leveraging production methods compared to the integrated qubits above. However this is somewhat limited due to macroscopic connections required for input output through fiber. This limits the amount of qubits that can be integrated on a single chip and so requires the use of many chips.

Unlike neutral atom quantum computers, it is not possible to store photons so tricks are required, such as backpropagating the quantum state through the system (keeping it in motion) and storing qubits for a short amount of time in very long optical fibers.

Atom based qubits

The third type of qubit are those that are using the properties of atoms themselves to create the qubit states.

the first two are the cold atom based quantum systems that this whitepaper is based on and trapped ions. These atoms/ions are isolated in a vacuum, kept in place using magnetic and optical methods and controlled using lasers or microwaves.

One other important type of qubit to be named is the color center qubit, where one atom in diamond is replaced (traditionally with a nitrogen atom called nitrogen vacancy or NV-center), but alternatives are now becoming popular).

This creates a qubit that has some similarities to the integrated qubits (as it's a manufactured diamond chip) but it mostly fits in this block, as the qubit is based around a single atom and is commonly controlled using light.

NVcenters have an obvious advantage for quantum communication. They are qubits in a wafer that allow for optical in and output, with much lower requirements for cryogenics compared to integrated qubits. For computing they are somewhat less developed compared to trapped ions and neutral atoms, with limitations in diamond wafer manufacturing and production, a lower fidelity and, and the development of integrated photonics interfaces another requirement to enable true scaling.

Of these three, trapped ions currently have the record for highest fidelity, but the gap is getting smaller. Neutral atoms are the most scaled quantum computing systems that currently exist, with over 1000 qubits per system now standard and increasing fast. Limitations in scaling occur in the amount of laser power required and splitting and individually controlling light beams to each atom, both of which have a potential solution in integrated photonics. Unique to neutral atoms is the ability to move atoms around, which allows any atom to interface with any other atom in the system. This reduces the amount of connections needed to be created but at the cost of speed, as this operation takes time.

In terms of sensors all three technologies have significant applications. Each technology has the capability of being miniaturized, no (or limited) requirements on cryogenics and many capabilities such as magnetometry, chemical sensing and RF analysis are distributed between the technologies, allowing each to operate in their own niche, while competing in others. Cold atoms in this space are unique due to their ability to be fundamental measurement standards and therefore self-calibrating. This enable measurements of not only the ultra precise level, but also in a large variety of metrics such as magnetic and electric fields as well as inertial forces.