Industry Perspectives on Quantum Technologies

Report produced by: Richard Murray (Innovate UK- UK), Peter Mueller (IBM Zurich Research- CH), Jean Lautier-Gaud (Muquans- FR), Kelly Richdale (IDQuantique- CH), Steve Maddox (e2v- UK), Freeke Heijman (Dutch ministry of economic affairs- NL), Tommaso Calarco (University of Ulm- DE)

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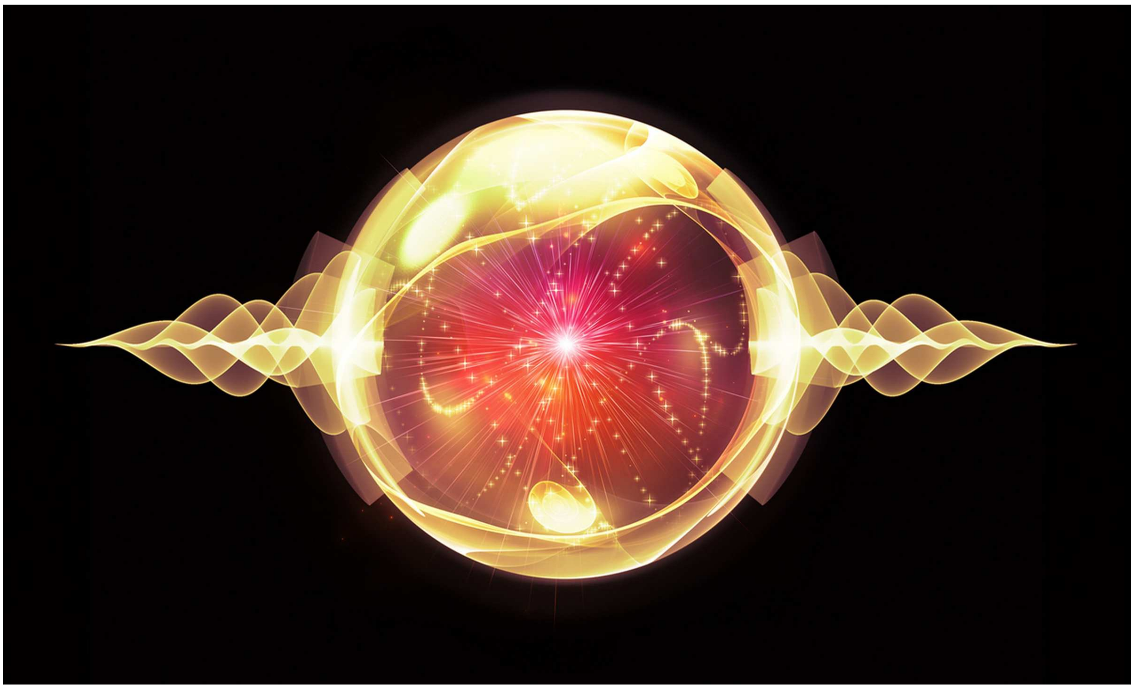

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Executive Summary

Quantum technologies are a new generation of optical and electronic devices that use quantum effects to significantly enhance the performance over that of existing, 'classical' technologies. There is mounting evidence that many of these quantum technologies are ready to transition into commercial products, with a significant opportunity for new businesses and job creation across the whole of Europe. This will strengthen the future position of European industries for many decades to come, in areas as diverse as: ICT finance, communication, health, space, construction consumer.

European scientists already have a worldwide reputation for work in quantum science. In order to translate this advantage into an economic reward European companies must be incentivised to develop, integrate and sell quantum technologies as products and services that will serve real-world, commercial problems.

This paper seeks to understand the current level of company interest in quantum technologies, and what is stopping companies from expressing a greater level of involvement. Secondly, it presents recommendations for action that will generate more industry traction from quantum technologies in the future.

To achieve this, the authors conducted a survey of company opinions with respect to quantum technologies. An analysis of the survey leads to six recommendations for the European commission and other national agencies.

1. **Public funding for technology development projects within companies**
2. **Stimulate European-wide co-working and networking**
3. **Coherent support to push technologies through all stages of development, from blue skies academic research to funding for supply chain and late stage product development.**
4. **Initiate early adopter programs within the public sector**
5. **Promote market-finding activities**
6. **Create an industry leadership group**

These recommendations are expected to accelerate the translation of science to real products that will create business growth. They will lead to a new, lucrative industry for Europe, creating a long-term economic return for the taxpayer.

Introduction – Why Quantum Technologies?

More than 100 years ago, a revolution occurred when mainly European scientists developed the foundations of quantum physics. These foundations have been used to underpin numerous scientific and technological advances such as the laser, and the transistor. We are now in the midst of a second 'quantum revolution' (Jonathan P. Dowling, 2003), where the rules of quantum physics are exploited to deliver devices with superior performance and revolutionary capabilities (see chapter What are the Opportunities for Quantum Technologies). In many instances, this transition to quantum devices is inevitable- such as electronic devices, which will naturally become quantum as they are miniaturized over the next decade.

These second revolution quantum devices are commonly known as 'Quantum Technologies' which are a new generation of solid state, electronic, optical and atomic devices with functionalities that are simply not possible using conventional techniques.

The academic networks within Europe are prepared for this upcoming era and European quantum technologies oriented scientists have an outstanding scientific output and worldwide reputation. In order to turn this leading position in research into business growth it is imperative that European companies become active in developing, integrating and selling quantum technologies as products and services that will serve real-world, commercial problems.

For the small numbers of companies who are already selling products based on quantum technologies (see chapter Existing Quantum Technology Markets), there is an opportunity to grow the market for these devices from sophisticated, niche markets into more mainstream markets, with higher volumes and greater profits.

The purpose of this document is to present an industry perspective of quantum technologies. This paper summarises the perceived development challenges and market opportunities, and gives suggestions for public sector actions which will help to overcome these challenges.

These initiatives will help to create a worldwide wave of quantum technology based applications that will create multiple, high-value business opportunities, as we saw when the transistor was invented.

What are the Opportunities for Quantum Technologies?

There is a significant opportunity to exploit the excellent science occurring in European academic laboratories, bring it to a professional engineering environment and to transition early scientific demonstrators of these devices into commercial products.

A detailed description of quantum technologies can be found within the QIPC report (Qurope, 2015). A simplified list of the opportunities for quantum technologies is shown below:

Quantum Sensing and Measurement Systems

Such systems use quantum effects to precisely measure properties of the environment, such as frequency, acceleration, rotation rates, electromagnetic fields, temperature.

- *Near-term technologies:* atomic clocks, quantum gravity sensors, magnetic sensors
- *Mid/Long-term technologies:* quantum magnetometer / electrometers, quantum gyros.
- *Markets:* natural resources exploitation and civil engineering, indoor positioning, sensors for healthcare (such as brain imaging and Magneto encephalography (MEG)), telecommunications, security and defence, time stamping applications, synchronization, underground resource exploitation and monitoring, infrastructure monitoring, precise positioning.

Quantum Metrology

These are systems which use quantum effects to allow for local, verifiable, reliable and robust calibration and measurement of the SI standard unit.

- *Near-term technologies:* atomic clocks.
- *Mid/long-term technologies:* higher precision quantum clocks, quantum-standardised SI units (e.g. Ampere, Candela).
- *Markets:* quality and safety control in industry (production, assembly lines…), time certification (commercial and financial transactions), and portable standard tests.

Quantum imaging systems

These devices use quantum effects to offer improved technical or fundamental noise and sensitivity limitations over classical imaging devices or techniques.

- *Near-term technologies:* NMR imaging, scanning tunnelling microscope

- *Mid/long-term technologies:* quantum-secured imaging, in-vivo cellular and neural imaging, single photon imaging.
- *Markets:* healthcare, biotechnology, infrastructure monitoring, security and defence.

Quantum Information and Computation

Computing architectures which use data held in quantum states. Allowing significantly faster and better problem solving, for certain types of computing problems.

- *Near-term technologies*: special-purpose quantum computers, non-classical algorithms, post-quantum algorithms.
- *Mid/Long-term technologies*: universal quantum computer, quantum memories.
- *Markets*: IT and computer industry, Big Data, telecommunications, defence and security, real-time weather forecast, cognitive computing and control systems.

Quantum Communications

Such communication systems use quantum effects to securely transmit classical data, or transmit quantum data.

- *Near term technologies*: quantum random number generators (QRNG) for secure key or token generation, point-to-point quantum key distribution (QKD) for secure key exchange in crypto systems.
- *Mid/long-term technologies*: quantum key distribution (QKD) global networks, quantum memories and repeaters, the quantum Internet.
- *Markets*: telecommunications, online gaming (QRNG), security and defence, high-quality entropy (randomness) for crypto functions & other online industries, quantum-secured commercial transactions, user authentication and ATM withdrawals.

Quantum Simulation

Quantum simulators are quantum systems, which for example simulate the performance of chemical or physical objects (materials) which are too complicated (or impossible) or too costly to study otherwise, thereby improving physical properties of existing materials or providing new materials.

- *Near-term technologies:* early studies of lattice materials, ultra-cold atoms, superconducting Qubits.
- *Mid/long-term technologies:* devices for direct simulation of superconductivity, complex (bio-) chemical reactions, advanced photonics, metamaterials, improved batteries.
- *Markets:* materials, pharmaceuticals, biotechnology, and energy efficient materials.

Quantum Enabling Technologies

Devices which are fundamental components to the construction of a quantum technologies system; these may have spin-off applications.

- *Near-term technologies*: cryogenic systems, stabilised laser systems, optical frequency combs, single photon source detectors, materials (e.g. semiconductors, superconducting junctions), high frequency electronics, device processing technologies and quantum algorithms, protocols and software.
- *Mid/long-term technologies*: on-chip cold atom devices, qubits and quantum information storage devices.
- *Markets*: There are many opportunities for companies to sell quantum components and sub-systems at first to the academic market, and then to the growing quantum industry. In addition, there are multiple spin off markets for cutting edge photonic and electronic devices.

The future market for these technologies is significant and far reaching: estimated at $1,150M in 2020 for quantum communications systems, growing at a 20.6% CAGR in 2015-2020, and $850M in 2020 for quantum computing systems, growing at a 30% CAGR in 2015-2020. (Market research media ltd, 2014)

Existing Quantum Technology Markets

There is a significant market today for the enabling technologies that comprise a quantum technology system such as vacuum cells, lasers, optics, cryogenic and semiconductor systems, and high specification software and electronics. The initial market for these devices is to the scientific and research community.

In addition, systems and devices that rely on quantum technology are already beginning to gain commercial traction in some specific markets. For example, Quantum Random Number Generators (QRNG) are already in commercial use with Loterie Romande (one of the biggest lottery operators in Switzerland), and Quantum Key Distribution (QKD) has been used by the canton of Geneva in Switzerland since 2007 to secure the transmission of their election results.

Commercial quantum gravity meters have already been provided to support hydrology survey and management in France. New generation atomic clocks have been chosen by European and French space agencies to prepare the next stage of the Global Navigation Satellite System.

Quantum technology based products are expected to be used first in small-volume applications which can bear higher unit costs. As technology develops further and manufacturing techniques are enhanced quantum technology devices will become miniaturized, cost-reduced and mass-producible. This will open up multiple new market opportunities and quantum devices will begin to be embedded in consumer devices such as mobile phones and cars.

Quantum Technologies in Europe

Over the last 15 years, the EC has invested more than €350 million in research on quantum technologies and quantum information (Omar, 2015). In addition there have been substantial investments made by individual member states: over the last 2 years, the UK, with a £270 million national quantum technologies programme and the Netherlands, with a €135 million Qutech investment have established large national programs for the translation of science into technologies and are seen as key milestones in the growth of a quantum technologies industry.
The sum of this investment means that European countries together are investing more funding into quantum technology science and research than any other country, according to publicly disclosed investments. More than 1/3 of quantum specialists are located at European universities and governmental laboratories. They published the most papers over the last decade and created the second highest number of patents worldwide (MEZ, 2015).

Europe also has a growing number of very innovative, small, medium and large sized companies working in areas that will form future supply chains for quantum technologies. These include:

- components manufacturers- such as Toptica (DE) in Laser technologies, and e2v (UK) in vacuum electronics and photonics
- manufacturers of quantum devices- such as IDQuantique (CH) selling quantum random number generators and quantum key distribution systems, and Muquans (Fr) selling quantum gravity sensing devices and atomic clocks.
- multinational enterprises- such as IBM (CH), Toshiba (UK) and Bosch (DE) who are interested in developing systems based on quantum technologies
  'end users'- such as Airbus and Alcatel-Lucent who are interested buying solutions, but who may not necessarily be interested in the underlying technology.

There is strong competition with other nations, outside of Europe and in comparison, funding of high-tech-SMEs within Europe is often challenging. Much of this is driven by a risk averse culture where innovation is seen often as a source of risk rather than an opportunity. This causes a high reticence by companies, venture capitalists and other sources of private equity to fund projects if they cannot see a real demonstration of the project to fund. For contrast, there is much anecdotal evidence of large USA companies supporting high-risk innovation, where in Europe it would be seen as too risky.

Public funding and coordination for innovation can help to convince businesses and private equity to invest. Programmes such as the Future Emerging Technologies (FET) to are useful to fight this trend. Within FET, 'Open' and 'Proactive' are useful sources of funds for academic research of early stage technologies, and the Key Enabling Technologies (KET)- such as the Photonics21 initiative are useful for later stage technologies. However, a consistent and coherent set of mechanisms must be available to support quantum technologies throughout their development. This funding model must bridge the funding gap from early stage research, covered by FET programmes, through to a more established technology which is covered by KET programmes. These support mechanisms should provide applicants with a reasonable chance of winning funding so that they are seen as a worthwhile investment of the time and resources that are required to submit an application.

Europe also does not have large-scale public procurement processes, such as the USA SBRI or DARPA models, which have been shown to be highly effective at bringing strategically important technologies to market. For example: DARPA sponsored the development of the chip scale atomic clock (CSAC) (Lutwak, 2011), which is now a world leading timing solution, used around the world in many commercial applications.

Global activities in Quantum Technologies

Worldwide interest in quantum technologies is increasing rapidly. Public scientific activity has grown over the last decade, measured by the number of authors publishing scientific papers. Europe still has the largest public research body in the world working on the topic, even compared to North America and Asia.

However, when looking at industrial and public funding, some challenges are foreseeable. Especially in the field of quantum computation, where big investments are needed to exploit the results of the science, the investments are growing fast in the US, with big projects of Google, IBM, Microsoft and Lockheed Martin. Also public agencies like NSA, NASA and DARPA/IARPA are investing for strategic reasons. In China, Japan and South Korea, quantum communication is high on the agenda, for example China is planning to launch a satellite for a quantum key distribution link in 2016.

Looking to industry co-authorships, Japan shows an efficient model of national research hub infrastructure, such as the Advanced Institutes, Riken and others, who perform close collaborations with industry. The USA has created an efficient strategy for producing patent publications, funding research calls that are also open to industry.

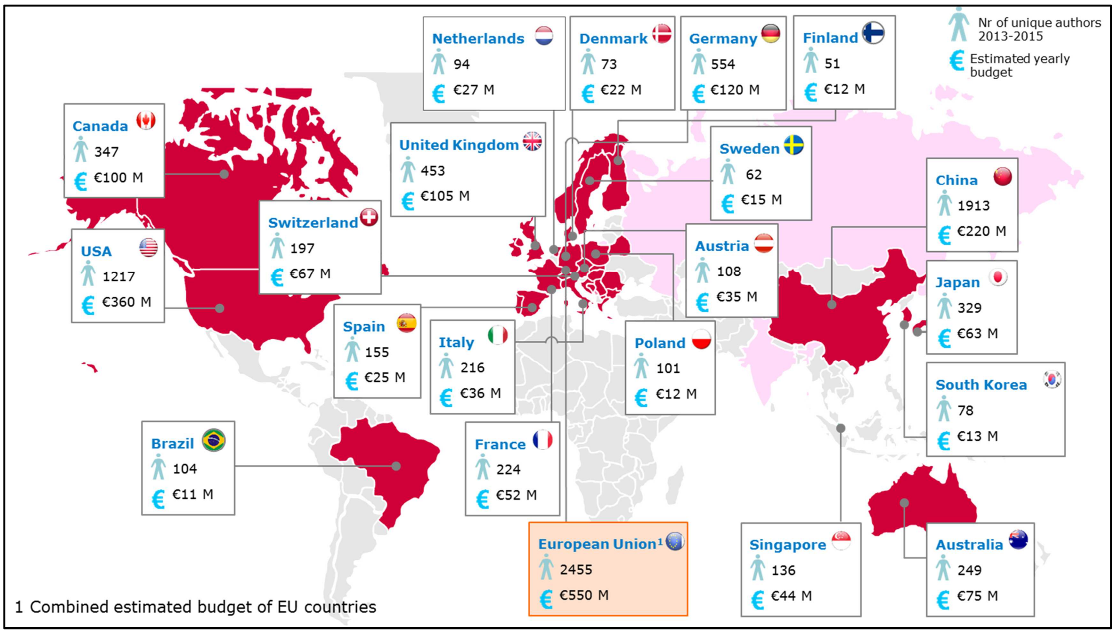

Figure 1 Global investments: Global investments and full time employees in quantum technologies in 2015. The sum of this effort is approximately 7000 researchers with a yearly budget of 1.5 Billion Euros **(MEZ, 2015)**.

What is the Current Level of Industry Interest for Quantum Technologies?

Quantum Technologies survey: understanding industry perspectives
In order to understand more about industry attitudes, a survey was conducted. In total 110 companies were contacted who were known to have some interest in quantum technologies, and 25 responses were received. ll of the companies who replied stated that they had some interest in quantum technologies. The questionnaire consisted of 15 questions, the results from which have been used along with other sources to reference this paper. In multiple choice questions, companies were permitted to vote for more than one answer.

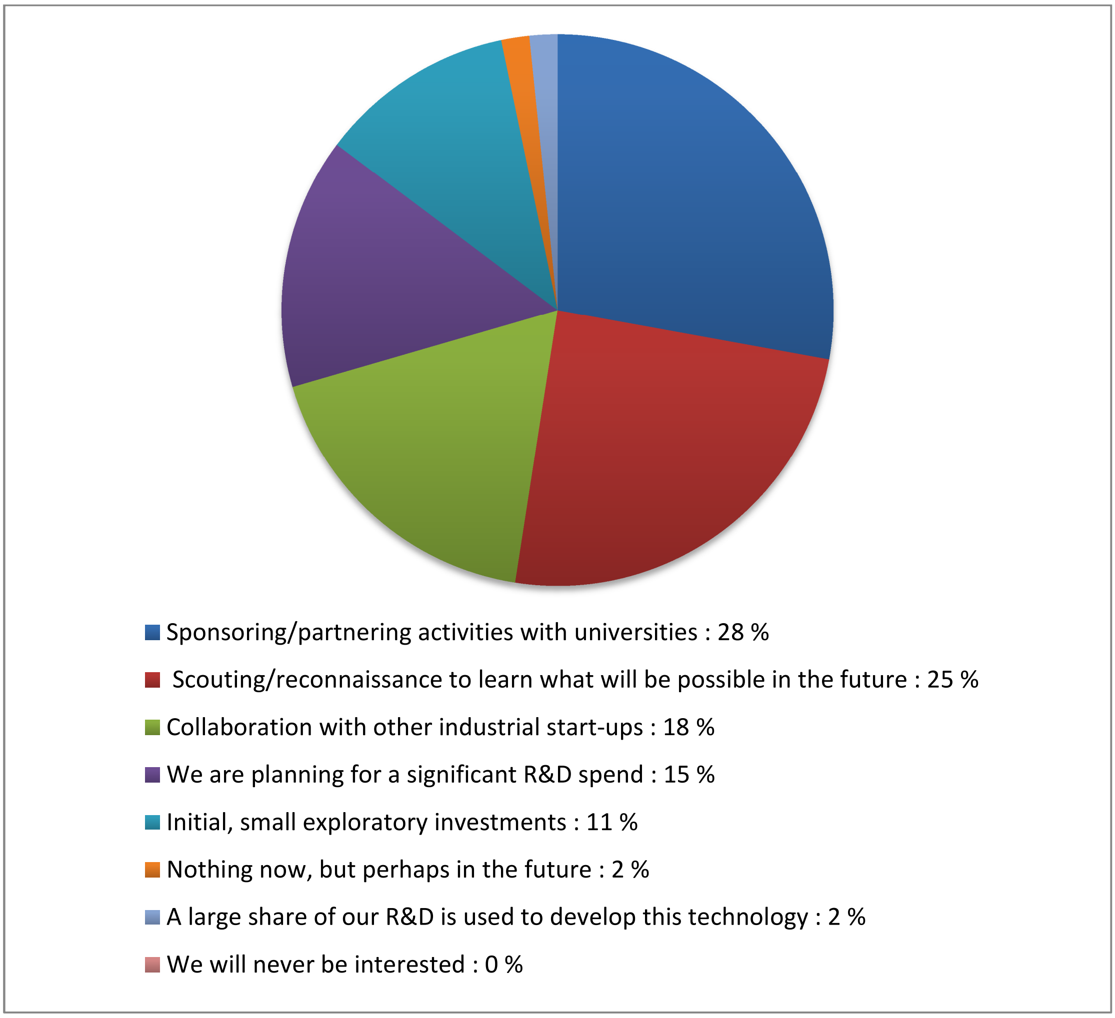

Figure 2 Industrial activities: 'What is your current interest/activity in quantum technologies?'

Many companies in the survey responded to say that ‘quantum enabling technologies’, such as components that can be sold to the scientific market, were very relevant to their business. For example IDQuantique produce revenue from the sale of single photon detectors and quantum random number generators which fuel the development of later stage quantum secure networks.

There are a small number of large companies that have the size and the capacity to undertake development projects on quantum technology which may have a very long development time, but which may have a large impact on future revenues. Today it is mostly American traditional ICT companies that have started to invest in quantum computers. Google, IBM, Lockheed Martin, Toshiba, Microsoft all have considerable R&D efforts to develop quantum computation systems. Recently Intel announced a $50 million investment in the Delft QuTech centre for the development of quantum chips.

This is because companies are only interested in undertaking work that leads to commercial, profitable opportunities within a very short time. Companies need a compelling case to invest, such as a short-term product that can quickly return revenue or a long-term product with the potential for a huge payback of investment.

Question: What relevance does your company see for the following technologies?

	Within 5 years				Within 10 years			
	Not Relevant	*Relevant (small percentage of the business or strategically important)*	*Medium Relevance (25-50% of business)*	*Very Relevant (core of the business)*	*Not Relevant*	*Relevant (small percentage of the business or strategically important)*	*Medium Relevance (25-50% of business)*	*Very Relevant (core of the business)*
Quantum enabling technologies:	4	9	1	7	1	6	4	6
Quantum sensor and timing::	7	13	1	2	0	7	3	5
Quantum metrology:	11	8	2	1	4	6	3	1
Quantum imaging:	9	10	0	2	2	9	4	0
Quantum communications systems:	3	13	1	3	0	8	4	4
Quantum computing systems:	9	10	0	1	3	6	6	1
Quantum simulation:	10	5	1	1	4	7	4	1

Figure 3 The relevance of quantum technologies: ‘How would you rate the relevance of the quantum technologies identified below to your organization within 5 years (left) and within 10 years (right)’? In this graph, red boxes indicate a large number of votes; green, a small number. Conclusion: companies are interested in many different types of quantum technologies, with most technologies having some relevance within 5 years, growing to medium or high relevance over 10 years.

Question: What size market does your company see for devices with the following characteristics?

	Within 5 years				Within 10 years			
	Niche Markets	*Multiple Niche Markets*	*General/ Consumer Use*	*Other*	*Niche Markets*	*Multiple Niche Markets*	*General/ Consumer Use*	*Other*
Sensing devices able to measure very small changes in the environment (e.g density anomalies underground)	9	6	1	0	3	8	5	0
Indoor or underwater position and navigation devices which do not need connection to a GPS satellite.	8	8	2	0	0	7	7	0
Portable devices offering a certified, traceable and secured measurements (e.g. timing reference)	9	6	1	0	1	8	5	0
Imaging systems, which can image delicate samples without damaging them	10	6	1	0	2	10	4	0
Computing systems which are capable of optimising large data sets	6	7	3	1	3	7	7	0
Communications channels which can be proven to be free from interception and eavesdropping	8	10	4	0	1	7	10	0
Computing systems which could model the performance of complex objects, such as materials, pharmaceuticals	7	6	2	0	3	8	7	0

Figure 4 Expected application areas: 'Indicate whether your company would see a market for devices with the following characteristics within 5 years (left) within 10 years (right)'. In this graph, red boxes indicate a large number of votes; green, a small number. Conclusion: companies thought that most applications for quantum technologies would serve niche or multiple niche markets within 5 years, growing to multiple niche markets, or general/consumer markets within 10 years.

A significant number of respondents had or were planning significant activities in quantum technologies: 15% of respondents were planning a significant R&D spend, 18% were involved in collaboration with industry start-ups and 28% were working with universities. 25% were performing scouting/reconnaissance to learn more about the technologies.

Question: What are the current foreseen roadblocks to a future quantum technologies industry?

For companies to have an interest in this new field, it is important that they are able to provide the evidence to show that there is a business case for a return on investment within a relatively short time frame, typically less than 3-5 years. Companies must be able to demonstrate that there are short-term commercial opportunities at sufficiently low risk, offset against opportunities for return on investment.

However, this return on investment may be complex, and difficult to predict. The survey asked companies to vote for what they believed to be the most significant barriers.

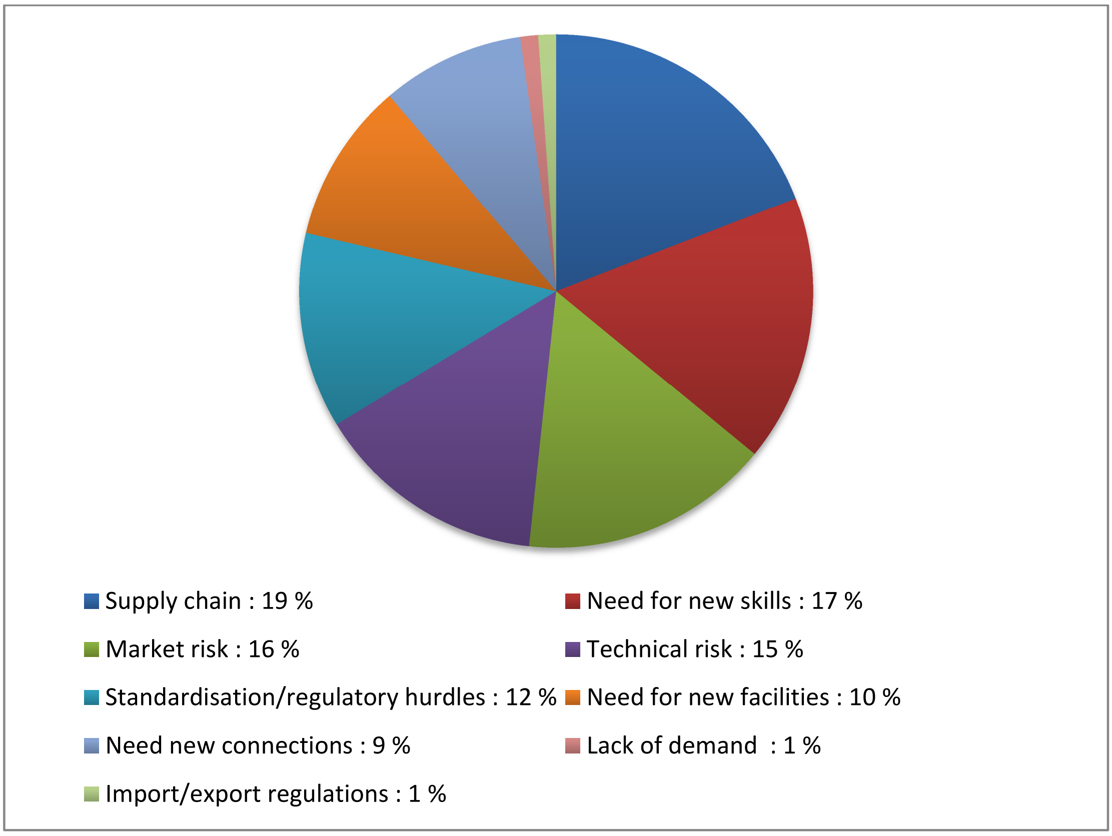

Figure 5 Barriers identified by industry: Answers to the question: What are the current barriers to commercialising or using quantum technologies within your company?

The largest barrier to the commercialisation of quantum technologies was perceived to be that the supply chain needs more development (19% of votes). This represents the view stronger links are needed between companies in the supply chain, including components suppliers.

The second greatest barrier was that new skills and expertise and understanding were needed (17%) due to the limited availability of trained engineers and technicians, who can work with the complex quantum systems.

Third greatest barrier (16%) was that the market risk was too great. When asked about the perceived value of quantum technologies for end customers, most respondents noted "*most people simply do now know what possibilities there are. However as media, news and big corporations are increasingly working in it, public demand will increase exponentially*" or "*There is lack of understanding of what benefits [quantum technologies] will offer*".

Respondents also noted that there was a need for technical challenges to be overcome, and that standardisation was needed.

This points to a circular argument – end customers can only begin to find solutions and applications to real problems when they have a evidence and understanding of the performance and limitations of a technology, while technology providers can only work towards a relevant technology once they are aware of the solution and application. This is an area where the EU could bring value to incentivize the development of quantum technologies to industry leaders, as well as promoting more engineering and applications around quantum technologies. "*Currently quantum technology in Europe is largely driven by academics, we need to shift the centre of activity to the end users and the industrial supply base. However the technical risk is high, so EU support is needed to drive commercialisation of a few key strategic areas*" (Industry Perspectives on Quantum Technologies Consultation questionnaire, 2015).

It was also noted that there is a lack of awareness within key market players, and that import/export regulations may present some barriers.

Question: How can local, national and European support be used to overcome these roadblocks?

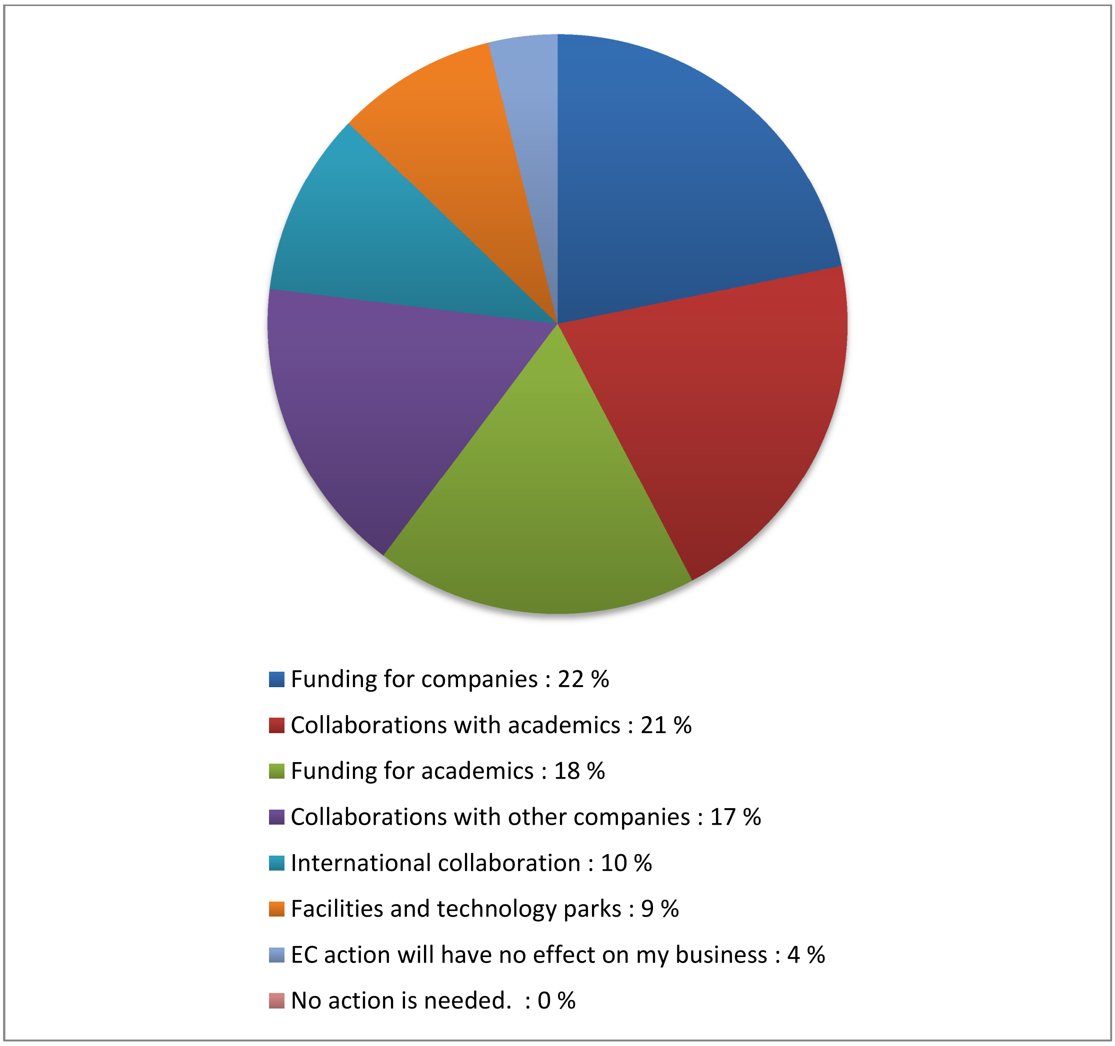

Figure 6 Actions for industry: Answers to the question: 'What actions should the European Commission take to help your company to achieve its ambitions in quantum technologies?'

When asked in the questionnaire *“What actions should the European Commission take to help your company to achieve its ambitions in quantum technologies?”* the most common answer was that funding is needed to undertake projects in companies (22% of votes). This shows that there is readiness to take on development projects within companies, and that some companies believe that the timing is right to start development projects to understand the opportunities or develop their own product or service. Companies stated that this funding would be useful to undertake marketing studies “*to understand immature but rapidly developing markets.”* or to spend on R&D activities, or for exploratory research.

The second most popular answer was that companies need funding to undertake collaborations with academics (21%) and that funding was needed for academics (18%), showing that knowledge exchange, and continuation of research within universities was important. A number of companies believed that funding was needed for collaborations with other companies (17%).

Some number of companies believed that international collaboration was needed (10%), or that facilities and technology parks were needed (9%).

Conclusions and Recommendations

Based on the result of the review, we recommend the following actions to accelerate the industrialization and commercialization of quantum technologies within Europe:

1. Fund technology development projects within companies

Support, such as funding should be made available to address the scientific, engineering and manufacturing challenges of bringing quantum technologies to the point of commercial products. Many of the required skills reside in companies and therefore funding must be made available for projects which are led by companies, performed within companies and in collaboration with the academia. The projects should be looking to deliver tangible and functional outputs such as working demonstrator units. Projects should support patent applications, allow for testing, validation and, if necessary, standardization tasks.

This action will create substantial interest within companies, and deliver devices that have been engineered for use and manufactured within a commercial environment. This will drive higher volume production, reduced costs and stimulate the growth of new markets.

2. Stimulate European-wide co-working and networking

The knowledge needed to bring quantum technologies to market is currently spread amongst many unconnected groups. A European-wide mechanism must be created to foster better links between these individuals: bringing academic groups in contact with companies, putting large companies in contact with small companies, and linking the future supply chain. It must also include other sectors, such individuals from private equity and standardisation.

This action will lead effective knowledge exchange between relevant people, to provide information to the people who might need it to support commercialisation efforts.

3. Coherent support for development of technologies at all stages of maturity, from blue skies academic research to funding for supply chain and late stage product development

There is a tremendous intellectual strength within European academia that should continue to be supported. Efforts should be made to make this network more accessible to newcomers, and to provide points of contacts for companies looking to foster relationships, to work and collaborate in the field.

This action will seed the creation of long-lasting and meaningful relationships that will enable greater knowledge exchange between academics and companies. The task will also address the education of engineers and the general public.

4. Initiate early adopter programs within the public sector

Support must be made available to link up procurement by public organisations, such as the European Space Agency, European Research Infrastructure, defence and other government departments to act as early adopters which may purchase and start to use the new technology.

This task will create a demand for quantum technologies that will incentivise companies to explore specific development programmes for a well-defined end market.

5. Promote market finding activities

Support should be available to enable companies to identify and clarify markets for quantum technologies by supporting non-technical projects that look to understand the potential benefits, relative to alternative solutions and in real world environments. This will bring a greater understanding and appreciation of the opportunities that quantum technologies may create to the companies that will actually, buy, sell or use them.

This task will clarify the market, use and business cases for quantum technologies, thereby developing them into a solution. This will allow companies to develop stronger product lines, with greater revenue.

6. Create an industry leadership group

An industry leadership group must be created who will represent the views of industry in this emerging sector, and provide direction to other individuals and organisations seeking to deliver commercialised products or strategies for commercialisation. In the first instance, this group will consist of the writing group for this document (disclosed on the front cover), who will be available for immediate consultation.

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