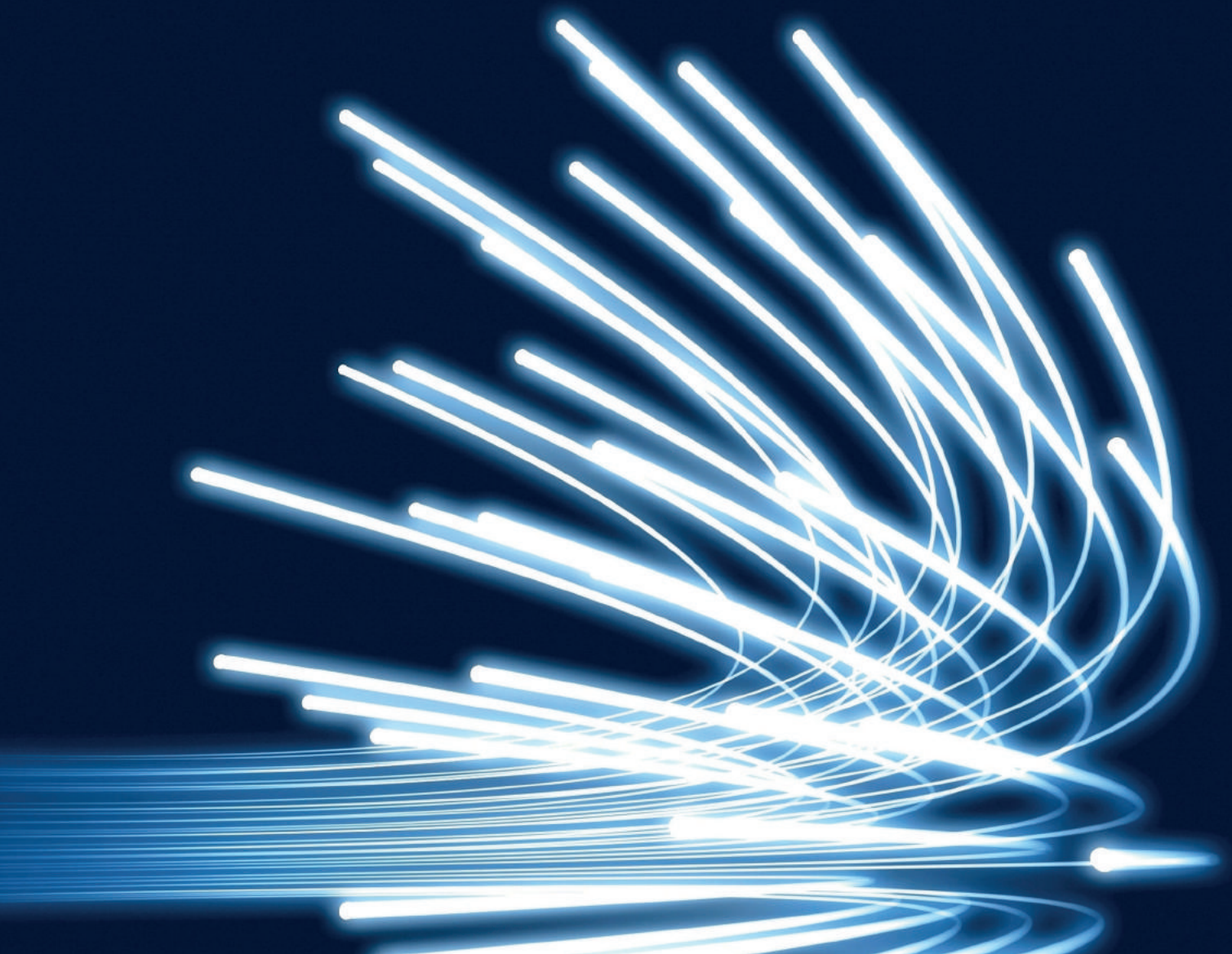


# THE UK MARKET FOR **QUANTUM ENABLING PHOTON SOURCES** 2018-2022

GOOCH & HOUSEGO, MILNER STRATEGIC MARKETING & UNIVERSITY OF BRISTOL  
**MARCH 2018**



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# FOREWORD

Quantum technology has the potential to change every industry in the UK. The applications of photon sources are in game-changing areas like quantum key distribution, precision timing and much more. Over the next 5 years, issues such as communications security, telecoms network synchronisation and speed of financial trading will become increasingly important for the UK. Quantum technologies could provide the solution to these issues.

The market described in this report is for quantum-enabling photon sources (either the sub-systems or closed system boxes) for the UK market only. The market size for these sources in 2022 is £63.6m but this is a fraction of the wider equipment market that it enables. This market includes detectors, cryogenics, environment monitoring and control, user and physical interfaces, dark fibre networks, electronic control, superconductor systems, fabrication, photonics integration, data acquisition and processing.

**By 2022, this means that the UK end-user enabled market (excluding defence) that uses photon source-based equipment is likely to be one or two orders of magnitude greater than £63.6m.**

Beyond 2022, there will be significant continued growth in overall end-user demand as non-quantum technologies are further substituted by the quantum enabled ones.

The UK currently has a leading position in quantum technologies, as a result of initiatives like the National Quantum Technologies Programme and there have been a number of technical breakthroughs achieved by the UK's universities and research programmes. The challenge now is to build on these successes to develop technologies for applications that have significant and tangible business benefits. Collaborations between academia and industry will ensure widespread adoption of quantum technology, crossing the 'chasm' from technically possible into a mainstream purchase for businesses.

This report explores the market landscape for photon sources in the near term. Although multiple reports have been written looking at the market over a 20-year horizon, this report focuses specifically on a 5-year horizon and the near-term events that will occur. We believe that by knowing which technologies are likely to be commercialised first, government, business and research institutions can invest in the areas that will provide the maximum return on investment and lead to a sustainable and long-term growth.



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# INTRODUCTION

Gooch & Housego, Milner Strategic Marketing and the University of Bristol undertook a project to find the future market for UK photon sources, funded by EPSRC and Innovate UK between September 2017 and February 2018. The aim of this project was to gain a realistic picture of what will happen in the market over the next 5 years, and where the early opportunities will be for novel photon source technologies.

Quantum technology enabling photonic sources have seen limited commercial success to date. However, various photonic devices used for pure research have reached a sufficient technology readiness level to be mass manufactured or incorporated into other devices. However, time-to-market of the various quantum technology applications that these devices enable is currently unknown. The project focused on 3 core groups of technologies within the full range of photon sources. These 3 groups (defined in Appendix 4) are:

- Laser sources
- Photon-pair sources
- Single-photon emitters

Through collaboration with multiple experts, 10 key sectors and 10 major applications were identified as the priority areas for photon sources in the near term.

## THE KEY SECTORS ARE:

- 1 Biomedicine/life sciences
- 2 Computing
- 3 Finance and banking
- 4 Gambling/gaming
- 5 Government
- 6 Mining/civil engineering/hydrocarbon exploration
- 7 Scientific/research/universities
- 8 Space
- 9 Telecoms
- 10 Transportation

## THE MAJOR APPLICATIONS ARE:

- 1 Clock technology/timing
- 2 LIDAR
- 3 Magnetometry & gravimetry
- 4 Medical imaging
- 5 Microscopy, imaging and calibration
- 6 Navigation
- 7 Non-QKD communications
- 8 QKD/quantum cryptography/secure comms
- 9 QRNG - quantum random number generator
- 10 Quantum computing and simulation

The combination of every application within every sector has been analysed and discussed in order to come up with the findings in this report. Experts from each sector have been consulted and the market landscape over the next 5 years has been specifically discussed, looking at laser sources, photon-pair sources, single-photon emitters and the applications of the technologies. In addition, workshops were carried out to analyse the impact of the major drivers in the market and discuss the different scenarios that could occur over the next 5 years, and to look at the path to industrialisation.

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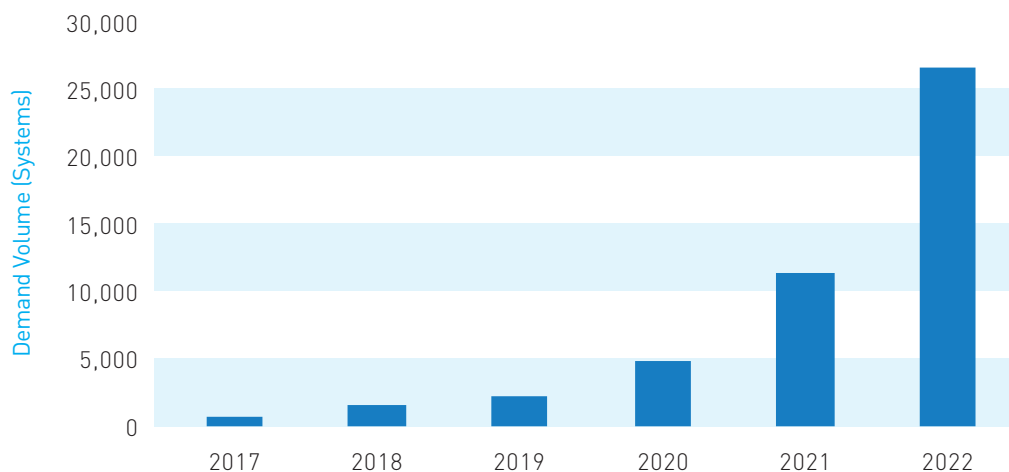
# THE PHOTON SOURCE MARKET OVERVIEW

We forecast that the UK demand for quantum enabling sources will grow from less than 1,000 systems costing £10.7m in 2017, to more than 26,000 systems selling for £63.6m in 2022. The figures below illustrate the overall growth on the market in volumes and value. In the following report, the detail behind these forecasts is laid out in three ways;

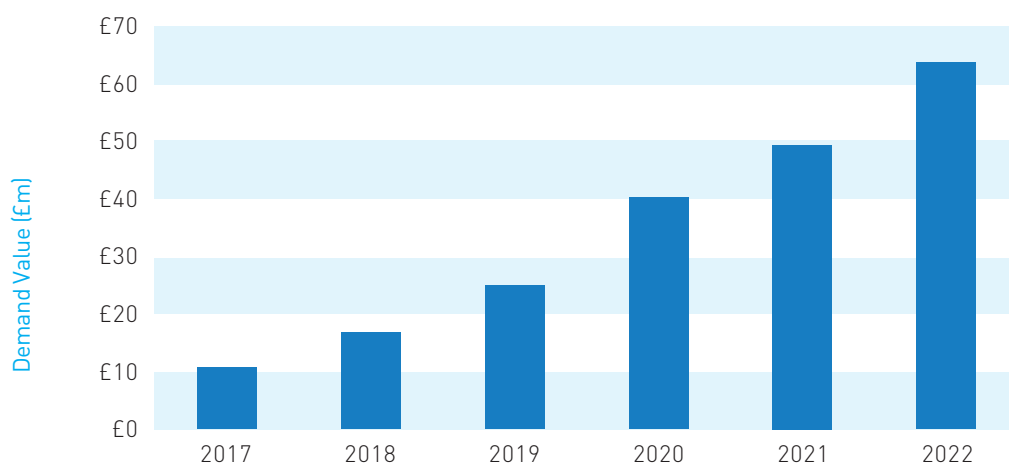
Taken together, along with the output from the Scenario Planning workshop (Appendix 2) and the Industrial workshop, we think this provides the best current overview of the UK Photon Source Market.

1. a technology perspective
2. a sector perspective
3. an application perspective

**PHOTON SOURCES: UK DEMAND VOLUME 2017-2022**



**PHOTON SOURCES: UK DEMAND VALUE 2017-2022**



# THE PHOTON SOURCE MARKET – TECHNOLOGY BREAKDOWN

This report focuses on three groups of quantum-enabling photon source technologies: laser and photon-pair sources, and single-photon emitters. Examples include narrow-linewidth lasers, spontaneous parametric down-conversion sources and quantum dots. Full technology group definitions can be found in Appendix 4.

## LASER SOURCES

Laser sources are the first technology to reach commercialisation and units are already being sold commercially. Over 2018-2022, laser sources continue to be the largest technology and will account for the majority of demand volume.

QKD within telecoms is currently undergoing trials and will reach commercialisation within the next 5 years, growing to a market value of £20m by 2022. It will become a major source of demand within laser sources, driven by the need for a secure communications network and will progress from trials to use in private circuits.

QRNG will drive volume within laser sources, accounting for 15,000 sales units in telecoms and over 8,000 sales unit in gambling and gaming in 2022. However, prices will be low for this application which means the market value remains relatively small overall.

## PHOTON-PAIR SOURCES

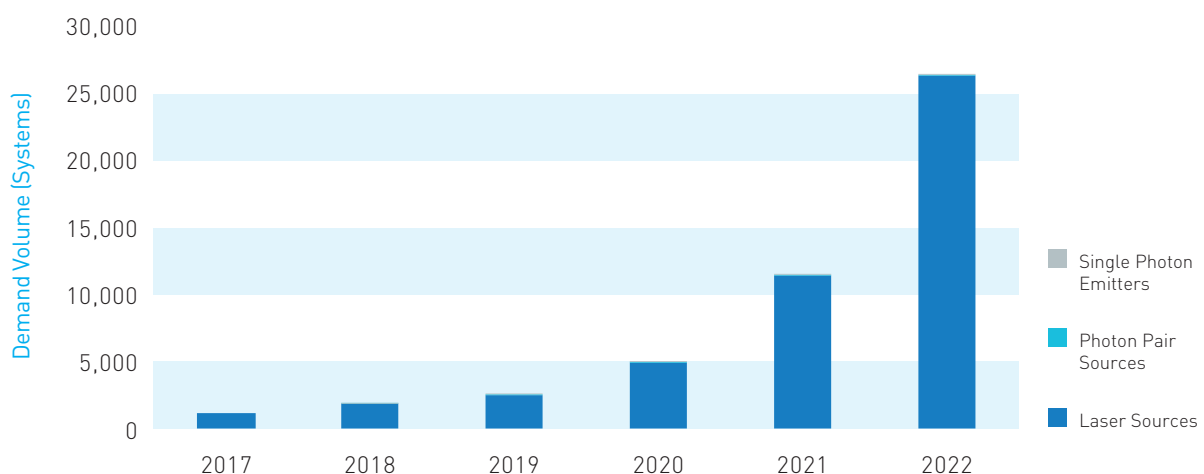
Photon-pair sources are currently seeing some sales within the scientific/research/universities sector, but further development of these systems is needed before they see widespread commercial adoption. Over the next 5 years some systems will be sold into the biomedicine/life sciences sector, but the uptake will be slow.

## SINGLE-PHOTON EMITTERS

Single-photon emitters will see limited commercial sales in the next 5 years, restricted to the scientific/research/universities sector.

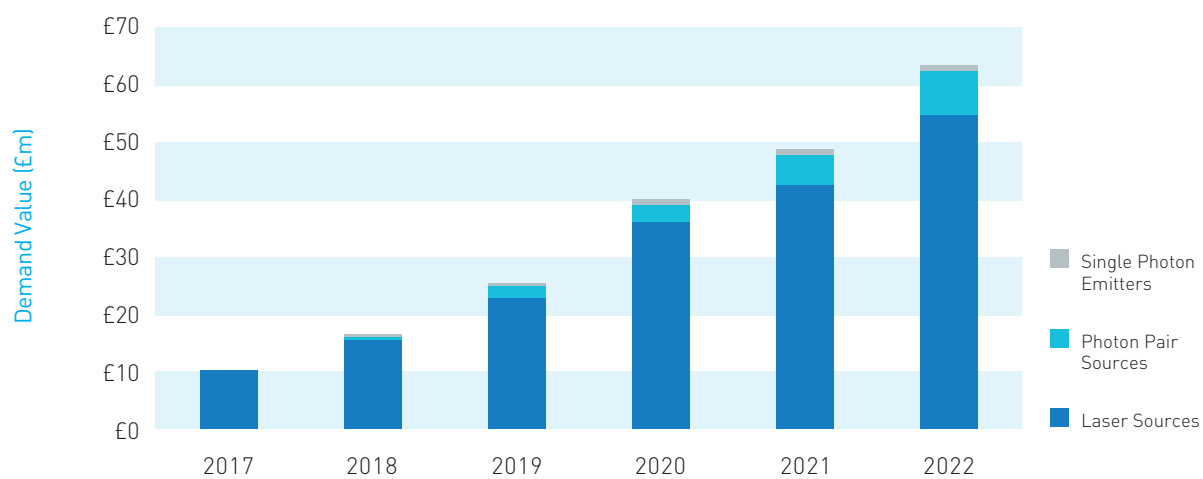
Single-photon emitters have the potential to become the go-to solutions for quantum computing and quantum secure communications, but they require further development before this is possible and this will not occur in the next 5 years.

PHOTON SOURCES: UK DEMAND VOLUME BY TECHNOLOGY 2017-2022





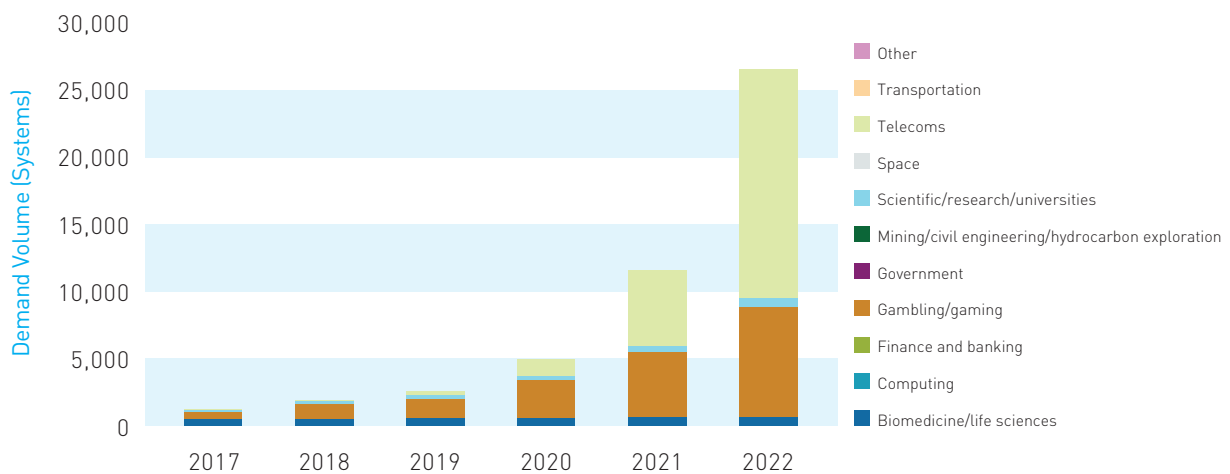
#### PHOTON SOURCES: UK DEMAND VALUE BY TECHNOLOGY 2017-2022



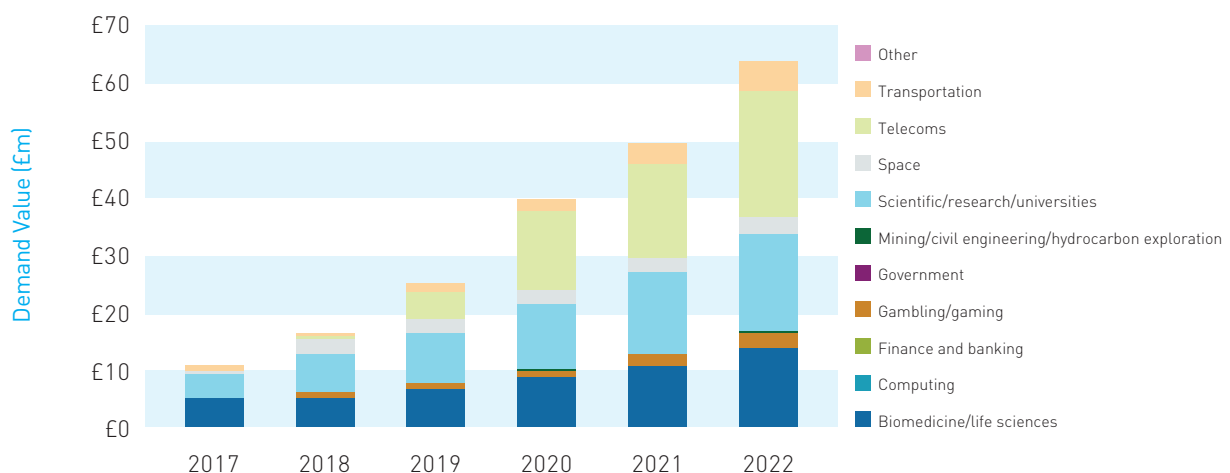
# THE PHOTON SOURCE MARKET – SECTOR BREAKDOWN

Aggregation of the photon-source technologies across the markets shows domination by 3 sectors; specifically telecoms, scientific/research/universities, and biomedicine/life sciences. By 2022, these have respective UK demand values of £22m, £17m and £14m. There is also significant activity in transportation, space, and gambling/gaming, with respecting demands of £5m, £3m and £3m. There is little demand in the other market sectors.

**PHOTON SOURCES: UK DEMAND VOLUME BY SECTOR 2017-2022**



**PHOTON SOURCES: UK DEMAND VALUE BY SECTOR 2017-2022**





The UK Photonics industry is strong and valued at £12.9Bn according to the UK Photonics leadership group and laser systems are a particular strength. There are roughly 120 companies who produce specialist high end lasers in the UK and of these around under a third are linked to the biomedical sector as a provider. An estimated ~200-300 microscopes incorporating laser sources are sold each year in the UK and the estimated total market for biomedical imaging systems containing high end lasers is currently ~£40M. This includes fluorescence, two photon and confocal microscopes, raman and laser spectroscopy, surgical lasers, endoscopy and flow cytometry. Mid-range microscopy/imaging systems featuring high end lasers cost in the region of £200-£250K with higher end systems reaching ~£700K. None of these imaging techniques are “quantum enabled” in either the lasers used nor in the images or information they obtain. Competition in these areas is high and dominated by large suppliers such as Siemens Healthcare, ANDOR, Oxford Instruments, Carl Zeiss, Leica, Bruker, GE Healthcare, JEOL and Perkin Elmer along with others. Most bioimaging centres running within a company, hospital or University will host a dozen or so systems and will replace or upgrade one per year on average. Key drivers include: hand held or portable instrumentation, improved fluorescence imaging methods and materials, non-linear spectroscopy, ultrafast laser sources and advanced photon detection, the use of multi-modal imaging (photoacoustic for example) and position in the body technology. A new National Healthcare Photonics Centre for Process Innovation will be opening in late 2018. This is expected to significantly accelerate the implementation and development of photonic discoveries into the market. However, there are only a handful of truly “quantum” or related laser based biomedical tools moving into the market and these will be integrated with existing systems being developed by established large manufacturers. The Fraunhofer Centre for Applied Photonics is involved in a project to reduce the cost of high performance lasers used in multi-photon excitation spectroscopy. It can take ~5 years for a new product to gain approval for use. There is a large regulatory and evidence burden for new technology in the area and there must be a clear cost differentiation to be attractive. These factors could be a significant barrier to entry for smaller companies. The ingress of new quantum-based laser techniques into the

biomedical market will likely be through collaboration and development with the larger suppliers.

Imaging using optical coherence tomography is also having a large impact in ophthalmology where detailed 3D pictures of the surface of the eye can be built up. Optical tomography imaging is higher in resolution compared to X-ray, MRI, CT and ultrasound but is restricted to a depth penetration of only a few millimetres in the body due to light scattering. Imaging in scattering mediums over many meters has already been demonstrated by the QuantIC hub and is further being developed in a collaboration between Fraunhofer Centre for Applied Photonics, Photon Force and Optocap as part of the Innovate UK funded rAmpart project. These techniques may be adopted into life science imaging. An early example of this is a collaboration between University of Edinburgh and Heriot Watt University for tracking the position of endoscopes within the body. Development in the medical sector for diagnostic equipment is clinician led and regularly built to their specification with existing components and architectures. Emerging quantum enabled imaging and diagnostic techniques in the sector will need to be promoted and developed in collaboration with point of use clinicians to be widely taken up. In total around 70 units of various optical tomography, laser squeezed light or spectroscopy systems are expected to sell in 2018 with a market value of £5M which is expected to grow slowly to £7M by 2022.

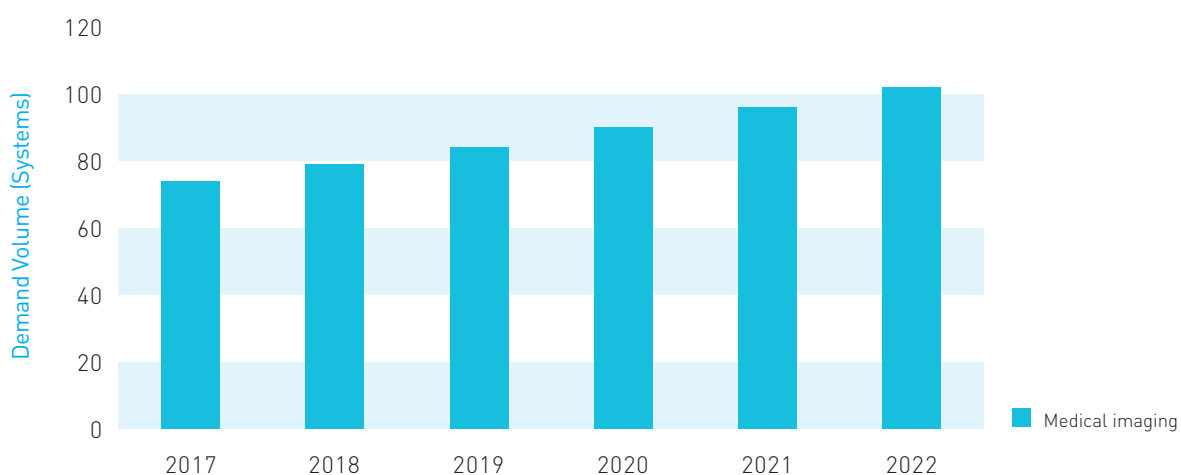
Around six dual photon source containing systems are predicted to sell in 2019 as existing research projects translate into the market. Shorter light pulses and entangled states may increase resolution in certain fluorescent or optical imaging modes. Fibre laser technology capable of these requirements is being developed as part of a collaboration between Chromacity, Covision and the University of Glasgow. Should a dual-source based imaging product prove successful then there will be a slow market penetration at a rate similar to the turnover for upgrades and replacements in the microscopy sector. Single or dual photon sources will have to demonstrate both a cost and functional advantage over existing laser or attenuated sources to be incorporated into a company’s next generation model. Given the current maturity of existing light sources it is unlikely that single or dual photon sources will be replacing laser modules in the majority of microscopy

or imaging systems. In applications where low light levels are needed this is currently accomplished by the attenuation or filtering of existing laser sources. For dedicated sources to have an impact in the sector there needs to be a “killer application” reliant on quantum enabled light sources. No sales are predicted for single-photon sources in this area for the next five years.

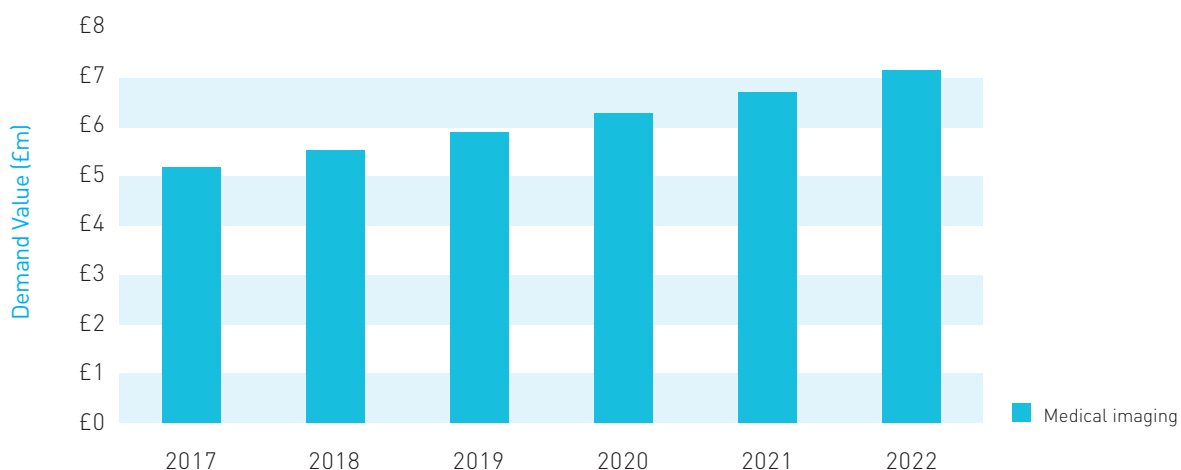
Potential applications are still in the research stage but there is interest in using low intensity light sources for optogenetics, where cell behaviour and signalling can be modified using light. Three potential areas where developments for dual photon sources are expected:

- Imaging in biology where the risks of phototoxicity and photomutagenicity are high
- Transmission microscopy through single cell layers where scattering probability is low and collection efficiency is high
- A general tuneable, spectrally stable low maintenance light source for applications with high collection efficiency

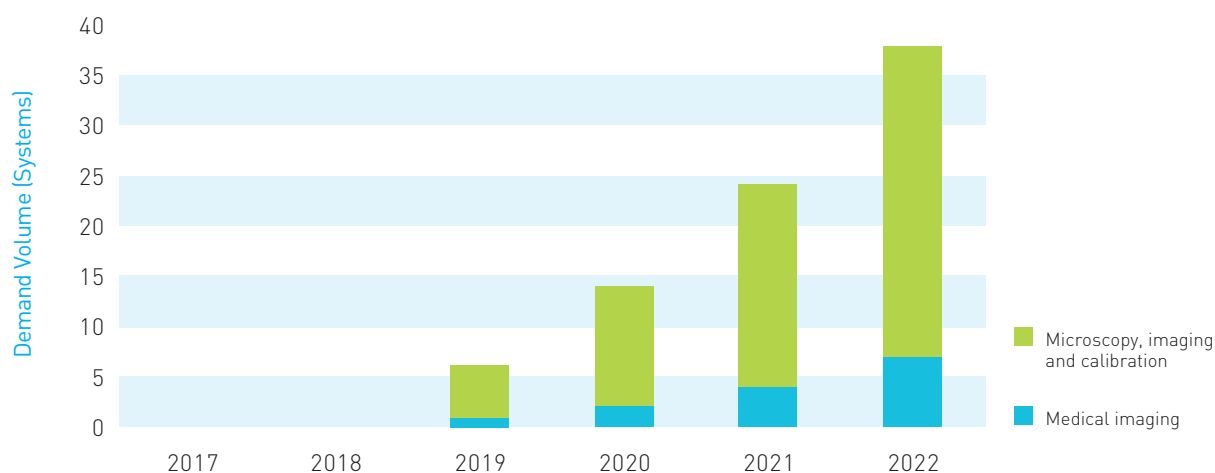
**BIOMEDICINE/LIFE SCIENCES LASER SOURCES UK DEMAND VOLUME (SYSTEMS) BY APPLICATION**



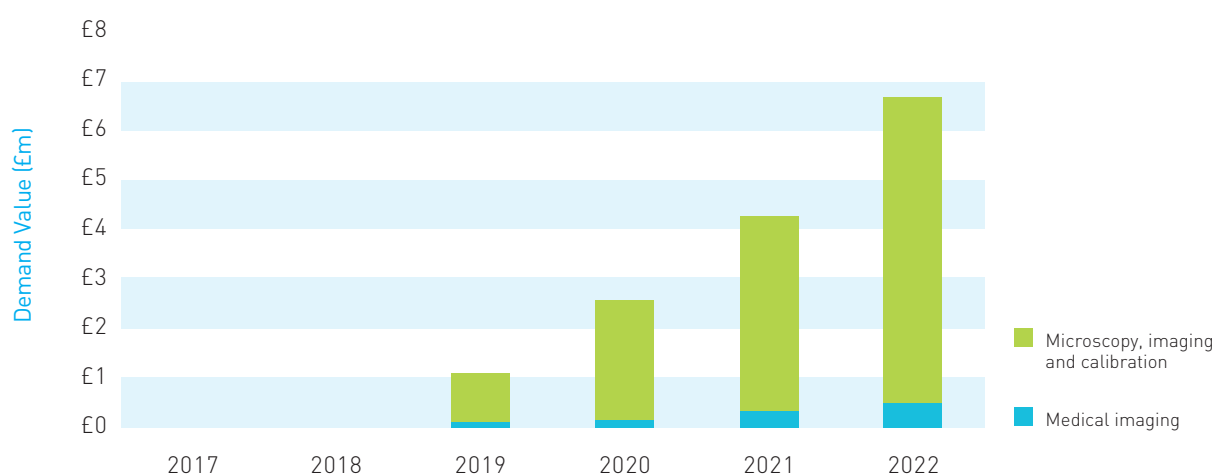
**BIOMEDICINE/LIFE SCIENCES LASER SOURCES UK DEMAND VALUE (£) BY APPLICATION**



#### BIOMEDICINE/LIFE SCIENCES PHOTON-PAIR SOURCES UK DEMAND VOLUME (SYSTEMS) BY APPLICATION



#### BIOMEDICINE/LIFE SCIENCES PHOTON-PAIR SOURCES UK DEMAND VALUE (£) BY APPLICATION



There is increasing public and private investment worldwide in this area. To date, around \$0.5B has been invested privately, through industrial R&D spending and venture capital, on the assumption of sales in the next 5 to 10 years. Although there will be no sales within the 5 year timeframe, first commercial prototypes of new generation quantum computers will become available.

The most important applications in this area are quantum computation and simulation. Although related, there are some important differences between them. Quantum computation focuses on solving problems that are inefficient on a classical computer but become efficient when quantum algorithms are employed. Some famous examples are the Shor's factorisation and Grover's search algorithms. On the other hand, quantum simulation focuses on recreating, in a controlled and measurable manner, the structure and dynamics of real quantum systems and interaction. This is especially useful in chemistry and biology, with applications in pharmaceutical research and material science. While a truly universal quantum computer would, in principle, be capable of dealing with both sets of problems, in the near to medium term, it is likely for quantum computers to be application specific.

There are currently three main quantum computing hardware approaches: superconducting, ion trap and optical. Current ion trap architectures require specialised narrow-linewidth lasers for cooling and probing of the ions. However, it is likely that lasers will constitute only a small subcomponent of the overall system. On the other hand, single and pair-photon sources lie at the heart of linear optical quantum computing. Current predictions suggest that a practical photonic quantum computer will require millions of photon sources. Therefore, chip-based approaches are the most promising, such as solid-state (e.g. quantum dots, diamond vacancy centres) or integrated parametric sources (e.g. based on spontaneous four-wave mixing). Regardless of the type of technology, sources for quantum computing will most likely remain optically pumped. Therefore, new lasers will have to be designed specifically for that task.

A number of companies and institutions actively developing quantum computers such as D-Wave, Google, IBM, Intel and IonQ. D-Wave quantum computer is currently the only such device available on the market. A number of other promising systems have been announced. However, these are still expected to be more than 5 years away from becoming fully developed commercial products.

There will be no sales within finance and banking over the next 5 years. Financial institutions view quantum technology as being made up of 3 different areas: metrology (sensing), quantum security and quantum computing. Metrology will not be a relevant application for the financial sector and activity in this area will be restricted to baseline research to keep colleagues informed.

Although security is a priority for the finance sector, it's about appropriate levels. Security is like an onion with multiple layers, and the layers that quantum can add to are already well protected. The greatest attack threat for banks is from the inside, for example data breaches by employees, so security priorities include areas like sophisticated communications surveillance. In addition, for banks there is a large risk involved in being the first to adopt any new technology and security is not used by banks as a differentiator. The sector is likely to work together as a consortium to agree industry standards and protocols, which they then adopt at the same time. It is unlikely that an individual bank would take on an extra level of security, either as an internal trial or a bilateral agreement with another bank/company in its supply chain, but institutions where there is market participation could drive adoption. Therefore, the first activity is likely to be with central counterparties such as regulators, central banks or trading venues that all banks need to connect into.

In order for QKD products to reach commercialisation over the next 5 years, suppliers will need to persuade banks to test out products on their systems. Banks are cautious about experimentation and small quantum companies are unlikely to trial or sell directly into banks; it is much more likely that current large suppliers like Cisco, Siemens, Fujitsu or BT will leverage their existing relationships to encourage banks to trial their quantum technology. Trials are forecast to occur over the next 2

years and commercialisation will occur in 7 years' time, as a commercial grade product is estimated to take 5 years to develop. When the technology is adopted, there will be a 'big bang' effect as all banks look to buy the technology at once.

Computation is core to bank operations and represents the most attractive long-term opportunity. Through simulation, banks can test out algorithms in a virtual environment to find out what works efficiently before building a real machine, which can be used in trading, risk or insight. It is forecast that quantum computation will take around 20 years to commercialise and become useful, but the opportunity is in pre-commercialisation; some banks will start developing relationships with the relevant institutions now and maintain awareness of progress so that they can make use of the technology first. Investment in the short term will be focused on buying knowhow and awareness rather than physical devices or equipment. In the early stages spending will be based around relationship building with institutions such as universities, and projects with quantum consultancies such as QxBranch, 1QBit and Cambridge Quantum Computing.

The investment profile for banks is wholly based on the potential benefit, rather than the underlying technology. Photonics is one of a number of technologies that could offer interesting solutions in the future. This is one of the few sectors that does not prioritise miniaturisation; the priority is capability. In the finance sector, some institutions are starting to implement clear strategies of how to adopt quantum technology over the long term, incorporating meaningful business benefits and the short-term activities that need to be carried out. This includes building partnerships and collaborating with industrial partners and academia as well as start-ups to understand how to integrate quantum technology into their operations.

Quantum random number generators (QRNGs) are the most relevant quantum technology for the gambling and gaming sector. There were an estimated 550 units sold in 2017 and sales are expected to grow in volume to over 8,000 QRNG modules in 2022, provided by companies such as ID Quantique, Whitewood, Quintessence Labs and KETS Quantum Security. However, this wider adoption will be driven by integrating this technology in slot machines, video poker and similar games in casinos. Therefore, the price per module is expected to drop to as low as £100 in 3 years and to £70 by 2022. The required key rates are very low so the simplest, slowest and cheapest QRNGs will dominate this market. 98% of total sales are expected to fall into this category.

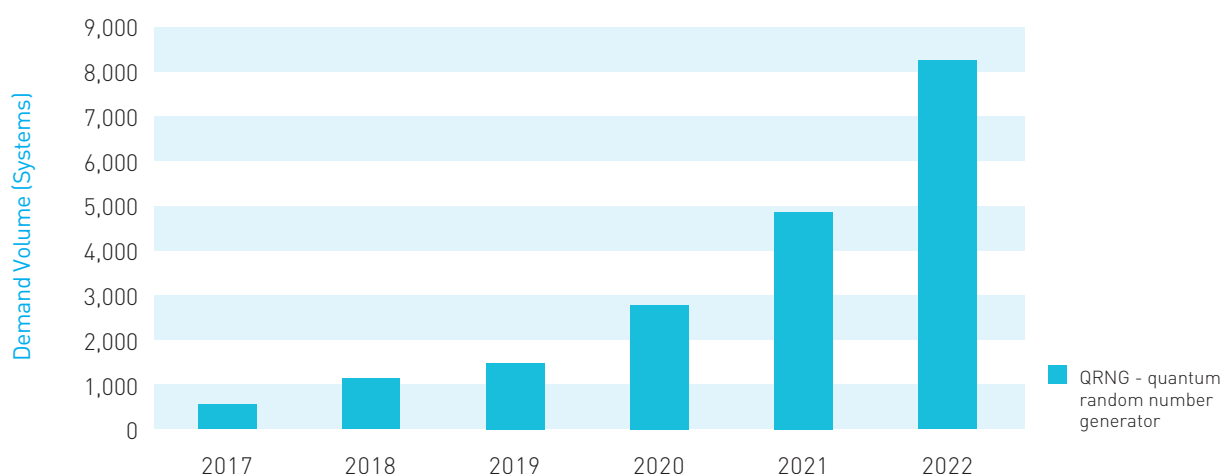
The commercial adoption of QRNGs in the offline gambling and gaming sector will be driven by individual large organisations. The largest casinos can operate over 1,500 slot machines. Each organisation's decision to roll out the technology across all or most of its machines is likely to trigger the increase in sales over the next 5 years. However, both the operators and their suppliers have to be persuaded that QRNGs can provide a

tangible benefit for a low cost. It will be necessary for the technology to be compatible with the current systems.

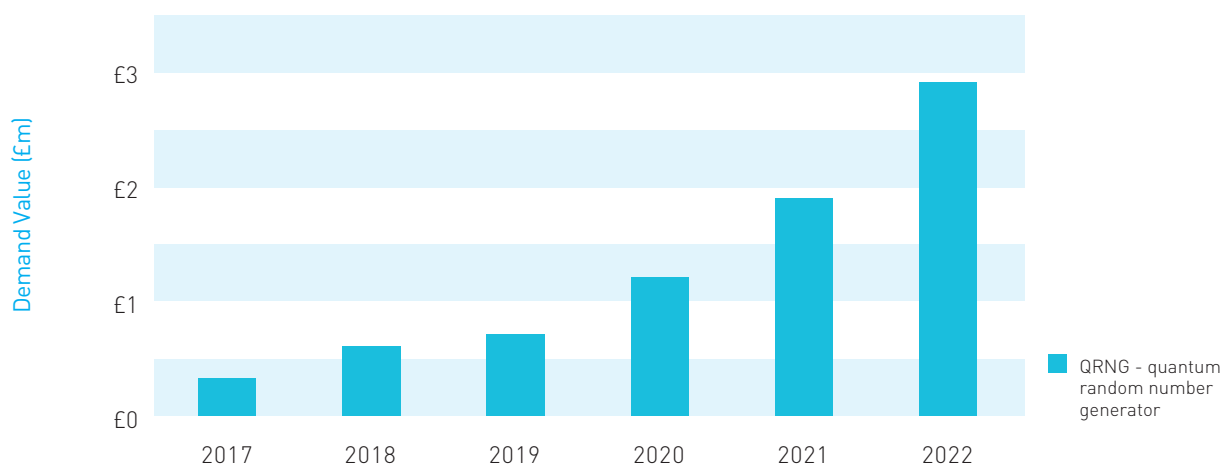
As far as the online gambling and gaming industry is concerned, high-speed network solutions will be most suitable. A small number of QRNGs placed inside a data centre will be sufficient to provide the necessary amount of random numbers for all the online games operated by a company. The fastest, most expensive solutions will be required and current high-speed QRNGs cost between £4k and £6k. Therefore, unlike the slot machine application, online gambling and gaming will be a low volume but high price area.

Standard laser sources will remain the dominant technology in the QRNG module. The advantage of photon-pair sources is certifiable randomness. However, their current high cost, higher system complexity and the low-key rates they deliver prevent their wider adoption. In the longer-term legislation could be introduced that mandates guaranteed randomness, which would drive photon-pair adoption, but this is unlikely to occur over the next 5 years.

**GAMBLING AND GAMING LASER SOURCES UK DEMAND VOLUME (SYSTEMS) BY APPLICATION**



#### GAMBLING AND GAMING LASER SOURCES UK DEMAND VALUE (£) BY APPLICATION





There will be no sales within government over the next 5 years. This sector largely overlaps the telecommunications and defence sectors. Secure communications is a priority for the government. Therefore, quantum key distribution (QKD) hardware, which typically contains a quantum random number generator module (QRNG), is the most relevant quantum technology.

However, the civil service does not directly run its networks. It relies on the information security and telecommunications industries to provide it with secure, reliable and cost-effective solutions. The government relies on GCHQ to provide the necessary technological and operational guidance. Over the next 5 years, there is a possibility of limited trial networks between certain ministries or generally government sites that require the highest level of information security. However, this will require the companies supplying the equipment and running the network to invest in and integrate QKD systems within the existing infrastructure. Although quantum cryptography solutions may be encouraged for protecting critical infrastructure, these systems will not be directly purchased by the government but instead by network operators such as BT.

In order for QKD products to be implemented in government communications networks over the next 5 years, the information security providers will need to persuade the civil service that these provide a significant

security benefit. In addition, for all but the most sensitive communication channels, these systems will also have to be competitive in terms of cost. The providers typically present a number of options and discuss with the government as to which one is most suitable given the required level of security and cost. Therefore, the current price of commercial QKD systems is seen as prohibitive. Even a relatively small network containing 5 to 10 nodes would cost between £500K and £1M in equipment alone. On the other hand, if implemented between specific government sites, the key rates, and therefore data speeds, are not required to be as high as they would be for a wider network. The current state of technology on this front is sufficient for this application.

In 2007 QKD was implemented and trialled during elections in the State of Geneva in Switzerland. The transmission of data from an entry centre to the state government's central data repository was secured using a quantum communications system. However, no such trials have occurred in the UK or elsewhere in Europe. Neither did the technology see wider adoption by the Swiss national or state governments. As the quantum communications systems only secure the transmission of vote tallies, they do not address the main vulnerability, the malicious software on the voting machines or voter fraud. QKD systems are unlikely to see wider adoption or trials in UK local or national government elections over the next 5 years.

Representing an established small and stable niche, this sector is dominated by classical gravity imaging technology for the geo-surveying market. However, such stasis is set to change with advent of quantum technology for laser-based geochemical detection, seismometry, magnetometry, and gravimetry. Opportunities for such quantum technology could range from the surveying of bedrock, to the detection of geological voids, the location of mineshafts and pipelines, the detection of corrosion and cracking, in-situ sensing within boreholes, UAV navigation, LIDAR/radar, and ground-observations from satellites.

With funds injected by Innovate UK, collaborative developments of quantum gravimeter demonstrators are set to establish the market. In particular, work at the Quantum Sensors and Metrology Hub as part of the REVEAL project with Teledyne E2V and Gooch and Housego, is creating instruments, based on atom interferometry that are already being shown to surpass their classical counterparts, with doubled sensitivity, and measurement time reduced by an order of magnitude. Field tests are already taking place as part of the Quantum Technology - Potential for Railway Infrastructure Project in a collaboration between the University of Birmingham, RSK, Network Rail and Atkins. In the UK, the first commercially built gravimeter has been exhibited by M Squared. Work on low-noise gradiometer-based implementations by the University of Birmingham, Teledyne e2v, Gooch & Housego, and RSK is expected to reach commercialisation by the beginning of 2019. And soon thereafter substantial uptake is expected in the area of hydrocarbon exploration.

Successfully implemented quantum gravimetry would provide a number of advantages that include:

- Increased sensitivity, and robustness
- Reduced surveying time with minimal operator training
- Reduced equipment size and cost: Classical examples cost ~£100k apiece.
- The facilitation of gravity surveys as standard procedure: Classical devices feature limited ownership by universities and research institutions, and there is a rather constant low-level commercial market served by just 8 such devices and 2 service providers.

Additionally, to geological analysis, the growth in such a quantum market promises many benefits that range from the monitoring of ground-water level to the location of underground constructions, detection of seismic activity, surveying of building sites, and maintenance of roads.

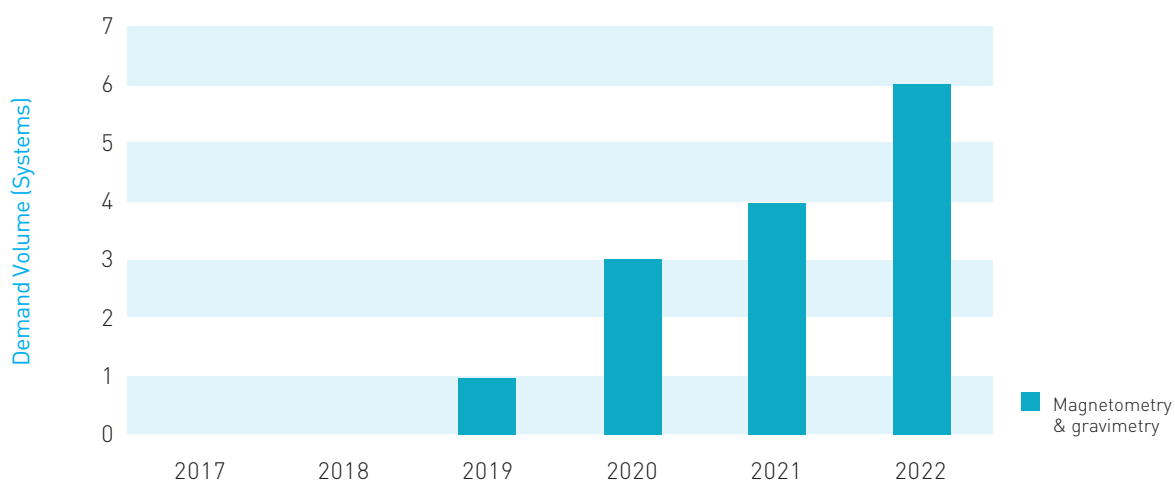
The initial market intake of quantum gravimeters would feature devices costing about £150k with the supporting laser sub-system at about 50% of this total. With falling prices reaching competitiveness with classical devices (Scintrex CG-5, Micro-g LaCoste FG-5), slow exchange to the new technology is expected as the average lifetime of a classical device is around 5 years. System purchase costs should then reach £200k per year in UK. The global market is much bigger, estimated at 100 systems per year with purchase costs reaching £4M.

There will be no sales of dual or single-photon sources in this application area within the next five years.

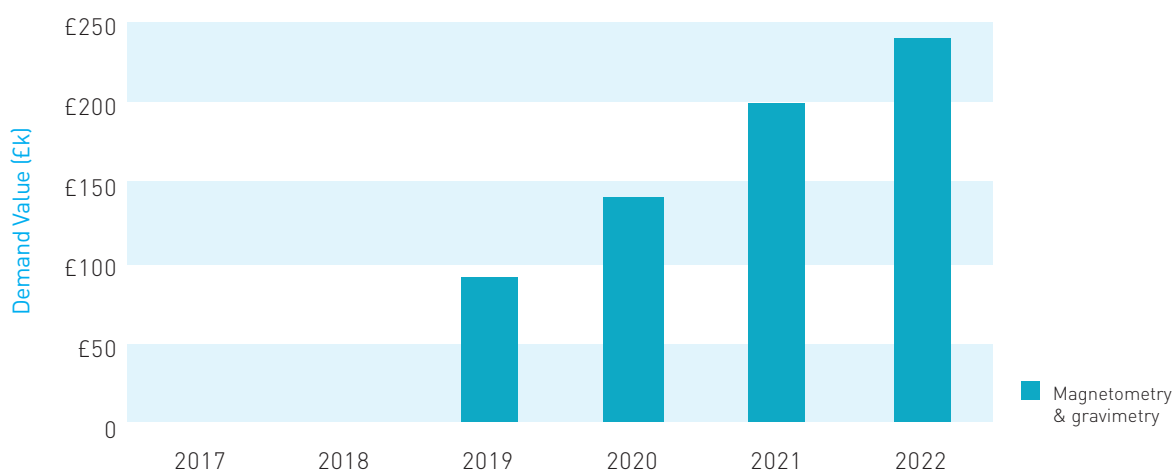
However, new markets are expected to grow strongly as UK gravimeter purchases could increase by £50M if shown to be successfully deployed in hydrocarbon exploration, as more countries implement gravity surveys fuelled by technological improvements and reduced costs, and as millions of potential customers take advantage of a maturing cost-effective technology.

Another promising project in the gravimetry area is Wee-G, a MEMS gravimeter, being developed at the University of Glasgow as part of the QuantIC hub. This will be a cost-effective and high-performance MEMS system with excellent long-term stability. The Wee-G is moving along a technology roadmap and in partnerships with Bridgeporth, Clydespace, Qinetiq, and Schlumberger QuantIC is exploring applications across oil and gas, space and security and defence. Part of this roadmap features the use of a squeezed light source to improve sensitivity. No predictions on volumes or unit price are available at this time although it is expected to be open up new opportunities when it reaches the market in terms of offering the potential for lower cost gravimeters which can be deployed in arrays to offer gravitational imaging. It is expected that the Wee-G may also diffuse into as yet unidentified sectors beyond environmental monitoring or civil engineering once it reaches the market.

### MINING/CIVIL ENGINEERING/HYDROCARBON EXPLORATION LASER SOURCES UK DEMAND VOLUME (SYSTEMS) BY APPLICATION



### MINING/CIVIL ENGINEERING/HYDROCARBON EXPLORATION LASER SOURCES UK DEMAND VALUE (£) BY APPLICATION



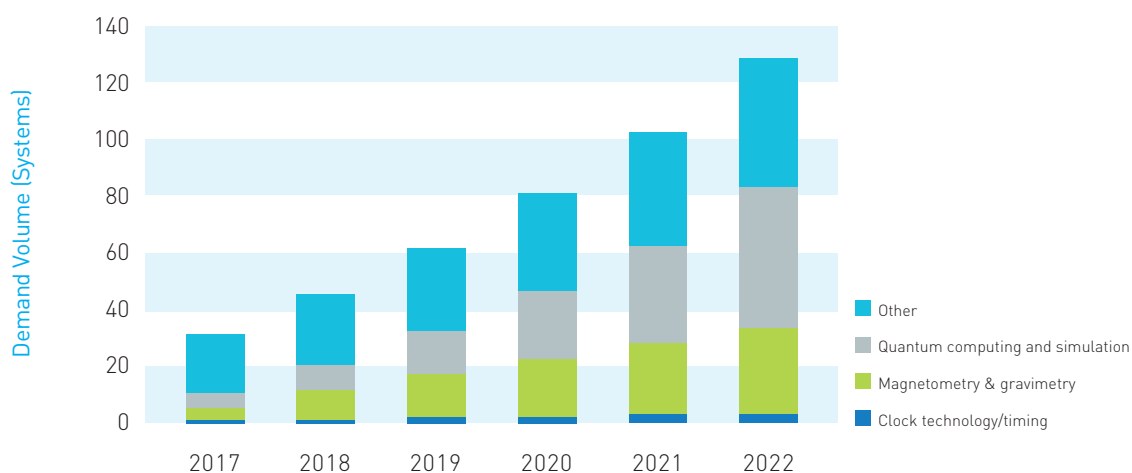
The member universities of the UK Quantum Technologies Strategy programme form the majority of customers for quantum related light sources. High performance research-grade lasers cost between £100 - 250K per unit depending on the application and the UK market in this sector is estimated to be around £6M per year. This is predicted to grow steadily to ~£14M by 2022 as labs continue to upgrade their equipment and instigate new research avenues. Growth depends strongly on continued UK or EU grant funding over the longer term for quantum research. Continuation of the very strong academic-industry partnerships are helping to drive sales in laser research as systems are needed for collaborative prototype development. This is enabled by the hubs having the internal finances to build minimum viable products and then attract industrial interest. This is further supported by a number of Innovate UK collaborations enabling ongoing development and transfer into the market.

Single frequency lasers are the most common type of high end laser being purchased and are used for cold atom and trapped ion physics in quantum computing. There is expected to be the largest growth in lasers for quantum computing rising from ~5 laser or multiple laser systems purchased per year to 50 by 2022. In lasers for gravimetry and magnetometry, around 10 systems will be sold per year rising to 30 per year by 2022. This is followed by high-end custom systems used in clock and timing applications for which a growth from 2 in 2018 to 4 per year by 2022 is expected. High-end systems for research into other applications will also grow from ~25 per year to 45 by 2022 driven by bespoke lasers for blue skies research.

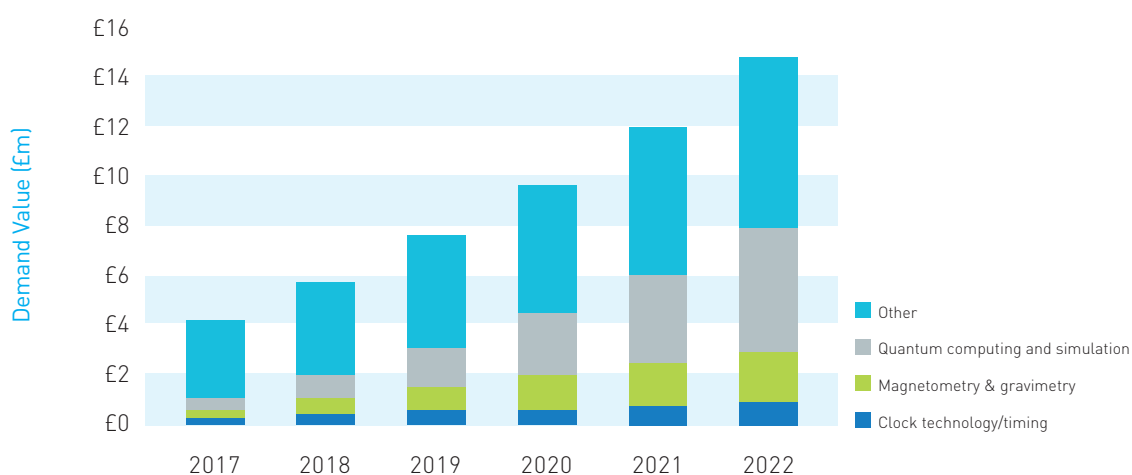
Single and dual photon sources are routinely assembled in the labs or as part of a purchased bespoke laser system from companies such as Toptica or M2 lasers. Researchers will customise their lasers further to suit their experimental needs and lasers themselves are often sold as customisable modules. Startups selling commercial photon-pair sources exist in France (Aurea Technology), Germany (Qutools) and the US (Qubitekk) and there have been low volume sales abroad but not to our knowledge in the UK in 2017. This suppresses the market for dedicated dual and single-photon sources as they can be built from an existing laser module by attenuation and modification. However, there is an argument to develop a low cost pump source for dual photon sources. Similarly, dedicated pump lasers will be needed for single-photon sources. The targets in both cases will be lower cost so that the overall system cost is not dominated by the pump laser (~£15K). Hence, as costs fall, the market for single or pair photon will grow as it becomes cheaper to buy a module than build from scratch. As applications mature the market will grow via sales to end users in other sectors rather than researchers.

Dedicated, rather than modified laser, single and dual photon sources are available, and an uptake is predicted to meet developing needs in quantum computing and quantum and fibre network research. It is predicted that 10 bespoke dual photon systems at a cost of ~£50K per unit with a combined value of £0.5M will be sold in 2018 increasing to 18 by 2022 with a market value of £0.9M. Single-photon sources often require expensive cryostats for operation making them more expensive per unit at around £150K with 4 units being sold in 2018 at a value of £0.6M to 8 units with a value of £1.2M in 2022.

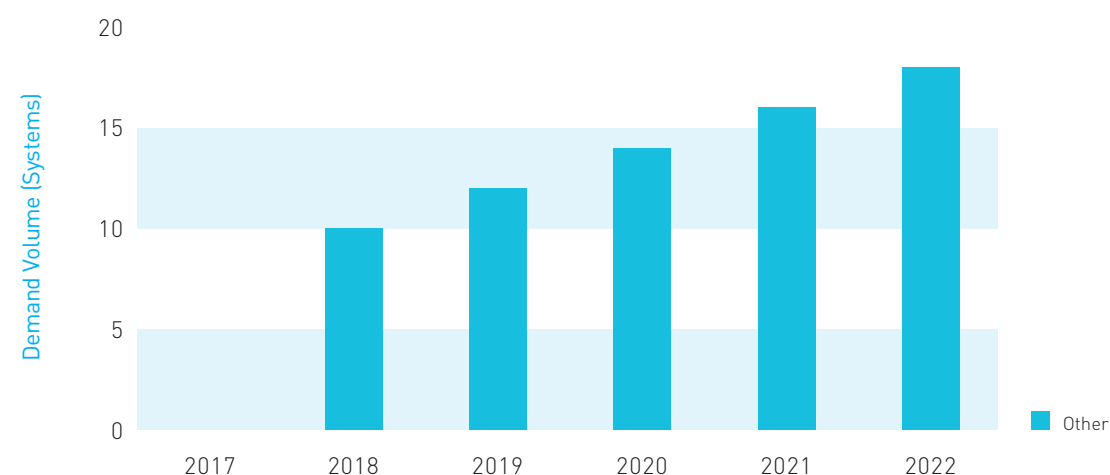
### SCIENTIFIC/RESEARCH/UNIVERSITIES LASER SOURCES UK DEMAND VOLUME (SYSTEMS) BY APPLICATION



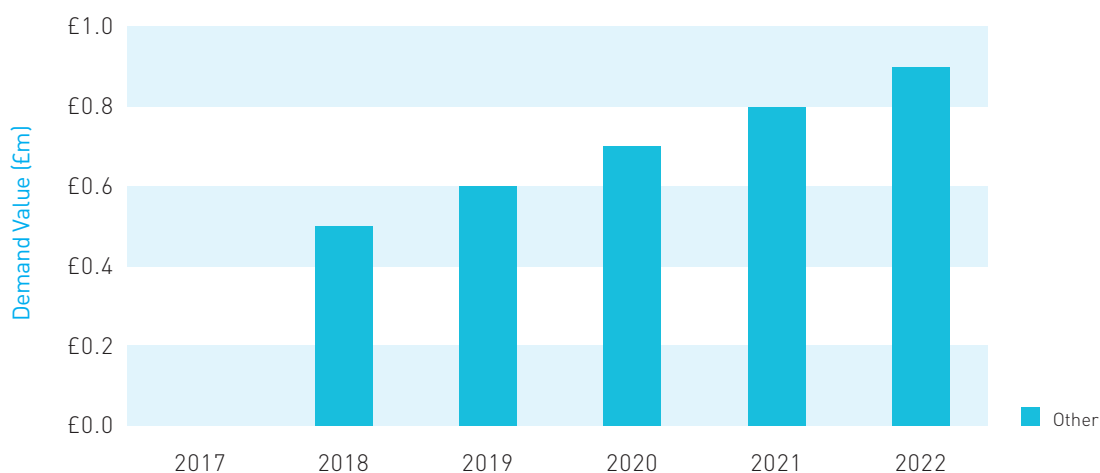
### SCIENTIFIC/RESEARCH/UNIVERSITIES LASER SOURCES UK DEMAND VALUE (£) BY APPLICATION



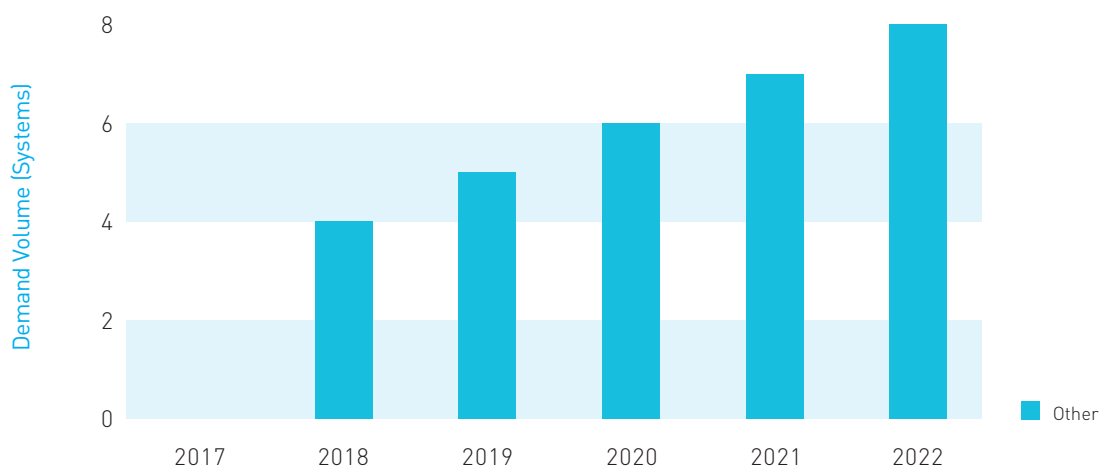
### SCIENTIFIC/RESEARCH/UNIVERSITIES PHOTON-PAIR SOURCES UK DEMAND VOLUME (SYSTEMS) BY APPLICATION



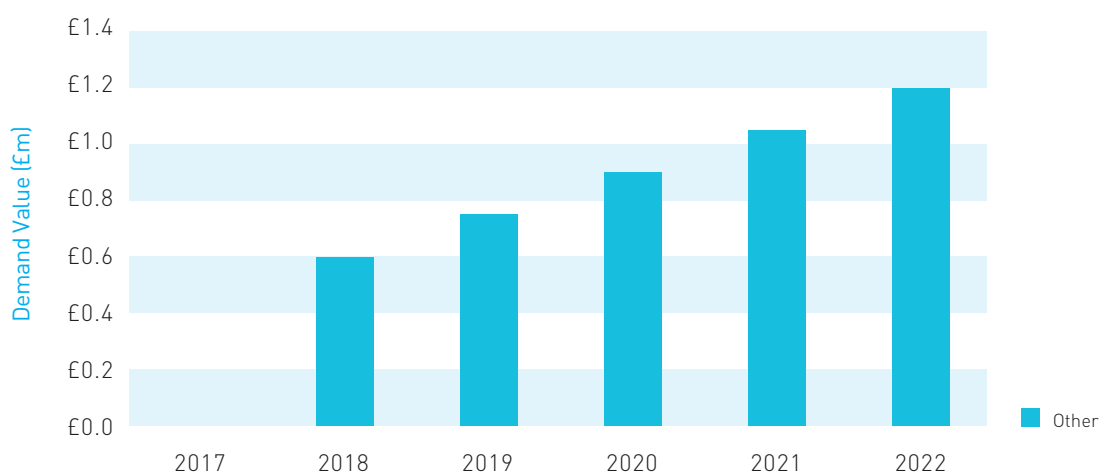
#### SCIENTIFIC/RESEARCH/UNIVERSITIES PHOTON-PAIR SOURCES UK DEMAND VALUE (£) BY APPLICATION



#### SCIENTIFIC/RESEARCH/UNIVERSITIES SINGLE-PHOTON EMITTERS UK DEMAND VOLUME (SYSTEMS) BY APPLICATION



#### SCIENTIFIC/RESEARCH/UNIVERSITIES SINGLE-PHOTON EMITTERS UK DEMAND VALUE (£) BY APPLICATION



While a fledgling market is envisaged for single/entangled photon sources as part of QKD distribution systems, a more mature and larger demand is expected for narrowband sources supporting laser-comms terminals.

QKD applications would manifest as trusted QKD nodes in space that circumvent issues of fibre attenuation over long distances (>100km) with no physically secure ground-based assets required. These would allow banks of keys to be built up and used by companies as needed.

As part of laser comms-systems, very high bandwidth downlink options would be added to existing satellite missions, especially on small satellites in constellations. These could be in tandem with existing RF solutions or as a replacement for them. Another sizable application is in the area of LEO high bandwidth, low latency communications relay systems. Applications here would be for large amounts of data to be sent around the world with the lowest latency possible. This would be ~1.5 times faster than fibre at high data volume, potentially feeding into various markets such as high frequency trading.

Narrowband lasers supporting space applications require qualification testing. For this we can expect an ongoing need for about 50 lasers per year, with each costing about £6.2k. Such low-cost devices support aspects

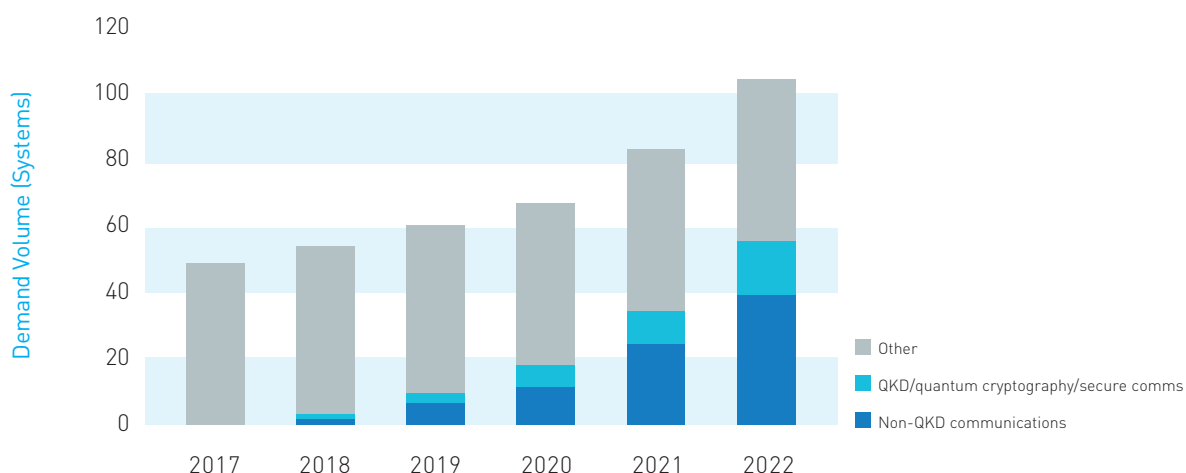
of non-QKD comms encompassing on-board signal processing and free-space communications, and are graphed under the category 'Other'.

Within a year, we could expect 1 or 2 QKD demo systems, each containing at least 2 sources. Once proven there could be a market for a constellation of satellites numbering in the 10's or 20's up to 2022.

Within a year, we can also expect 1 or 2 comms-terminal demos. But these could ramp up significantly after that. Assuming readiness of the ground station networks, then comms terminals could become routine for LEO satellites by 2022. Taking redundancy into account with 2 terminals per satellite, the total UK market could grow to 40 -50 per year range by 2022. The comms-terminal technology could even represent the game-changing technology needed to stimulate the small satellite market growth towards even larger volumes.

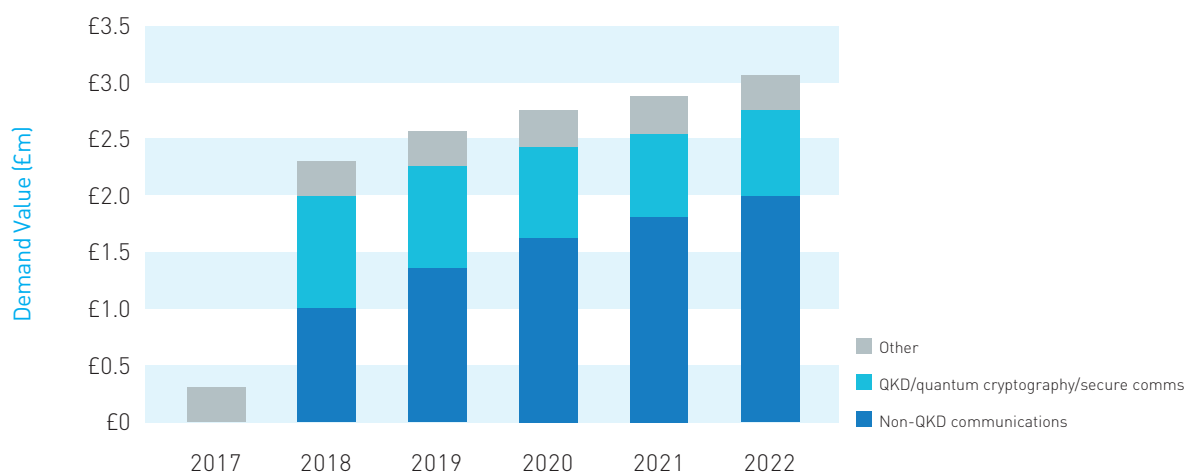
In terms of prices, initial pathfinder systems could cost >£500k. However, <£200k is expected for ongoing QKD sub-systems and comms terminals to reach their expected volumes. Whilst further demand would then kick-in economies of scale, price reductions to about £50k would be needed to make viable terminals on smaller (cubesat) satellites, which would open up a new and larger market area of lower specification devices.

**SPACE LASER SOURCES UK DEMAND VOLUME (SYSTEMS) BY APPLICATION**





#### SPACE LASER SOURCES UK DEMAND VALUE (£) BY APPLICATION



Telecoms has the potential to be the largest sector for photonics over the next 5 years. Laser sources in QKD (quantum key distribution) represent a major opportunity and could be installed in multiple networks. Currently, demonstrators are being set up by various telecoms companies such as BT and equipment is already available off the shelf from Toshiba and ID Quantique. Devices are presently used for research and testing purposes rather than live implementations. Initial sales will be to projects such as the NDFIS (National Dark Fibre Infrastructure) which will implement QKD over the next 5 years. After this initial trial interest, it is likely that systems will be sold into niche private networks and then roll out to business. Telecoms will supply into sectors that require secure networks, such as defence and finance, and the product will be niche but commercially available from the key market players.

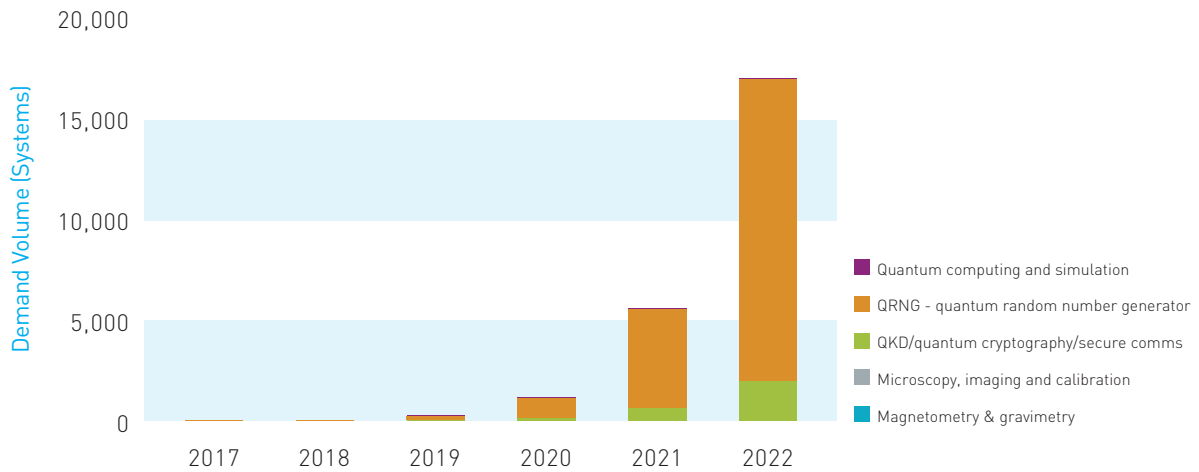
However, there are barriers to uptake that will need to be overcome. There is currently no independent proof that QKD is a reliable or secure solution, and it is essential that the National Physical Laboratory or National Cyber Security Centre verify it before widescale rollout. Individual companies will also want to use penetration testing to ensure the devices are secure, which will be a challenge due to the unique nature of the technology. Standardisation, accreditation and alignment need to take place over the short term before companies can consider integrating quantum technology into their systems. In addition, the photon sources need to work with the rest of the existing network and the integration barriers will need to be explored and overcome.

As well as the QKD application, QRNG (quantum random number generators) will be used in every device that requires encryption and penetration testing is currently being carried out as part of an Innovate UK project to ensure that this technology is secure. Volumes will be high but the price per unit will be low. Gravimetry could be used for finding underground cables, although this will be a longer-term application. An Innovate UK project called FINDIT, with BT, RSK and University of Birmingham, is currently working on this technology but commercialisation is yet to be achieved.

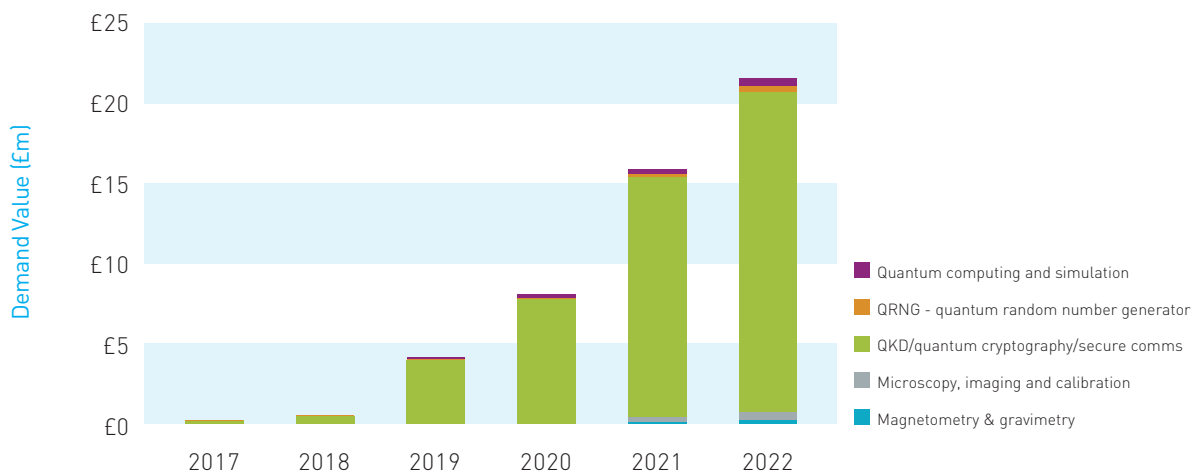
In the longer term (beyond the 5-year time horizon), quantum applications could be in clocks; with the advent of 5G, base stations need to be increasingly accurate and GPS timing is not always reliable. To achieve time synchronisation, clocks would need to be deployed across the whole network so they would need to be miniaturised and inexpensive. Single-photon sources could be used in non-QKD communications, but this requires further development before it becomes commercially feasible.

The majority of the sales value in the telecoms sector will be from QKD laser sources due to the high price of these devices. Systems currently cost ~£100k but this will fall to around £10k when greater volumes are achieved in 2022, and the network economics will need to make sense for widescale rollout to be achieved in the long term. However, the majority of the sales volume in the market is from QRNG which will be used to secure the IoT as well as being at the heart of a QKD system.

### TELECOMS LASER SOURCES UK DEMAND VOLUME (SYSTEMS) BY APPLICATION



### TELECOMS LASER SOURCES UK DEMAND VALUE (£) BY APPLICATION



The UK government has set a challenge for Connected and Autonomous Vehicles (CAVs) to be on the road by 2021 and has invested £150M in over 51 ongoing collaborative R+D projects. Autonomous vehicles are predicted to be a large sector worth £52 Bn by 2035 of which the enabling technology will be worth £5.2Bn. A large amount of research is ongoing in this field for improvements in processing power, secure communications between vehicles, object detection and vision in varied environments. The QuantIC hub has produced a number of demonstrator imaging systems which are expected to have an impact. A prototype camera capable of seeing moving and stationary objects around corners has been developed in a collaboration between Heriot Watt, JJC Bowers and Thales UK. Heriot Watt has also developed optical time of flight techniques which are being field tested in collaboration with Sikorsky Helicopters and Lockheed Martin which can image through turbid mediums such as snow, fog or sand. 3D LIDAR (laser range finding) systems jointly developed with Horiba and Leonardo are capable of realtime 3D video rates. LIDAR systems are a key requirement for this market but are currently too expensive and bulky for large uptake outside of research. Space and cost are key factors in automotive design and the price per unit for a LIDAR system would ideally be £30 or lower. Current commercially available systems suitable for CAV use have recently dropped in price dramatically from around £55K to £6000. This is still too expensive for large scale uptake. Large form factors are also too obtrusive for incorporation into car designs due to mechanically rotating optical components. This problem has been recently mitigated by the development of smaller solid-state LIDAR systems which have no internal moving components. The QuantIC Hub is involved in the development of significantly smaller solid-state LIDAR systems using UK based manufacturing. LIDAR system sales are expected to be mostly to academic-industrial

research projects and coordinated by the UK government Centre for Connected and Autonomous Vehicles.

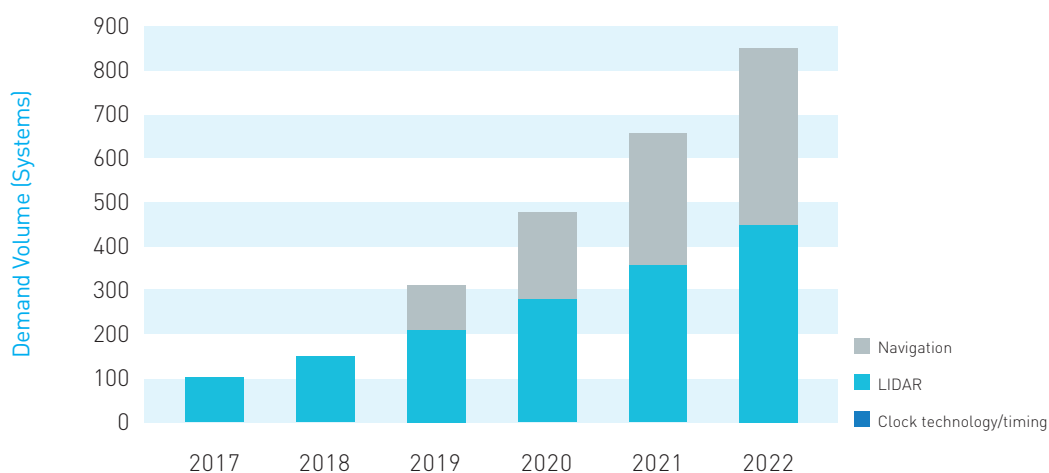
Estimated sales are 150 units per year in 2018 with a value of £0.9M rising to 450 units per year by 2022 worth £2.7M. This may be significantly higher as the research accelerates to meet the government targets.

The LIDAR system evolution is focussed on improvements in the solid-state detectors, using eye safe laser technology and eliminating cross talk between separate systems. The light sources for LIDAR must necessarily be bright as the number of photons returning to the detector will be low and must compete against ambient sunlight. For this reason, it is unlikely that single and dual photon sources will be used in LIDAR or other automotive applications in the next five years.

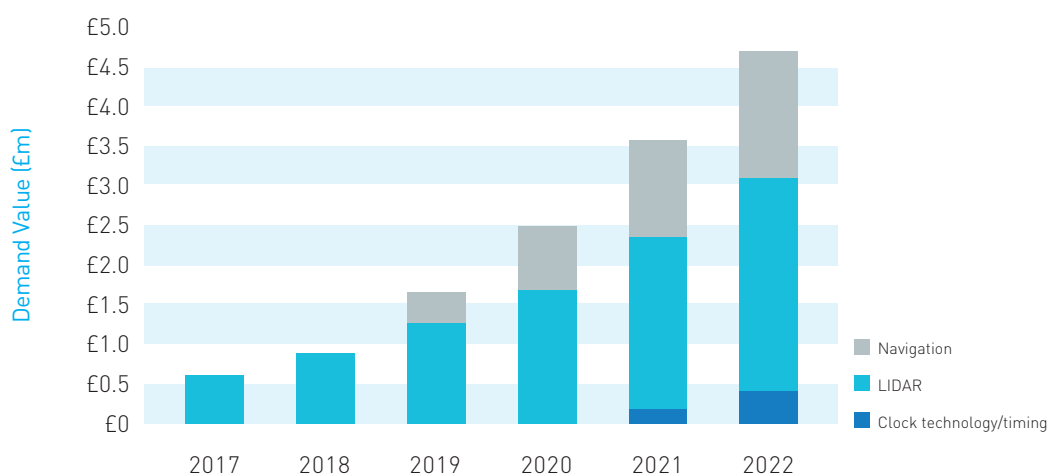
The miniaturisation of atomic clocks will mean that GNSS or GPS systems may become more accurate as clocks can be placed on satellite systems. Conversely, accurate satellite free navigation will become possible and this will have a large impact on maritime and aerospace navigation systems where backup timing or underwater operation is required. A number of collaborative projects are ongoing involving Teledyne E2V, the National Physical Laboratory, Cardiff University, SME Chronos Technology, TMD Technology, University of Bath, IQE, Compound Semiconductor Technologies, Heriot Watt and the Fraunhofer Centre for Applied Photonics. These projects are focussed on improvements in clock accuracy, stability, optical fibre clocks, refinement of VCSELS laser sources development of frequency combs.

Miniature atomic clock volumes in the hundreds are predicted to be sold for incorporation into proving systems around 2019 and the market share is expected to rise from £0.4M to £1.6M by 2022. Larger higher end systems with extra precision are expected to go on sale in 2021 with 1-2 units sold into highly specialist markets.

### TRANSPORTATION LASER SOURCES UK DEMAND VOLUME (SYSTEMS) BY APPLICATION



### TRANSPORTATION LASER SOURCES UK DEMAND VALUE (£) BY APPLICATION



# THE PHOTON SOURCE MARKET – APPLICATION BREAKDOWN

## CLOCK TECHNOLOGY/TIMING

Beyond the 5-year time frame, clock technology will become important in the telecoms sector for synchronising base stations across the network. Extreme time-resolution is a future application in this area.

## LIDAR

LIDAR will principally be provided to the scientific, research and universities market over 2017-2022. The number of laser source systems sold will grow from 100 in 2017 to 450 in 2022, but the price per unit will be low at around £2k per unit and will continue to fall, meaning the market value remains under £1m over the forecast period. This could be subject to drastic increase if LIDAR becomes cost-effective in the automotive industry at a price point below ~£30 per unit.

## MAGNETOMETRY & GRAVIMETRY

Gravimetry will be important in the mining/civil engineering/hydrocarbon exploration sector. Commercialisation is forecast for the beginning of 2019, when gravimeters will be used for geo-surveying such as bedrock analysis, detection of underground features and site surveying. Systems will initially cost around £150k and will be based on laser sources.

In the longer term, gravimetry could be used within other sectors such as telecoms for locating underground cables. Research projects to investigate such uses are ongoing.

## MEDICAL IMAGING

The medical imaging sector is clinician led and imaging systems for commercial sale are built and developed to the specifications of point of care practitioners. Laser sources are used in a range of current imaging systems such as optical coherence tomography, molecular spectroscopy, photoacoustic imaging, endoscopy and raman spectroscopy. Multi-modal imaging, where two or more separate techniques can corroborate one another, will be a strong driver for new imaging modes to be requested and incorporated into next generation equipment. There are no current medical imaging techniques utilising dual or entangled photon sources in

the commercial sector but this is predicted to change as current research developments translate to the market and demonstrate clinical benefits.

## MICROSCOPY, IMAGING AND CALIBRATION

Over the next five years improvements in diode and fibre laser technology will enable more cost effective, lower maintenance alternatives to expensive Ti:Sapphire systems used in fluorescent or excitation based high end microscopes. These improved lasers will be phased into system upgrades or new purchases. Laser sources will continue to be the mainstay of microscopy systems with continued refinement of power, line width and pulse resolution, but photon-pair sources enabling sub-shot resolution or more esoteric imaging modes will start to penetrate the market in 2019 if a clear benefit is demonstrated.

## NAVIGATION

Developments in VCSEL and compact laser systems will enable small form factor atomic clocks and more accurate accelerometers. These clocks will be suitable for GNSS and GPS use in smaller satellites and on the ground. They will also be accurate enough for satellite free navigation in low signal or marine environments. Initial sales of these clocks will begin in 2019 to defence, transport and maritime sectors. The market value will rise from 0.4M in 2019 to 1.2M. Pair and single-photon sources are not currently used for navigation purposes.

## NON-QKD COMMUNICATIONS

Over the next five years, specialist laser sources will have applications in non-QKD communications. However, the adoption of these technologies will be limited and confined to the space sector.

## QKD/QUANTUM CRYPTOGRAPHY/ SECURE COMMUNICATIONS

QKD represents a large near-term opportunity within photon sources. Initially QKD will be implemented using laser sources, but in the long-term photon-pair sources could be used instead if the technology can be developed appropriately.

## QRNG - QUANTUM RANDOM NUMBER GENERATOR

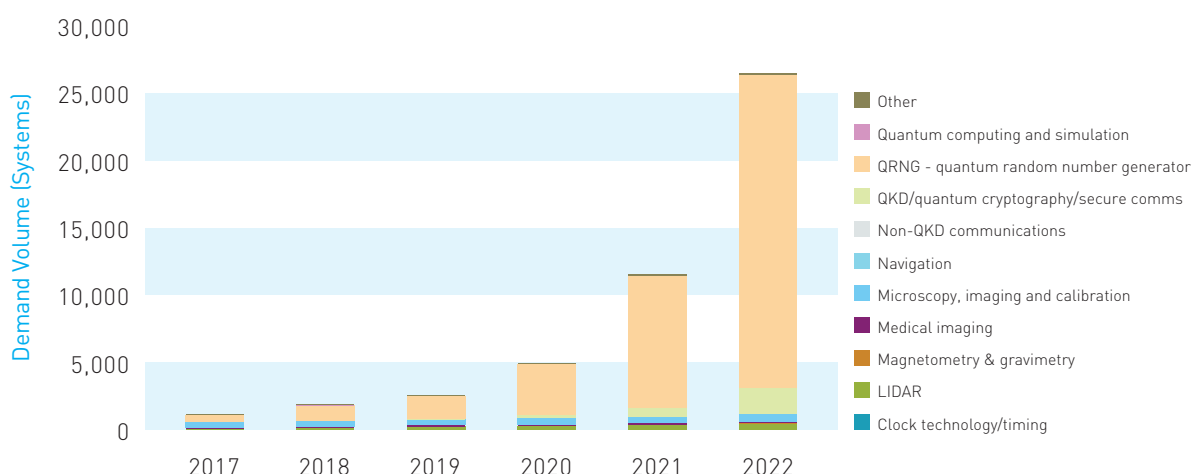
QRNG will account for the majority of sales volume within telecoms, growing from 5 systems per year in 2018 to 15,000 systems per year in 2022. It will be incorporated into every device that requires encryption, which will drive the growth in sales volume.

QRNG is the highest volume application within the gambling and gaming sector and will mainly be used within slot machines in casinos to provide randomness. However, price pressure will be high due to the low value of each slot machine. Some more expensive network devices (£4-6k) will be sold to online gambling sites, but the sales volume will be low compared to the physical gambling machines.

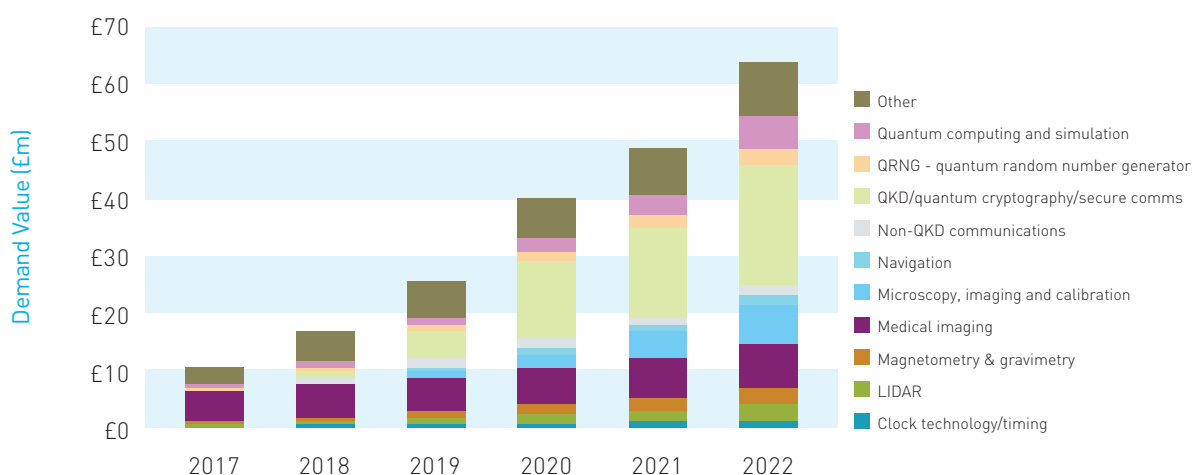
## QUANTUM COMPUTING AND SIMULATION

Experts do not believe that a quantum computer will be developed within the next 5 years. However, it is currently possible to test out quantum algorithms, for example using Microsoft's LIQUi|> software architecture and tool suite for quantum computing. Companies in sectors such as finance and banking and telecoms are adopting a 'watch and wait' approach, monitoring developments in academia, investing in knowhow and awareness and purchasing small numbers of systems so that they will be ready when the technology reaches commercialisation.

PHOTON SOURCES: UK DEMAND VOLUME BY APPLICATION 2017-2022



PHOTON SOURCES: UK DEMAND VALUE (£) BY APPLICATION 2017-2022





# CONCLUSION – THE ROUTE TOWARDS MAXIMISING UK MARKET GROWTH

The UK's strategic QT programme is now driven by the UKRI, with most industrial funding filtering down through Innovate UK projects. Inspired by a US lead and subsequent EC funding, the UK has developed a coherent strategy that is now the envy of the world:

*Simon Plant: "We shouldn't lose sight that there has been a lot of industrial engagement, Innovate UK strongly supports QT by attracting tech developers for systems' integration, and there are a number of agencies working to identify the synergies and where funds can be profitably expended."*

*Paolo Bianco: "So far, our (UK's) supply chain is the most advanced and integrated this side of the solar system. There is still a lot to do, but we are starting from a strong position."*

*Max Perez: "Compared to the US, the level of collaboration in the UK is noteworthy – any change must not be to the detriment of that."*

Our project has already identified an aggregate UK demand for photon sources exceeding £60m pa by 2022.

Nonetheless, we should not be complacent. We must adopt a methodology of scenario planning and other practices (see Appendixes 1 & 2) to maximise demand for quantum-enabled laser sources, as well as fully consolidate the fledgling photon-pair and single-photon markets. In particular, we must adopt a methodology of industrial best practice (see Appendix 3) to fend-off nascent QT competitors – notably China – and keep the UK ahead of the game. Key industrial requirements comprise:

- Co-locating industry within the academic hubs.
- Identifying "killer" QT applications.
- Winning potential mainstream orders, such as from the government, or military.

The full Appendix-3 strategy is encapsulated under 6 broadly-themed requirements:

- Continuing pre-R&D market-study.
- Ongoing QT strategy from the UKRI, Innovate UK, and other funding bodies.
- Encouraging movement of QT from academia to industry.
- Removing barriers to production.
- Creating and following independent standards.
- Increasing customer demand, and incentivising the growth and proliferation of active companies.

# ACKNOWLEDGEMENTS

WITH THANKS TO  
PARTICIPANTS FROM  
THE FOLLOWING  
ORGANISATIONS:





# APPENDIX 1: METHODOLOGY

The project methodology involved 5 different methods of research:

- Primary research questionnaire
- External market driver impact and uncertainty scoring
- Scenario planning workshop
- Modelling and forecasting with sector experts
- Industrial workshop

## PRIMARY RESEARCH

Interviewees were asked the following six questions through structured interviews:

- 1a) What market sectors have already adopted QT-systems driven or enabled by sources of light?
- 1b) What additional market sectors do you expect to adopt such technology within the next 5 years?
- 2 What applications are specific to the Question-1 market sectors?
- 3 Considering the technologies of emitting multiple and single-photons, what photon source types are required for the Question-2 applications?
- 4 What are the key attributes inherent to Question-3's photon sources that will determine the technology's rate of adoption?
- 5 What are the external drivers that will impact the growth of adoption of Question-3's photon sources?
- 6 What will happen to prices for Question-3's photon sources over the next 5 years in the UK?

The questionnaire was completed by 35 experts from industry and academia, liaising with the hubs, academics and business development officers within the UK Quantum Technology Programme as well as leading industrial contacts.


## EXTERNAL MARKET DRIVER SCORING

Respondents were asked to allocate scores for the uncertainty and the impact of each of the 11 key external market drivers that had been identified during the primary research. Scoring was done completed by each of the 21 respondents using an Excel spreadsheet.

Uncertainty was scored on a sliding scale from 0-100, where 100 was highly uncertain. Impact was scored on

a relative basis for each of the 3 different technology groups; respondents were asked to allocate 100 points between the various drivers, where highest points were allocated to drivers with the highest impact.

The scores were averaged and plotted to determine the critical drivers for each of the technologies (drivers with the highest impact and uncertainty).



**Scenario Planning: The future market for UK photon sources**  
**Driver Scoring Exercise**

**QUESTION: Which of the following drivers will have the greatest UNCERTAINTY between now and 2027?**

Consider the level of uncertainty around whether or not the driver will occur. If the uncertainty of whether or not it will occur is high, allocate a high number of points to it. If the uncertainty is low, allocate a low number of points to it.  
**ACTION:** Please now score each driver between 0 and 100 to indicate its uncertainty. Where you think there is low uncertainty, score a low number of points and where there is a high degree of uncertainty score a high number of points.

Driver	Uncertainty
A major breakthrough in quantum development is achieved	20
A killer quantum application is developed	80
Computing becomes powerful enough to crack current security approaches	80
Government significantly changes its funding and support of quantum photon sources (increase or decrease)	80
Other countries accelerate their quantum development	10
Major war/terrorism/hacking events occur	10
Market awareness of quantum photon sources significantly increases	60
Price of associated key components significantly changes (increase or decrease)	60
Quantum legislation or regulation is implemented (either pro or anti)	80
Proof that quantum devices provide a benefit to business e.g. more cost-effective	70
Society develops a pro or anti attitude towards quantum	80
Other (please state)	

**QUESTION: Which of the following drivers will have the greatest IMPACT on the market for each photon source technology group between now and 2027?**

If the driver occurred, how large an impact would it have on the adoption of the photon source technology? Would it cause the development to greatly accelerate, develop in a different direction or stall altogether (high impact)? If the impact is high, allocate a high number of points. If the impact is negligible, allocate a low number of points (or zero).  
**ACTION:** For each of the 3 technology groups, please distribute 100 points over the drivers to indicate their relative IMPACT. You may give any individual driver a score between 0 and 50 but the total for each column must equal 100.  
**TECHNOLOGY GROUPS:** See separate 'Technology Definitions' sheet

**TECHNOLOGY GROUP 1: LASER SOURCES**

Driver	Impact
A major breakthrough in quantum development is achieved	10
A killer quantum application is developed	20
Computing becomes powerful enough to crack current security approaches	20
Government significantly changes its funding and support of quantum photon sources (increase or decrease)	3
Other countries accelerate their quantum development	4
Major war/terrorism/hacking events occur	20
Market awareness of quantum photon sources significantly increases	0
Price of associated key components significantly changes (increase or decrease)	0
Quantum legislation or regulation is implemented (either pro or anti)	0
Proof that quantum devices provide a benefit to business e.g. more cost-effective	8
Society develops a pro or anti attitude towards quantum	0
Other (please state)	
<b>Total</b>	<b>100</b>

**TECHNOLOGY GROUP 2: PHOTON PAIR SOURCES**

Driver	Impact
A major breakthrough in quantum development is achieved	10
A killer quantum application is developed	20
Computing becomes powerful enough to crack current security approaches	20
Government significantly changes its funding and support of quantum photon sources (increase or decrease)	10
Other countries accelerate their quantum development	4
Major war/terrorism/hacking events occur	20
Market awareness of quantum photon sources significantly increases	0
Price of associated key components significantly changes (increase or decrease)	0
Quantum legislation or regulation is implemented (either pro or anti)	0
Proof that quantum devices provide a benefit to business e.g. more cost-effective	8
Society develops a pro or anti attitude towards quantum	0
Other (please state)	
<b>Total</b>	<b>100</b>

**TECHNOLOGY GROUP 3: SINGLE PHOTON EMITTERS**

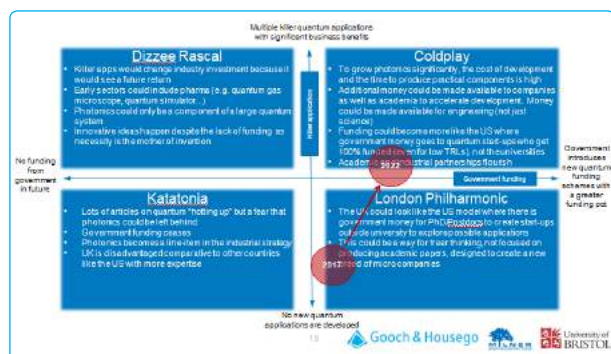
Driver	Impact
A major breakthrough in quantum development is achieved	10
A killer quantum application is developed	20
Computing becomes powerful enough to crack current security approaches	20
Government significantly changes its funding and support of quantum photon sources (increase or decrease)	10
Other countries accelerate their quantum development	4
Major war/terrorism/hacking events occur	20
Market awareness of quantum photon sources significantly increases	0
Price of associated key components significantly changes (increase or decrease)	0
Quantum legislation or regulation is implemented (either pro or anti)	8
Proof that quantum devices provide a benefit to business e.g. more cost-effective	8
Society develops a pro or anti attitude towards quantum	0
Other (please state)	
<b>Total</b>	<b>100</b>

Please return your completed sheet by Monday 13th November 2017

## SCENARIO PLANNING WORKSHOP

A scenario planning workshop was carried out over 2 days with 10 industry and academic participants to explore the different possible futures that would result from the interaction of the critical drivers. This technique means participants think 'outside the box' and consider all of the possible futures that could occur.

The 3 critical drivers for each technology were plotted in pairs and the axis scales were agreed for each driver. The workshop participants were split into 2 syndicates and asked to complete a number of exercises over the course of the workshop. During each exercise, participants were given a chart where 2 of the 3 critical drivers for each technology were plotted against each other. The syndicates had to think through the consequences of the interaction of each of the pairs of drivers (high vs low), for each technology, and write down the characteristics of the scenario. Each scenario on the chart was named and the likely position of the UK in 2017 and in 2022 was plotted.



## MODELLING AND FORECASTING

A market model was built to forecast the most likely future for laser sources, photon-pair sources and single-photon emitters over the next 5 years. For each of the 3

technology groups, the market was forecast for each of 10 individual applications within each of the 10 sectors and aggregated to form a view of the UK market as a whole.

As well as taking into account the opinions of the industry and academic experts at the scenario planning workshop, specific sector experts were consulted on the most likely future for each technology. Market forecasts were devised and tested in collaboration with these experts and their intelligence on the current and near-term future was discussed.

## INDUSTRIAL WORKSHOP

With 34 national leaders of technology transfer and industrialisation, the project held a culminating 1-day industrial workshop whose goals were to disseminate the project's forecasted markets, and to define an overall UK-based strategy for their acceleration. A morning session of presentations saw 8 sector experts identify market opportunities to 2022 for narrowband laser sources, single-photon sources, and photon-pair sources differentiated by market sector and application. The afternoon session imagined the emergence of a nascent QT ecosystem with the delegates splitting into 2 syndicates to discuss the 3 generic topics: mechanisms of technology transfer, ramping-up of production, and infrastructure needed to meet demand. Outputs from the afternoon session are covered in Appendix 3.



## APPENDIX 2: SCENARIO PLANNING OUTPUT

The scenario planning workshop provided the opportunity to explore the key drivers. The interaction of the critical drivers was extensively examined through multiple (27) scenario planning grids with experts from industry and academia to determine the possible alternative scenarios that could develop over the next 5 years and assess the UK events that would cause each scenario to happen. Multiple scenarios were created for each of the three technology types in 2022 and the following sections describes key elements of the scenarios.



*Scenario Planning workshop, London 21st and 22nd November 2017*

## LASER SOURCES

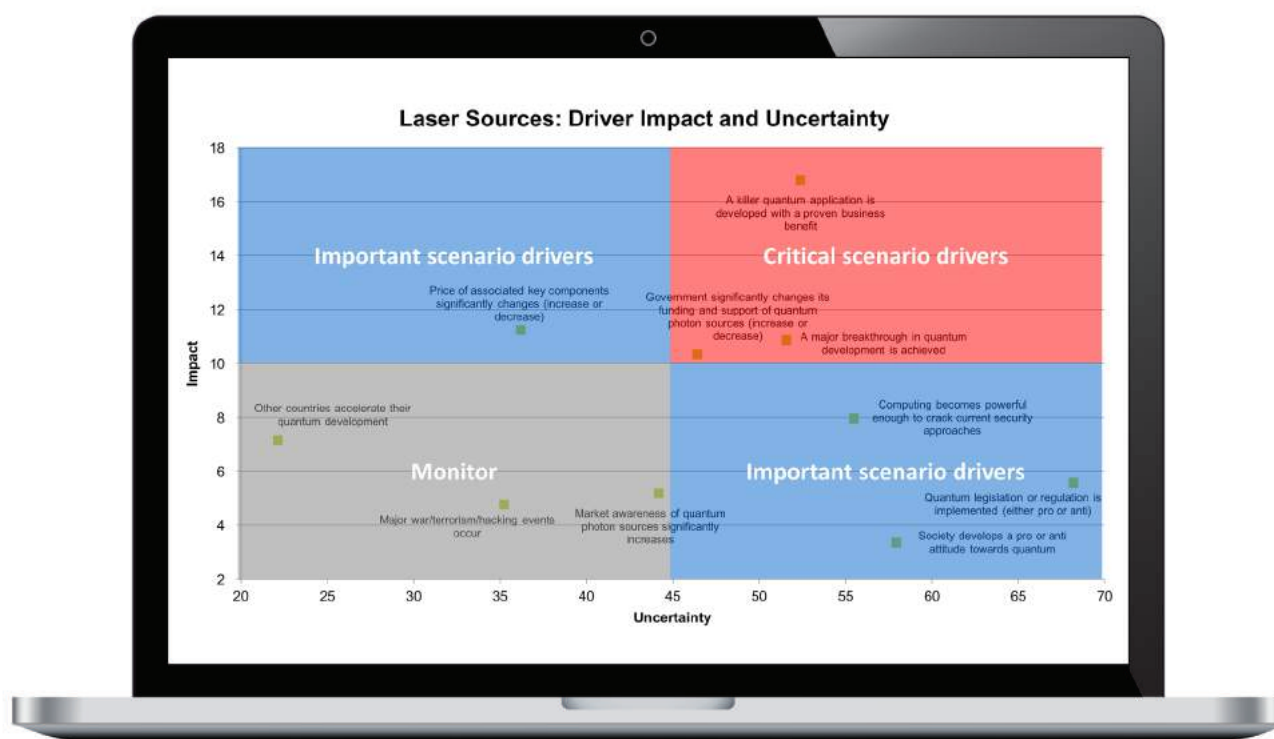
The turning point for the development of laser source technology is the development of applications that have tangible business benefits. This will lead to investment from industry as well as from government and make the technology sustainable in the long run. Industry and academia need to collaborate in order to make this happen. Funding could become more like the US where government money goes to quantum start-ups who get 100% funded (even for low TRLs), not the universities, and this could encourage freer thinking about technology development.

High demand is needed in order to warrant volume from fabrication labs. This is likely to be done in low-cost regions such as China, India or Africa and imported into the UK rather than being fabricated domestically.

If no killer application is found over the next 5 years, there is a real possibility that research and development into quantum photonics could be abandoned. Incremental improvement and refinement could happen, but large-

scale rollout will not occur. Development will focus on making sources smaller and more compact and if new industrial applications are found, companies will quickly develop new manufacturing lines based on technology that already exists.

Government funding encourages a focus on state applications such as military and defence rather than private sector applications. However, it ensures a future pipeline of technology research within academia and encourages more 'openness' of the technology, rather than it being patented and protected by individual businesses to give them a competitive advantage. Technical breakthroughs and practical business applications need to be continually developed in order to justify sustained funding streams. If the UK does not continue funding, there is a danger that other countries such as China will exploit the technology first and there will be a brain drain out of the UK.





## PHOTON-PAIR SOURCES

If current security approaches are cracked, QKD will be the major application. Development of photon-pair sources will be heavily protected due to the defence implications of the technology, and the technology will not be able to be patented. Sophisticated quantum network protocols will be developed. Within QKD, the development of repeaters is essential in order to create a full quantum network. Technical breakthroughs could create fast, low cost, heralded sources for quantum computing; fast, low loss switches; or ultra low power laser diodes.

One scenario that is a real danger to the UK is where current security approaches are cracked, but QKD technology cannot be developed fast enough to protect communications. In this scenario, there will be major world upheaval, a financial crisis and a regression to traditional forms of communication. The best solution to this would be an international agreement not to use quantum to breach each other's security, similar to the Cold War. It is possible that today's communications could be recorded and stored to decrypt in future when security is cracked. Technology development and government funding will focus on 'new hope' post-quantum cryptography or elliptic curve cryptography.

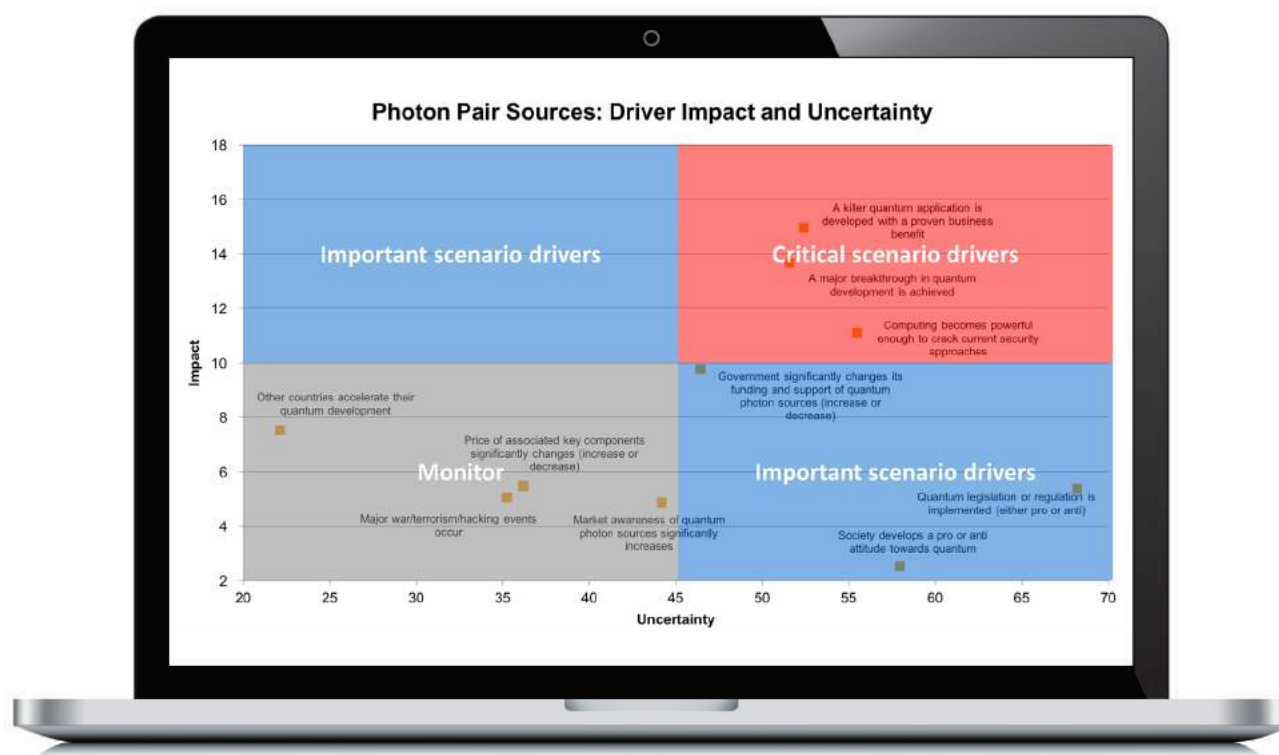
Whether or not current security approaches are cracked will be crucial in the development of photon-pair

sources; if QKD is not necessary, alternative applications will be developed in

- Spectroscopy
- Imaging
- Sensing
- Gas detection
- Quantum computing
- Metrology
- Quantum teleportation
- Fundamental quantum research testing the laws of physics

Similarly, if no business applications are developed and no multiplexor is possible, then sales will continue to be to research institutions as component technologies and development will focus on existing areas such as squeeze and sub-shot noise.

Quantum needs to ensure that public perception remains positive: without applications, quantum could become known as a solution looking for a problem. The QT programme is currently strong in its applications based development approach and this must continue in order to capitalise on the UK's lead in this area.



## SINGLE-PHOTON EMITTERS

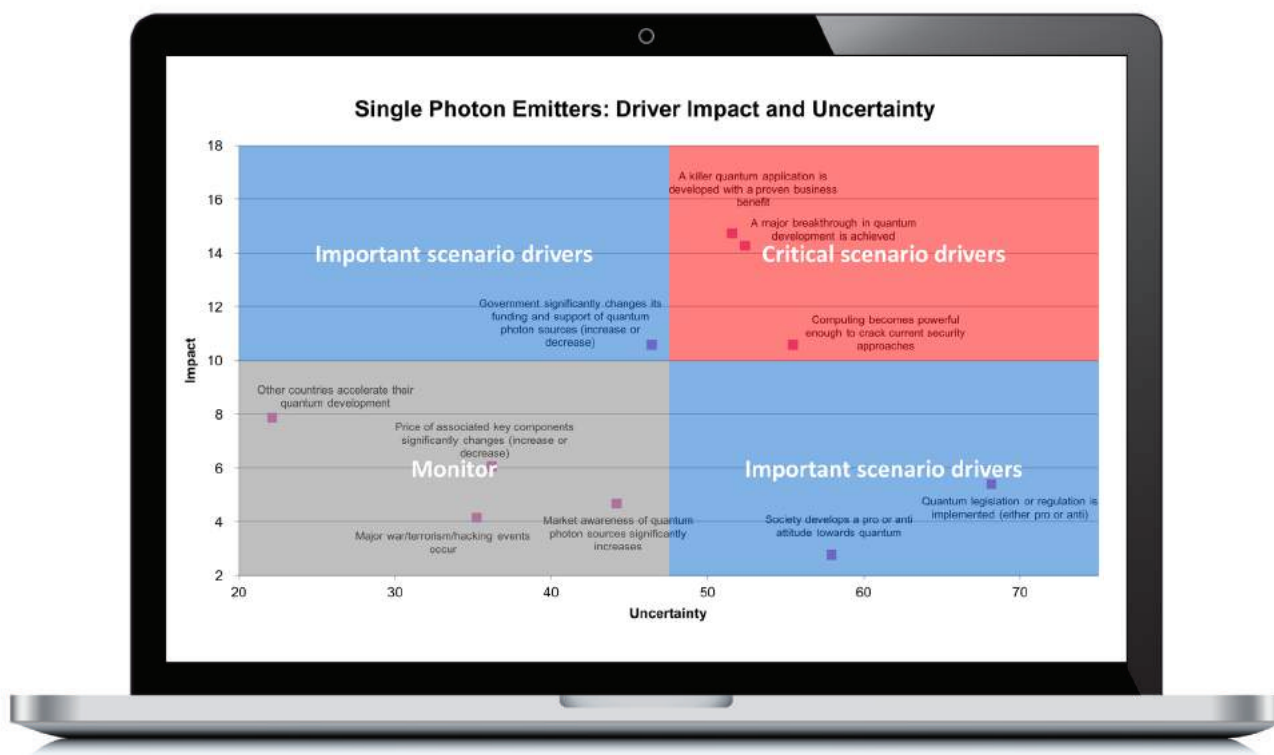
If current security approaches are cracked and single-photon emitter applications can be developed to solve the security problem, then the UK financial market could see increased activity due to its world-class security. Better time-stamping would also benefit the financial markets. The threat to physical infrastructure would be a priority, protecting transport and communications and geopolitical relations will be tense. There could be increased government and commercial transparency as communications could be made public at any time, in a 'Quantum Wikileaks' situation. Imports and exports of single-photon sources would be restricted, and the freedom of academia would be limited. Large companies such as Google and IBM could collaborate in order to solve the pressing security problem.

The major breakthrough that is needed is the ability to mass manufacture identical single sources with low part-to-part variability, leading to a low price per source. In parallel, breakthroughs in single-photon detectors will be needed. This would have a game changing effect for quantum computing, leading to significant growth in quantum fields, acceleration of component markets, increased jobs and upskilling in quantum areas.

If quantum computing is successful then this will lead to various breakthroughs in other industries, such as biomedicine, life sciences, pharma, oil and gas, weather forecasting, simulation of natural disasters, AI for the stock market, self-learning algorithms, and faster trading in financial markets.

As with the photon-pair situation, if current security approaches are cracked but applications cannot be developed to deal with the risk then the UK will have to rely on traditional technology which risks economic consequences. Technologies such as IoT, smart cities and autonomous car adoption will stall.

If the technology does not progress beyond its current state then devices would only be used as a test bed for research, performing basic algorithms and is likely to be a detector rather than a computer. If a value proposition cannot be identified, then single-photon emitters will not be pursued by the UK and knowhow of the ultra-high precision fabrication learnt from "quantum" device research will be used for other technologies/applications.



Across the 3 quantum technology types, the factors shown the figure below were found to be crucial across scenarios:



## APPENDIX 3: INDUSTRIAL WORKSHOP OUTPUT

Pooling of the workshop's syndicate outputs has generated the following strategy for the UK to remove hindrances to commercialisation, and maximise market growth:

*We need a continuing programme of pre-R&D-market-study to:*

- 1 Assess technological maturity; in our case that of various QT light sources and sub-systems.
- 2 Identify commercial opportunity and demand.
- 3 Provide rigorous market assessments.

*We need an ongoing QT strategy from the UKRI, Innovate UK, and other funding bodies that:*

- 1 Provides for flagship activity with large projects and contracts.
- 2 Includes activities across the sectors - not just simply the direct supply chain - that involves, for example, geologists and clinicians etc, as well as the user industries.
- 3 Fosters stronger leading engagement with all stakeholders, including the scientific sector, QT hubs, incubator labs, manufacturers, system integrators, and end-users.
- 4 Maintains adequacy and continuance of QT funding routes.
- 5 Incentivises and supports collaborative programmes.
- 6 Selects projects according to strategic fit, community agreement, and market demand.
- 7 Provides expert review of investment proposals.
- 8 Maximises availability of external talented individuals and fabricating companies.
- 9 Strongly encourages the transfer of technology.
- 10 Sustains the operative framework for our universities, innovation-centres and companies.
- 11 Reaches a critical mass of self-sustaining investment through flexible and responsive funding into Phase 3.

*We need to encourage the movement of QT from academia to industry by:*

- 1 R&D by academics being done jointly with industry when it is about developing engineering solutions that should be taken out to industry.

- 2 Encouraging PhD/postdoctoral sponsorship, and student placements.
- 3 Encouraging QT-Hub fellowships.
- 4 Incentivising company co-location within the QT Hubs.
- 5 Facilitating more pilot trials through industry-led collaborations and innovation centres.

*We need to remove barriers to production by:*

- 1 Industry identifying and laying-out to the funding bodies, what it needs to happen before it invests, which risks need to be overcome, and how big the return of investment is for UK.
- 2 Achieving sufficiency of joint-working between industry and academia.
- 3 Integrating with current infrastructure.
- 4 Increasing the competency and number of product design engineers, within industry, to aid the production of specialist prototypes.
- 5 Improving technical performance relative to the classical contribution, such as in measurement resolution, stability, size, weight, and input power.
- 6 Achieving lowered costs relative to the classical competition.
- 7 Simplifying contractual red-tape in regard to collaboration agreements, IP negotiation, etc.
- 8 Training more people with fundamental laser-engineering skills.
- 9 Maturing the fabrication capability.
- 10 Triggering investments towards for mass production by standardising future applications.
- 11 Gaining trusted suppliers and consolidating the supply chain map.
- 12 Inhibiting 'quantum cowboys' within the nascent QT markets by encouraging serious players, and establishing high reputation, standards, and consumer confidence.
- 13 Deepening the involvement of end-users.
- 14 Encouraging international development and engagement.

*We need to create and follow independent standards, and thus attain the benefits of:*

- 1 Technological compatibility.

- 2 Established test-beds that enable broad-based testing in various applications.
- 3 Device qualification.
- 4 Biomedical compatibility.
- 5 Air-transport compatibility – e.g. for lasers and rubidium sources.
- 6 Safety of disposal.
- 7 Compliance with REACH.

*We need to increase customer demand, and incentivise the growth and proliferation of active companies through:*

- 1 Identification of killer applications.
- 2 Encouraging potential mainstream orders, such as from the government or military.

- 3 Increasing the quantity and capability of technology demonstration.
- 4 Ensuring funding is most efficiently provided.
- 5 Fostering deeper engineering thinking.
- 6 Attainment of improved human skills.
- 7 Improving production capability.
- 8 Raising awareness of QT, both generally, and in terms of the capability of its quantum-enabled photon sources.
- 9 Looking at roadmaps for different sectors and seeing if there are areas where quantum fits and provides a benefit. Then raise the benefits with the end-user industries.



*Industrial workshop, London 13th February 2018*

## APPENDIX 4: TECHNOLOGY GROUPS DEFINITIONS

### LASER SOURCES

- Shot noise-limited, i.e. the photons in the beam exhibit Poisson distribution
- No entanglement
- Coherent beam
- Bright

### PHOTON-PAIR SOURCES

- Sub shot noise, i.e. sub-Poissonian photon counting statistics when measured in correlation (i.e. with two detectors)
- Only 2 photons (1 pair) are generated randomly in time at each trigger event such as down-conversion. Multi-photon events, i.e. multiple pairs, are undesirable
- Can generate entangled pairs of photons
- The output is a 2-mode squeezed state, i.e. the two outputs are highly correlated
- Probabilistic output, i.e. each trigger event such as a pump pulse has a certain chance of generating a pair of photons
- Very low power/photon number output (typically ~femtowatts)
- Triggered optically, i.e. by a laser

### SINGLE-PHOTON EMITTERS

- Sub shot noise
- Solid state, semiconductor
- Emit 1 photon at each trigger event
- Deterministic generation, i.e. every trigger event generates a photon
- Very low power/photon number output
- Can in principle be multiplexed with fast switching to emit lots of photons in lots of modes
- No entanglement by default but multiple emitters (or 1 if temporally) can be used to generate entanglement
- Typically require cryogenic temperatures (<10K)
- Triggered optically or electrically

#	CATEGORIES	SUB-CATEGORIES	EXAMPLES
1	LASER SOURCES	Narrow-linewidth Attenuated/weak/faint OPO Optical frequency combs Pulsed	Q-switched, mode-locked
2	PHOTON-PAIR SOURCES	Atomic cascade SPDC  SFWM	Bulk Periodically poled Waveguide (periodically poled) Gated Multiplexed DSF BSMF PCF SOI waveguide
3	SINGLE-PHOTON EMITTERS	Single molecule Color (vacancy) centres in diamond Quantum dots Single ion in cavity Single atom in cavity Ensemble (Rb, Cs)	DBT Si, N, Cr GaN, CdSe/ZnS, InAs (in cavity)



## APPENDIX 5: SECTORS (SIC 2007 CODES) DEFINITIONS

SECTOR	SIC 2007 CODES
BIOMEDICINE/LIFE SCIENCES	7211 : Research and experimental development on biotechnology
COMPUTING	6201 : Computer programming activities 6202 : Computer consultancy activities 6203 : Computer facilities management activities 6209 : Other information technology and computer service activities 6311 : Data processing; hosting and related activities 6312 : Web portals 6399 : Other information service activities n.e.c.
FINANCE AND BANKING	6411 : Central banking 6419 : Other monetary intermediation 6420 : Activities of holding companies 6430 : Trusts; funds and similar financial entities 6491 : Financial leasing 6492 : Other credit granting 6499 : Other financial service activities; except insurance and pension funding n.e.c. 6511 : Life insurance 6512 : Non-life insurance 6520 : Reinsurance 6530 : Pension funding 6611 : Administration of financial markets 6612 : Security and commodity contracts brokerage 6619 : Other activities auxiliary to financial services; except insurance and pension funding 6621 : Risk and damage evaluation 6622 : Activities of insurance agents and brokers 6629 : Other activities auxiliary to insurance and pension funding 6630 : Fund management activities
GAMBLING/GAMING	9200 : Gambling and betting activities

SECTOR	SIC 2007 CODES
MINING/CIVIL ENGINEERING/ HYDROCARBON EXPLORATION	0510 : Mining of hard coal 0520 : Mining of lignite 0610 : Extraction of crude petroleum 0620 : Extraction of natural gas 0710 : Mining of iron ores 0721 : Mining of uranium and thorium ores 0729 : Mining of other non-ferrous metal ores 0811 : Quarrying of ornamental and building stone; limestone; gypsum; chalk and slate 0812 : Operation of gravel and sand pits; mining of clays and kaolin 0891 : Mining of chemical and fertiliser minerals 0892 : Extraction of peat 0893 : Extraction of salt 0899 : Other mining and quarrying n.e.c. 0910 : Support activities for petroleum and natural gas extraction 0990 : Support activities for other mining and quarrying 4110 : Development of building projects 4120 : Construction of residential and non-residential buildings 4211 : Construction of roads and motorways 4212 : Construction of railways and underground railways 4213 : Construction of bridges and tunnels 4221 : Construction of utility projects for fluids 4222 : Construction of utility projects for electricity and telecommunications 4291 : Construction of water projects 4299 : Construction of other civil engineering projects n.e.c. 7112 : Engineering activities and related technical consultancy
SCIENTIFIC/RESEARCH/UNIVERSITIES	7219 : Other research and experimental development on natural sciences and engineering
SPACE	5122 : Space transport
TELECOMS	6110 : Wired telecommunications activities 6120 : Wireless telecommunications activities 6130 : Satellite telecommunications activities 6190 : Other telecommunications activities
TRANSPORTATION	4910 : Passenger rail transport; interurban 4920 : Freight rail transport 4931 : Urban and suburban passenger land transport 4932 : Taxi operation 4939 : Other passenger land transport n.e.c. 4941 : Freight transport by road 4942 : Removal services 4950 : Transport via pipeline 5010 : Sea and coastal passenger water transport 5020 : Sea and coastal freight water transport 5030 : Inland passenger water transport 5040 : Inland freight water transport 5110 : Passenger air transport 5121 : Freight air transport

The remaining SIC codes were all classified as 'Other' sector.

Separate data was gathered on the number of universities and aggregated with the SIC 2007 code information on scientific/research companies.

As there is no SIC code specific to environmental monitoring, separate data on the number of organisations was gathered from secondary internet research. This includes Defra, the Environment Agency for England and Wales, the Scottish Environment Protection Agency and the Department of the Environment for Northern Ireland.



## APPENDIX 6: APPLICATION DEFINITIONS

APPLICATION	DESCRIPTION	EXAMPLES
CLOCK TECHNOLOGY/TIMING	Atomic clocks that are embedded within networks to provide high-accuracy timing and network synchronisation	Clock technology Network synchronisation Timing
EXTREME TIME-RESOLUTION	Devices using 3D ranging or time-gated imaging which is not affected by aberrations or the line of sight being blocked	Beyond line-of-sight Extreme time-resolution
LIDAR	LIDAR uses pulsed laser light and sensors to measure distances to targets	
MAGNETOMETRY AND GRAVIMETRY	Detecting small changes in gravity or magnetism can be used to map underground landscapes	Detection of subterranean features such as oil reserves and archaeology Environment monitoring Field mapping Fundamental physics using time and gravity in space Gravitational measurement of reference frame. Gravity fields Gravity sensing from space Local gravitational acceleration measurement Seismology Sensing magnetic signatures of ships Sensing of magnetic and electric fields Soil compactness detection with gravimeters for agriculture Surveying for magnetic fields or gravity
MEDICAL IMAGING	Imaging is usually done by taking multiple sensors (or multiple sensor locations) and producing an image (2D, 3D) of the parameter of interest. Medical imaging refers specifically to medical or biosciences applications.	Biomedical imaging Brainwave sensors Heart sensors Imaging low light levels for biosciences
MICROSCOPY, IMAGING AND CALIBRATION	Imaging is usually done by taking multiple sensors (or multiple sensor locations) and producing an image (2D, 3D) of the parameter of interest. Includes devices that measure single-photons and systems that use quantum effects to mitigate limitations in detecting light	Covert surveillance over long distances Extremely low light levels sensing Imaging with single/squeezed/entangled photons Industrial inspection Industrial processes monitoring Microscopy (or other scientific analysis) Photo sensor research Single-photon detector calibration Sub-shot noise measurements - microscopy, research-driven Visible/IR cameras
NAVIGATION	Navigation uses quantum sensors and inertial sensing to replace traditional navigation methods	Inertial sensing Navigation
NON-QKD COMMUNICATIONS	Communications equipment that does not directly incorporate quantum key distribution	Memory, repeaters, synchronisation

APPLICATION	DESCRIPTION	EXAMPLES
QKD/QUANTUM CRYPTOGRAPHY/SECURE COMMUNICATIONS	Quantum key distribution (QKD) uses photons to transmit a secure key which cannot be intercepted without causing detectable errors in the system	<ul style="list-style-type: none"> <li>Amplifiers</li> <li>Data encryption and storage</li> <li>Distributed systems, like secure communications through a satellite, clock reference etc.</li> <li>Ethernet encryption</li> <li>Information/data security</li> <li>Quantum cryptography</li> <li>Quantum key distribution (QKD)</li> <li>Secure communications</li> </ul>
QRNG - QUANTUM RANDOM NUMBER GENERATOR	Devices that exploit the inherent unpredictability of quantum processes to generate random bit sequences	
QUANTUM COMPUTING AND SIMULATION	Quantum computers are devices which use qubits (which can be zero, one or both) to exploit information, and can be applied to compute information faster or to simulate situations	<ul style="list-style-type: none"> <li>Artificial Intelligence</li> <li>Quantum computing</li> <li>Quantum simulators</li> <li>Simulating new drugs</li> </ul>
SENSING	Sensing is detecting values or changes of some parameters, using quantum features like superposition	<ul style="list-style-type: none"> <li>Enhanced distributed sensing</li> <li>Trace gas detection - real-time education (HE)/gas sensing</li> <li>Ultrasensitive sensors in industry and medicine</li> </ul>

