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THE IMPACT OF QUANTUM TECHNOLOGIES ON THE EU'S FUTURE POLICIES

Part 3 Perspectives for Quantum Computing

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Title The Impact of Quantum Technologies on the EU's Future Policies: Part 3 Perspectives for Quantum Computing

Abstract

This report describes a survey of opinions in relevant technology communities regarding the best options for research and development of quantum computing, the likely impact on various sectors, and the expected timescales. The survey is intended to contribute to the preparatory discussions for the quantum technology Future and Emerging Technology (FET) Flagship, planned for 2020-30. The overall view of the participants on the technological perspectives for quantum computing is positive and it is seen as likely to be benign.

Table of contents

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Executive summary

This report details a policy foresight study of the emerging field of quantum computing, based on an online survey of the expert community. Altogether, 131 people participated in the survey, out of which over 100 rated themselves as having "Very High" or "High" level of expertise in the field of quantum computing.

The study is intended to contribute to preparations for the planned Quantum Technology Future and Emerging Technology (FET) flagship, planned for 2020-30, within which Quantum computing has been proposed as a domain. It is also intended to inform other policy areas which could be affected.

Quantum computing is an emerging new and radically different information technology. Its advocates foresee it as a future large industry, with a potential impact of a similar scale to conventional IT and of key importance for European Union policy for the digital single market and for industry and growth. Sceptics counter that a host of scientific and technological questions remain unresolved, and that quantum computing will only be of importance in the very long term or never.

This study sought to gather stakeholder opinion in relevant technology communities, in order to improve understanding regarding the best options for research and development of quantum computing, the likely impact on various sectors and the expected timescales. Most of the people who chose to respond to our invitation are working directly in the field, members of a scientific community which believes in the value of its work and is eager to express its enthusiasm for its subject, and how and why it should be supported. Although they do have an interest in promoting the technology, such experts are the only people who are sufficiently knowledgeable to have well-justified opinions.

This is part 3 of the report of a wider study of quantum technology. Part 1 concerns quantum technology for time and part 2, quantum communications.

Key conclusions

The overall view of the participants on the technological perspectives for quantum computing is positive. There is also a strong consensus that social and economic effects of quantum computing are likely to be benign, with benefits outweighing risks. There is concern that Europe might fall behind international competition in the field. These views support the plan for quantum computing to be one of the domains within the FET flagship.

The view of the respondents is that it is premature to push quantum computing towards the product development phase, since it is still unclear which approaches show the most promise. Quantum computation and, to a lesser extent, quantum simulation, differ in this respect from the other domains: quantum communication and quantum sensors and metrology. Novel paradigms for quantum computing are expected to emerge from basic research.

The clear preference among the respondents for an investment in quantum computing at the basic research and lower technology-readiness levels is in contradiction with the aim of the flagship, which is a focused development effort, aimed at more rapid application.

Main findings

The degree of promise of the applications of quantum computing was as follows: quantum simulation and chemistry; materials science and optimization (very promising); database search, cryptanalysis, machine learning and pattern recognition (rather promising); cloud safety, aerospace, fluid dynamics and economics and finance (somewhat promising); exoplanetary research, smart city simulation and software validation (less promising).

Despite the belief that quantum computing could compromise existing cryptographic systems on this time scale, there was a strong consensus among respondents that quantum computing is likely to be both beneficial and safe, with only light regulation needed. The most benefit is seen for basic knowledge and applied science, with benefits also for health, security, education and training.

Remarkably, a majority thought quantum computing likely to have an economic impact in future as great as, or even greater than, conventional IT has had. On the other hand, there was also a majority for the idea that quantum computing would, in future, be only one among a number of coexisting computational methods of similar importance. Some thought it likely to lead to concentration of the sector, but more disagreed.

Quantum computing is not seen as a job-destroying technology; the main effect on employment will likely be creating new jobs. There is optimism about the possibility of a new generation of quantum programmers arising.

The majority view is that quantum computing will be feasible for certain applications in 10-15 years and, even for the ambitious application, breaking current cryptographic protocols, in less than 20 years. Notably, as shown in Figure 1, there was a clear correlation between the expected timeframes and the deemed impact of the applications.

Synergies are perceived with nanotechnology, electronics material science and engineering and, to a lesser extent, chemistry.

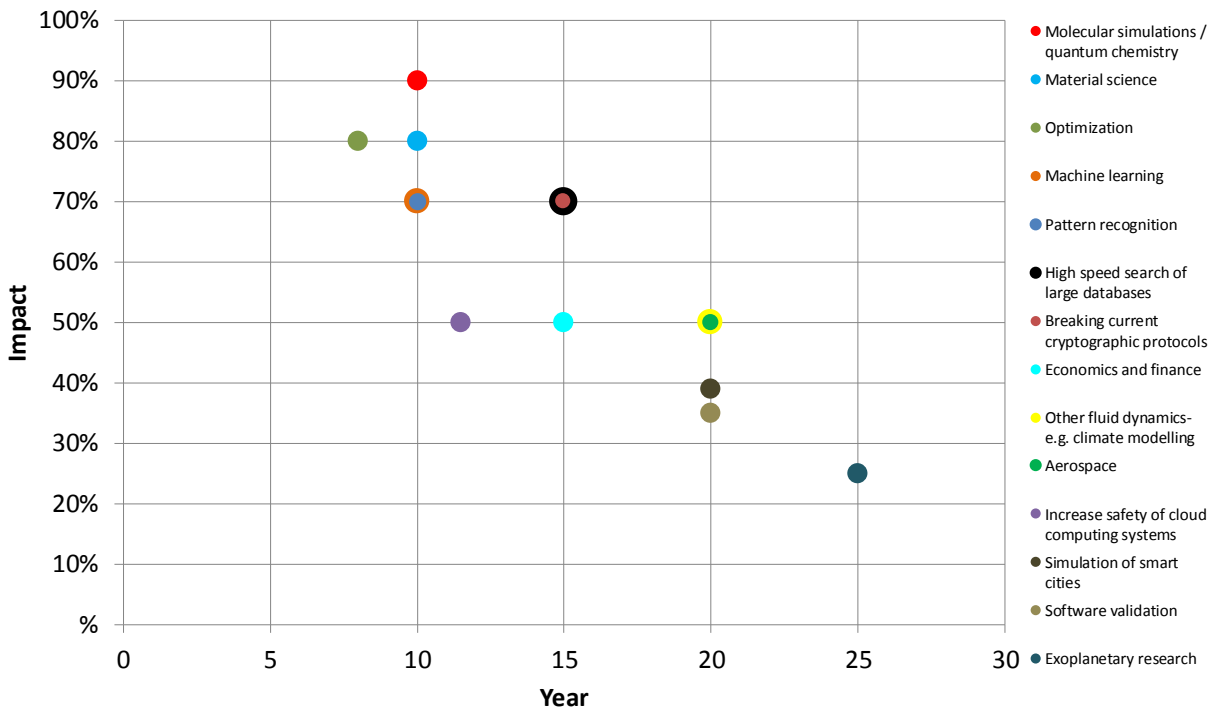


Fig. 1 Deemed importance of quantum computing for various applications versus expected implementation time scale.

Regarding the relationship between quantum hardware and software, the consensus was that their developments would reinforce each other. There is no consensus on the most promising hardware platform for quantum computing, with five major ones all thought credible, both intrinsically and with regard to Europe's potential. Europe's greatest strength in this field is believed to be in communications and interconnect, but strengths are also seen in other areas. There is no clear consensus about the utility of existing quantum algorithms, although most respondents were at least to a degree positive, and there was a consensus that a growing number of useful algorithms will be found.

A small-scale quantum computer is thought likely to be of educational value for software developers and engineers. Presently, physicists are much more aware of quantum computing than scientists in general but the respondents felt that equal priority should nevertheless be given to engineers and computer scientists for training, with chemists somewhat lower priority.

The highest priorities for funding from the European Union public institutions, according to the majority of respondents, should be basic research and enabling research, with financial instruments chosen accordingly. Among other sources of funding, national governments are most favoured, as they are seen as willing to accept these priorities. There was nevertheless quite some optimism about private industry being willing to do so too.

1 Introduction

The aim of this report is to highlight some potential implications quantum computers may have for the policies of the European Union. The main motive is the plan for quantum computing to be included as a major theme within a proposed new EU Future and Emerging Technologies (FET) flagship [HLSC Final report, 2017]. Further, if a successful large-scale quantum computer is developed, there may be consequences for other areas of public policy including cybersecurity, the digital single market, health and industry. The potential threat to cryptography, including the cryptography used to protect commercial transactions on the internet, is a very serious concern. The application of quantum computing for search may become important in policy areas involving citizens' records, including health. Possible applications in engineering, materials technology and chemistry may also have a high enough economic effect to be significant in policy terms.

The potential of quantum computing is now attracting the largest IT companies, with Google and IBM investing in superconducting platforms and Microsoft in topological quantum computing. Quantum computing startups are also now appearing. [Srivastava, Choi and Cook,2016] have published a survey of commercial investment in quantum computing, including the current market, research status and public perceptions, which it is planned to keep updated.

Quantum computing is still at too early a stage of development for a substantial body of policy analysis work to have been conducted, which is a reason why this present study was undertaken. Some related policy issues are included in the [Quantum Manifesto, 2016], a key document, widely endorsed by the quantum technology community, which advocated establishing the FET Flagship. In a similar vein is the more recently released [Quantum Software Manifesto, 2017]. Two other works giving overviews of the scientific issues, based on the opinions of respected researchers in the field, are: [QUROPE Roadmap, 2015 and [Aspuru-Guzik et al., 2015].

This present report is centred on a survey of a larger group of stakeholders' views and is intended to be less strongly focused on purely scientific matters than the latter two reports. It uses the "real-time Delphi method", an online-questionnaire-based foresight method explained in section 3. We have included in section 2 some general remarks on quantum computing to make clear aspects that we consider important for the interpretation of the Delphi study. A computer can be seen from several different perspectives, which condition our understanding of the potential role of a quantum computer as well. The questions presented in the Delphi study are consequently divided into categories in section 3, according to different perspectives. Section 4 contains the conclusions that we were able to infer using this and other available information.

This report is the third part of the final report of the JRC Quantum Technology Study, and accompanies reports on Quantum Technology for Time and on Quantum Communications.

2 Background on quantum computing

Quantum computing takes advantage of the quantum mechanical principle of *superposition of states* to perform computations in a special *parallel* way. With this technique, a very large improvement in computing speed can, in principle, be attained, as determined by the laws of physics.

We will refer to any existing or potential member of this new family of computers, constructed by exploiting certain principles of quantum physics, as a *quantum computer*. When needed, explicit reference will be made to special computers like analogue computers and supercomputers (very large parallel computing machines). By *classical computer*, we will mean the digital computer as known today, which, from the perspective of its physical components, is the result of the progress in constructing switching circuits based on transistors.

Although transistors are fabricated using solid-state physics knowledge informed by quantum mechanical principles, i.e. the theory of the electron band structure, the devices themselves can still be well-described by classical circuit theory and, in the case of digital devices, Boolean algebra. The behaviour of a quantum computer, however, is described using quantum principles: states, operators, superposition and entanglement.

Quantum computing differs from classical computing at a very fundamental level. It is certainly not just an incremental improvement in hardware design, algorithm design, parallelisation or networks. The advent of quantum computing re-opens, as a matter of practical engineering, some basic computer science questions which have, for the most part, been considered only in academic circles.

From the computing science perspective, the conventional computer is only one among many possible means of realizing the algorithms that are computable, both efficient and non-efficient. Problems also exist that are not solvable by any computer, even in principle. From the perspective of the software engineer, the classical computer is a combination of software applications and physical components controlled by an operating system. From the perspective of the communication and control engineer, the classical computer can be interpreted as an agent or a node in a net of communications that should guarantee some services, inviolability of data, correctness and reliability of the operations performed. These perspectives are also important for quantum computers.

Even if a quantum computer is considered simply as a new type of computer, its relationship with current computers has to be analysed, and from all the perspectives mentioned above. The questions included in the Delphi study described in Section 3 were framed with this in mind. Questions 10 and 11, address the potential architectural problems. Question 15 addresses the development of quantum algorithms, while the potential need for a new generation of software engineers is covered in question 6 and question 14.

Effective quantum computing brings not only a challenges related to the construction of the machines, but also requires new specific competence in software engineering that must consider the overall architecture of the computing machine and the theoretical limits of the algorithms for solving a problem. This is why a future scenario in which some kind of quantum co-processor, in analogy to present graphical co-processors, is considered in computer architectures exploiting both classical and quantum processors.

For people looking from a practical point of view, whose main interest is in applications, technological developments are critical. Researchers are now striving to achieve *quantum supremacy*: carrying out a computation on a quantum computer which would be unfeasible on any classical one. From a research standpoint, achieving it even on restricted or artificial problem is significant. For real applications, quantum supremacy is still highly speculative. While acknowledging this, we nevertheless believe the range and distribution of the views we have received in the survey help to give some foresight.

2.1 Algorithms

Any computer, including a quantum computer, needs an algorithm to solve a given problem. Its realisation depends on the architecture of the computer. For classical computers, with standard architectures, the task of adapting the algorithm to the computer is now largely conventional and more or less automated. This is not true for quantum computers. An algorithm designed for a classical computer cannot be simply ported to quantum hardware to run at improved speed. Algorithms must be re-designed and the software engineer performing this job must consider specific problems related to the architecture of a quantum computer.

Quantum algorithms generally begin with an initialization step in which an ensemble of qubits is put into a known state, such as all zeroes. A transformation is then applied to produce a superposition of states which encodes different candidate solutions. The qubits are then made to evolve in such a way that the part of the superposition that encodes the correct solution grows at the expense of the part that does not. The evolution is terminated when the correct solution is found, or found to high probability, and the state is read out.

Problems which have been addressed in this way fall into two groups: order finding algorithms, to determine some global property of a function, such as a period or median, and search algorithms e.g. to find the result to a query [Stolze and Suter, 2008].

A full survey of quantum algorithms is beyond the scope of this report; we refer the reader to [Jordan] for an online state-of-the-art catalogue and [Montanaro, 2016] for a formal review article. The latter includes a table of quantum algorithms which have been implemented in hardware; it is reproduced and updated in Table 1 below. We stress that these are fundamental algorithms, not complete applications.

Table 1 Implemented quantum algorithms

Algorithm	**Technology**	**Problem solved**
Shor	Bulk optics	Factorisation of 21
Grover	NMR	Unstructured search, N=8
Quantum annealing	D-Wave 2X	Ising model on a "Chimera" graph with 1097 vertices
Harrrow-Hassidim-Lloyd	Bulk optics, NMR, superconducting qubits	2 × 2 system of linear equations

Another class of problems for which quantum computers have been proposed is *quantum simulation,* in which the goal is to evaluate the amplitudes of all relevant quantum states of a system. It is much more ambitious than semi-classical models which take account of quantum behaviour by means of an approximation. For example, simulation of molecules is today carried out by methods such as molecular dynamics and the force field approach, in which atoms are treated as classical objects, except that certain parameter values are derived from quantum mechanical calculations on simple systems. A full quantum mechanical molecular simulation would entail considering all the possible combinations of all the atomic states. For all but the simplest molecules, this is a problem far too large for any classical computer to handle but it might, in principle, be treatable by a quantum computer. In quantum simulation, many of the limits given by the classical architecture, in which a quantum computer should be embedded, are not present. As an example, data is dynamically generated instead of being transferred. So, a legitimate question is whether the first real applications for quantum computers will come out from simulation, as was early suggested [Feynman, 1982]. This question is addressed in question 2 of section 3.

Some important constraints on quantum algorithms are known. It has been shown that not all the known solutions of problems by classical algorithms can be converted into quantum algorithms with improvements in speed; an example can be the sorting of the elements of a set of numbers by direct comparison [Høyer, 2001], [Klauck, 2003]. Identification of problems where quantum computers offer no advantage is important in cryptography, as the basis of quantum-safe algorithms i.e. those which could not be broken by a quantum computer and could replace present algorithms in the future [ETSI, 2015].

Another order of problems comes from the transfer of data. At input, the time for preparing a quantum superposition of states-where a considerable amount of data is transferred from a classical memory device-can downgrade significantly the expected performance. At output, the final state of a computation is defined via a measurement operation which extracts a classical portion of a quantum state at a certain time. When more than one of such classical portions is needed, the computation must be repeated. So, the overall performances can be limited by the type of input and output required. An additional drawback is that the performance of a quantum processor is limited by the time the superposition of states is guaranteed. Hence, there are defined intervals in time in which the performances are boosted by the quantum effects. The combination of these two facts poses important problems to the designer of an algorithm since only specific algorithms or defined parts of them can be given as instructions to a quantum processor for a limited interval in time. A long list of instructions should be consequently split into several parts whose results are "classically" re-assembled after the computation.

2.2 Models for quantum computing

By model is meant here the overall concept and scheme by which computation is to be realised. Models for quantum computing can be split, roughly speaking and following the considerations in section 2.1 above, into three categories: machines for quantum simulation, machines for quantum annealing and machines for circuit quantum computing.

A machine for quantum simulation is a well-controlled, well-understood quantum system whose states can be made to correspond to those of another quantum system whose behaviour is not known. For example, a quantum simulator for an application in chemistry might consist of a controllable solid-state system which can be configured to have equivalent quantum states to some molecule of interest.[1]

To the second category, simulated annealing, belong the only quantum computers presently on the market: manufactured by D-Wave systems. An array of qubits, each of which interacts only with its nearest neighbours, is set up in a known state which is then steadily perturbed until it represents the problem of interest, while preserving some feature well-enough to allow the identification of a global minimum or maximum, with high probability.[2]

Circuit quantum computing is the most ambitious of the three models. It aims to construct machines able to encode *any* computational problem by means of quantum

(1) By abuse of analogy, computers for quantum simulation in this respect resemble the analogue computers of the fifties and sixties: an algorithm is coded in an electric circuit and, set the appropriate input values of voltage or current to the input wires, the output can be read (in real time) as the corresponding voltage or current on the output wires; very efficient, but limited by the need, for computing another algorithm, to re-configure the circuit. In some cases, the circuit can be designed for solving a class of problems, like systems of differential equations or finding optimal solutions, given a set of constraints.

(2) [Nishimori] gives a more complete and very readable explanation of quantum annealing.

logic gates.[3] Basic theoretical criteria for the types of gate which must be used and their properties are well-established [Feynman,1985], [DiVincenzo, 1995], [DiVicenzo, 2000]. Crucially these, in principle, allow fabrication of quantum integrated circuits. The most difficult practical challenge is that the quantum states in the gate circuits must remain coherent i.e. their phases must stay synchronized, during the calculation.

Circuit quantum computing has been shown to be equivalent to a sub-class of quantum simulated annealing called quantum adiabatic computing, in which the system remains strictly in an eigenstate while it is perturbed [Aharonov et al., 2007],[Mizel et al., 2007]. The D-wave machines, however, do not fit into this category, and are more limited in the problems they can be set-up to solve.

2.3 Hardware platforms

A full description of all the hardware platforms under consideration for quantum computing is beyond the scope of this report but we briefly state here the major approaches.

Trapped ions qubits:

Quantum information is stored in the electronic states of an ion. Transitions occur between energy levels determined by orbital configuration, hyperfine structure, and possibly Zeeman splitting. An oscillating (Paul trap) or stationary (Penning trap) electromagnetic field confines each ion in a specific spatial position. Linear traps have been built holding ~10 ions and more than 200 in a 2D trap for quantum simulation. Laser pulses are used to cool the ions, initialize the qubits, perform logic operations, and measure the final state; entanglement is achieved by exploiting Coulomb interactions among the ions. Trapped-ion qubits are long-lived systems, identical to each other. Their initialization, manipulation, and read-out are highly reliable processes. Quantum algorithms have been run in systems composed of 5 fully interconnected qubits, and quantum simulations with as many as 53. Research is focused on achieving faster gate switching times and fidelity as well as the number of qubits, the end goal being to accomplish all three together. In the quest for scalability, it has been demonstrated that initialization and control can be achieved by broadcasting microwave radiation, thus dispensing with the multiple carefully aligned laser beams. To limit crosstalk noise, large-scale systems are to be based on multiple separated trapping regions, with information transported between them by physically moving the qubits or by coupling them to photons travelling between the traps.

Superconducting qubits:

A superconducting loop with a Josephson junction, i.e. a very short non-superconducting break, allowing interference effects between quantum states on either side, constitutes a two-level energy system. Depending on design parameters, it can store quantum information in charge, phase, or flux states, or in several hybrid configurations. Superconducting qubits are fabricated with conventional integrated circuit technology, have typical dimensions of ~μm, are kept refrigerated to well below 100mK, and can be controlled with standard electronic instrumentation. Qubit coupling can be achieved in different ways, e.g. via photons confined in a transmission line or using microwave cavities. Entanglement among 72 qubits has been recently demonstrated (Google), and a quantum processor with 20 superconducting qubits is made available on-line by IBM. With respect to trapped ions, superconducting qubits have shorter coherence time, compensated for by faster quantum gates operations. They seem also more amenable to

(3) Circuit quantum computers do not consist of the familiar AND, OR and NOT gates of classical digital logic but of reversible gates which have additional control lines e.g. CNOT, CSWAP and CCNOT [Fredkin and Toffoli, 1982]. Reversible gates are well understood and classical ones can be implemented without great difficulty. [Muthukrishnan, 1999] gives a helpful brief survey of the basic literature in quantum gate theory.

large scale integrated systems, which simplifies the implementation of error correction codes, e.g. in a two-dimensional qubits array.

Photonic qubits:

Photonic states can be used to store quantum information e.g. in polarization or energy, and are remarkably robust against environmental disturbances. On the other hand, entangling photonic qubits to realize a quantum gate is a challenging task: a major breakthrough was the discovery that it can be achieved by using simple linear optical networks composed by elements such as mirrors, beam splitters, and phase shifters. The realization of a linear optics quantum gate requires auxiliary photons whose management represent a significant resource overhead. Conversely, scaling up the system by using e.g. silicon photonics is perceived as simpler than for matter-based qubits. Shor's quantum factoring algorithm has been tested on an optical chip comprising 4 photonic qubits and integrated waveguides. The advancement of quantum computation based on linear optics strongly depends on the availability of enabling devices such as high-performance single photon emitters and detectors.

Semiconductor qubits:

A powerful motivation for embodying qubits in semiconductors is to leverage the huge know-how and the potential of the existing manufacturing technologies. Semiconductor-based solutions are less mature with respect to the ones already examined, and several approaches are still being investigated: they comprise different materials, both bulk and nanostructured, with quantum information stored in nuclear spin, electronic spin, or other quantum states, and controlled electrically, magnetically, or optically. One of the possible routes is to use nano-scale silicon "quantum dots" within which electrons are so tightly confined that they start behaving as if they belonged to individual atoms, thus occupying discrete energy levels. The spin of an electron stored in a quantum dot couples weakly to the environment, thus constituting a promising qubit, which can be controlled by the local application of an oscillating magnetic field. Electrical pulses are then employed to couple two adjacent qubits, in order to realize a Controlled-NOT quantum gate. The system is scalable, compatible with current microelectronic features, and fabricated with standard CMOS process: it thus offers concrete prospects of realizing large scale quantum processors.

Topological qubits:

In a topological qubit, quantum information is stored in the collective behaviour that an ensemble of particles may exhibit under specific and carefully controlled conditions. A classic example is the fractional quantum Hall effect experienced by electrons in a two dimensional gallium arsenide heterostructure: at low temperature and under a strong magnetic field, the electrons react to external perturbations by rearranging themselves via long-range interactions that keep their overall energy unchanged. In principle, such phenomena allow implementing a qubit immune to environmental sources of quantum decoherence, leading to a fault-tolerant processor that doesn't require burdensome quantum error correction. Topological quasi-particles suitable for information processing, called non-Abelian anyons, such as Majorana fermions, have been experimentally demonstrated, e.g. in superconducting nanowires: work is now in progress to improve the qubit quality in order to allow a reliable control of the stored information. Quantum computations will then be made by manipulating the world lines of the quasi particles. embodying the topological states, according to the mathematical formalism known as braiding.

3 Real-time Delphi study

3.1 Methodology

The need to address the quantum computing topic differently from other aspects of quantum technology was recognized early in the study, since quantum computing is at a far earlier stage of technology readiness than quantum communication, timing, sensing and imaging technology.

A formal foresight method was considered necessary.[4] Standard methods exist [Forlearn] based, broadly, on one of two approaches:

1) Define a range of possible scenarios
2) Construct a vision or roadmap

It was clear from the technology readiness considerations that the first of these fitted the subject better. [5]

Standard foresight methods may be further divided into those based on focused workshops and those based on surveys. Delphi surveys are a very well-established method, with a history of over 50 years of use. Traditional Delphi surveys are conducted by asking the participants questions in two or more rounds. They thus combine the advantage of a survey and workshop method, by allowing a wider number of participants than can easily participate in workshops, while including an element of dialogue. The Real-time Delphi (RTD) method is a "roundless" Delphi in which the results, both quantitative and qualitative, are updated in "real-time", as responses are submitted. The participants are allowed to revisit the questionnaire and re-consider their answers in response to the answers of others, at any time during the period the survey is open. A consensus may be reached at the end, even if does not exist at the start.

The RTD method was selected because:

1) RTD is particularly well-recognized as a tool for *technology* foresight, and the study falls clearly into this category.
2) The expert community was known to be quite large and geographically dispersed.
3) It consists almost exclusively of people with very high information technology skills, who are completely comfortable with using on-line methods.
4) The relevant skills and tools were available in-house.

The Global Futures Intelligence System (GFIS) platform from independent think tank "The Millennium Project", was used for the RTD, on grounds of familiarity [Millennium]. No alternatives were considered because GFIS had been found satisfactory by JRC in previous projects.

(4) Discussions for a foresight study in quantum computing began in October 2015 when the quantum study team sought help in-house from the JRC Foresight and Behavioural Insights Unit, which had expertise in suitable methods.

(5) A European roadmap for Quantum Information Processing and Communication does exist, produced by the QUROPE network [QUROPE Roadmap, 2015], but it addresses only the technology considerations, not the broader ones. Moreover, the quantum computing section is divided into separate sections for the different hardware platforms so, in that respect, actually has the character of a range of scenarios.

Process

Beginning at the end of September 2016, two Calls for Expression of Interest were published on the QUROPE mail server explaining the RTD exercise and proposing a workshop to define the questions. A limited number of individuals known to the team were invited personally.

A workshop with 21 attendees, 5 JRC staff members and 1 student observer was held, in which draft questions suggested by the JRC team were discussed, substantially revised and added to the questionnaire in real time, and then further revised and finalised in on-line discussions. Appendix A presents the entire questionnaire.

An initial list of names for the target group was drafted, consisting of people known directly or indirectly by the team and people recommended by the workshop participants. An internet check was carried out on every person, except those already well-known to the team, consisting of an examination of research group or company webpages, curricula vitae and publications lists, as far as was available.

A final list of 250 names for the target group was defined, with a reasonable representation of different fields of expertise, organisation types, locations, genders and career points. A real balance was deemed impractical, and not useful to aim for, given the uncertainty of who would respond.

The RTD was launched at the end of March 2017 and left active until mid-May.

Altogether, 182 people accessed the questionnaire, out of which 139 provided answers. More than 100 of those who responded rated themselves as having "Very High" or "High" level of expertise in the field of quantum computing. There was no automatic restriction to invitees and a few extra participants joined while the RTD was live, but care was exercised not to allow the group to grow in an uncontrolled fashion. In particular, when several people from the same organisation joined at their own initiative, we allowed only a limited number, choosing those had replied to most questions.

3.2 Overview of questions

The questions asked in this study cover four main perspectives from which a *computer* can be seen:

- The technical problems are covered mainly by questions 2, 3, 4, 10, 11, 12, 15.
- Problems related to society, economy and investments are treated by questions 4, 5, 6, 7, 8, 9, 13, 14.

These two main groups can be further divided. The first group includes a software engineering perspective (question 10), the distinct roles played by classical and quantum algorithms (question 11), the potential hardware and physical components of a quantum computer (question 12), the software engineering and theoretical computer science aspects (question 15), while questions 2 and 3 address the potential improvement in current computer applications or fields of application.

Question 4 concerns scientific and technical applications and belongs to both groups.

The second group addresses applications from the perspective of more general societal aspects (questions 4 and 5). Moreover, question 5 deals explicitly with the potential distinct role in the main social aspects a quantum computer could play, in comparison with the role played today by a classical computer. The economic aspects and funding of research and development of a quantum computer are covered by questions 6, 7, 8 and 9. Question 13 addresses the distinct role potentially played by Europe with respect to the rest of the world in hypothetical technical fields useful for the development of quantum computers while question 14 investigates the potential consequences for education (mainly in the IT field).

The complete list of the questions with sub-questions can be seen in the section "3.3 Question-by-question analysis" and in Appendix A. Following is a succinct list of the aspects addressed by each question:

Question 1: *Participant's self-assessment*--asks about their own expertise in the field of Quantum Computing and the area(s) they work in.

Question 2: *Main drivers*--concerns reasons to believe in the future utility of quantum computing and the justification for publicly funding its development.

Question 3: *IT applications*--looks at the subjects of question 2 from the perspective of the IT applications, and the timeframe for their realization.

Question 4: *Technical aspects, scientific and engineering applications*--concerns some sectors of science and technology that could benefit from an improvement in efficiency of computation, and the expected timeframe.

Question 5: *Social aspects*--deals with the consequences of an improvement in efficiency of computation to the society in general, with focus on potential new regulations.

Question 6: *Economic aspects*--aims at exploring the consequences on the economy in general, and more specifically in the IT sector.

Question 7: *European public funding I*--collects the experts' opinions about the current state of the physical realization of a quantum computer, in respect of what should be publicly funded.

Question 8: *European public funding II*--concerns the specific way for funding research and development of a quantum computer in relation to two envisaged phases of the FET flagship.

Question 9: *External funding*--investigates about the possible funding complementary to the European public route.

Question 10: *Quantum computing software and hardware*--enters into the possible relations between applications and physical components.

Question 11: *Quantum computation's future place*--asks about the role the quantum computer, if realized, will have in the computational landscape.

Question 12: *Quantum computing physical platforms*--asks about merits of the various hardware approaches being taken, and the European potential in each.

Question 13: *European strengths*--asks whether European IT industry can have an advantage (both for algorithms and physical platforms).

Question 14: *Education*--deals with the potential changes to the education--mainly of IT specialists and engineers--caused by the wide use of quantum computers.

Question 15: *Status and Evolution*--addresses specifically the algorithms and aims at understanding the spectrum (very specialised to general purpose) of the algorithms efficiently executed by a quantum computer.

Question 16: *Open-ended*—invited the participants to add other comments, suggestions, concerns, etc. related to European policy and strategy concerning quantum computing.

3.3 Question-by-question analysis

Question #1 Participant's self-assessment

Please indicate your level of expertise in the field of quantum computing and the area(s) you work in.

Motive

It was recognized that the target group needed to consist of people at different career points, as well as people with different fields of expertise, including experts in the possible applications as well as in quantum computing itself. We had intentionally invited people with different career profiles and it would be possible to use the information we had to answer the question ourselves, for each person who had replied. But it was thought necessary to check whether our perception of the participants agreed with their perception of themselves.

It was also thought that it might be possible to analyse differences of views according to career profile. Any analysis of differences would have to be done a posteriori since we had no control over who would reply. By asking both questions it would be possible to detect differences of views in each dimension. We have not yet attempted to perform this deeper analysis.

Results

1.1 Level of expertise

Very high – has successfully proposed projects and directed work ***64***
High – has produced original work and/or contributed to advances ***34***
Medium – has extensively studied the area and its scientific literature ***21***
Low – has studies the area and read popular science articles ***9***
No significant exposure to the area ***2***

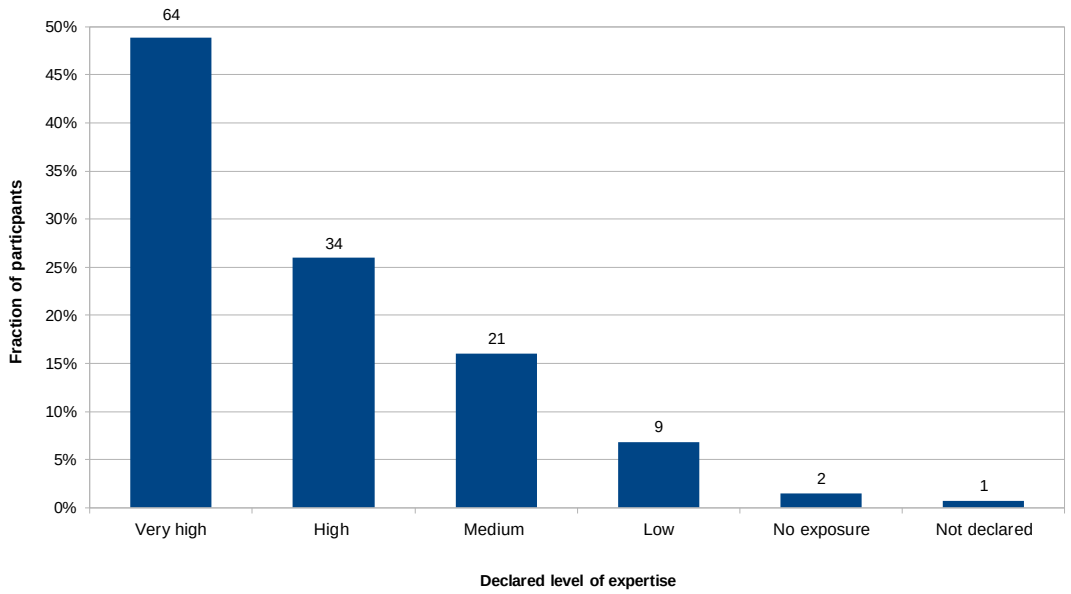


Fig. 1.1 Declared level of expertise

1.2 Field of expertise and location

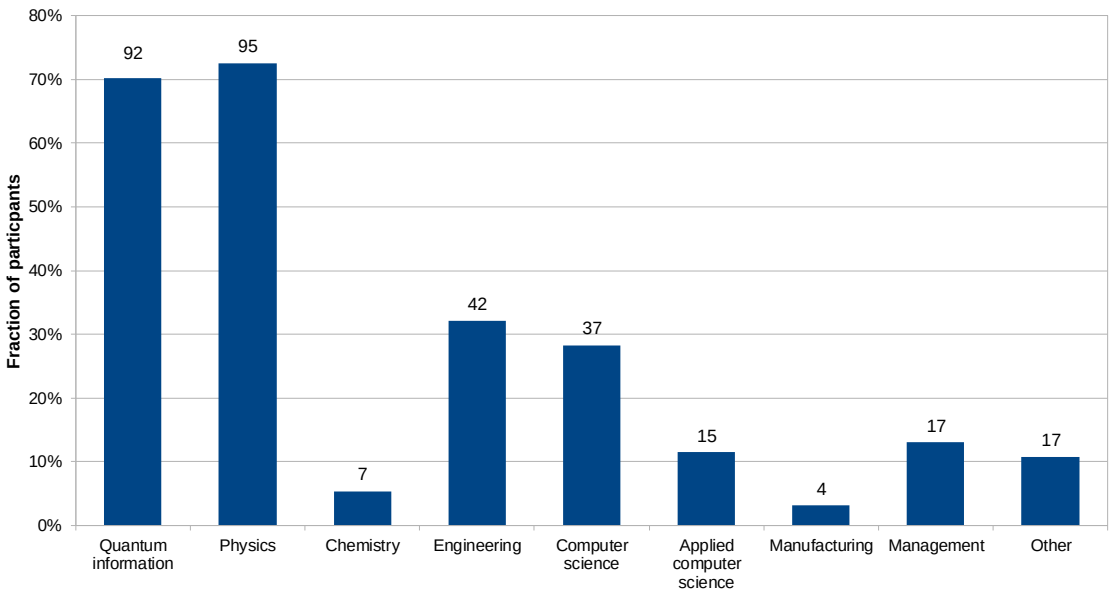


Fig. 1.2 Fields of expertise

Note: the total is greater than the number of participants because some respondents declared expertise in more than one field.

The "other" fields declared were mostly managerial in character: project coordination, consultancy, policy and technology management and commercialisation. Five participants declared expertise in: human and social aspects of IT, science communication, materials science, mathematics and quantum biology. Two declared, but did not specify, their other expertise.

In conclusion, the participant group was diverse but had a strong preponderance of physicists and quantum information experts and physicists. This does mean that the views we received were mainly from the relevant scientific community, which can be expected to be positive about the value of its own work.

As for geographical participation, the vast majority were from Europe (as had been intended). The following graph shows the number of participants by geographical regions, counting everyone who answered question 1-1 and also indicated their location.

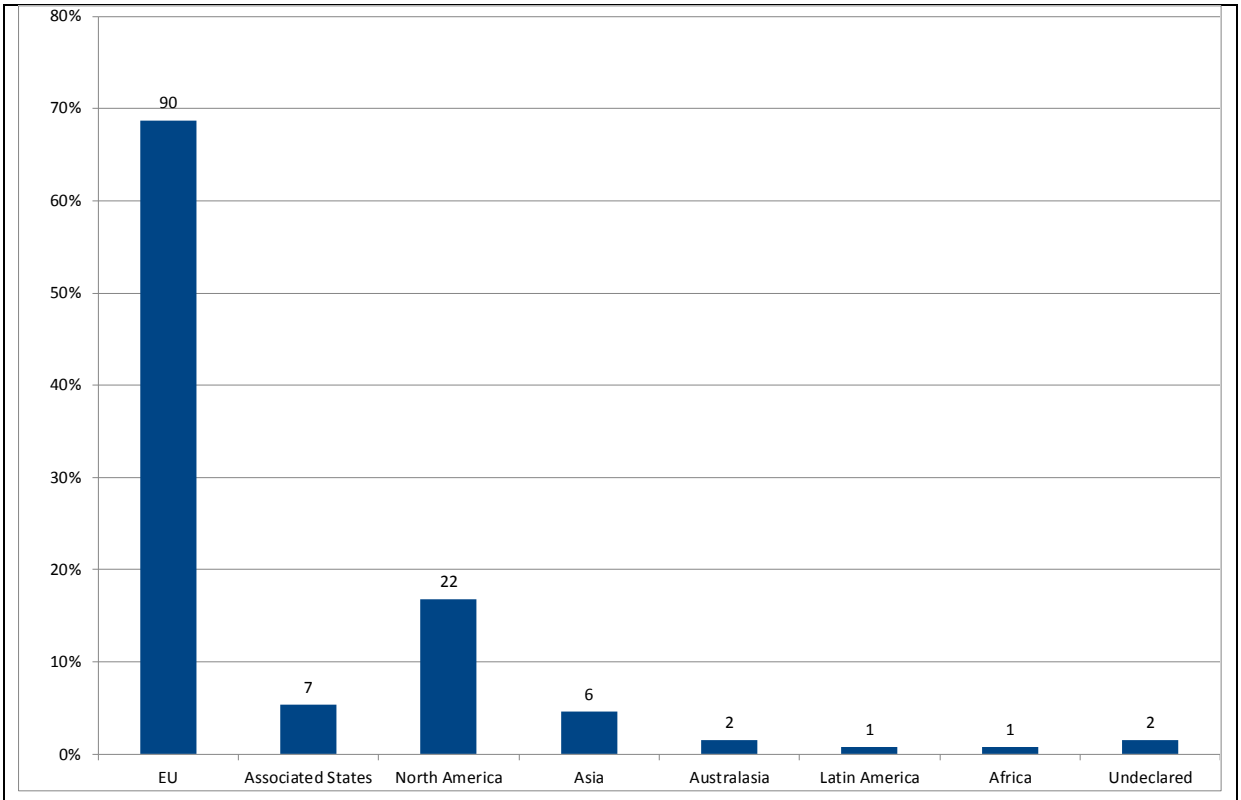


Fig. 1.3 Geographical distribution

Note: Associated States refers to non-EU states which participate in Horizon 2020.

Question #2 Technical aspects, drivers

Please assess the following drivers for large-scale manufacturing of quantum computers:

Addressing optimization issues
Increasing energy efficiency of computing
Increasing processing speed in specific applications
Having the ability to control quantum systems
Simulating quantum systems
Simulating classical complex systems
Enhancing machine learning
Attacking and defending data security
Other (please specify in the textbox after "Submit")

Sub-question 2.1: Main reasons. Which would be the main reasons for quantum computing to be useful?
Please rate the potential drivers on a scale of 0 to 100 (from 0 = not important reason to 100 = extremely important reason)

Sub-question 2.2: Funding priorities. Which do you think would be the priorities for public funding support? Please drag the drivers to order them.

Sub-question 2.3: Level of confidence. Please indicate your level of confidence in your own answers to the questions on "Main reasons" and "Funding priorities".
(from 0=not confident at all to 100=extremely confident)

Motive

The usual advantage claimed for quantum computers over classical computers is increased speed due to intrinsic parallelisation, which is thought to be achievable for some but not all computational tasks. A quantum computer could carry out what are now feasible, but time-consuming, tasks much more quickly or carry out some tasks which are now unfeasible. Question 2 addresses the reasons why people might want to have such an advantage.

Some also assert that quantum computers could achieve speeds which can be achieved by conventional large–scale computing more easily e.g. with less power. D-Wave systems already advertise this as an advantage of their machines. We wished to find out what the views were on the relative importance of different types of advantage, both in general and for funding priorities.

Sub-question 2.1: Which would be the main reasons for quantum computing to be useful?

The results are shown in Figure 2.1 and Table 2.1 below.

The highest score is for simulation of quantum systems, reflecting the belief that it is likely to be the first application where quantum computers will show a clear advantage, given that it is an intractable problem for classical computers, as several participants commented. Also mentioned were commonalities between quantum simulation, control and machine learning.

The other reasons for quantum computing to be useful which were cited were: understanding biological processes (e.g. protein folding and many-neuron connectivity), computational chemistry, foundations of quantum mechanics, fundamentals of computability, pharmaceuticals, materials, quantum internet, machine learning and

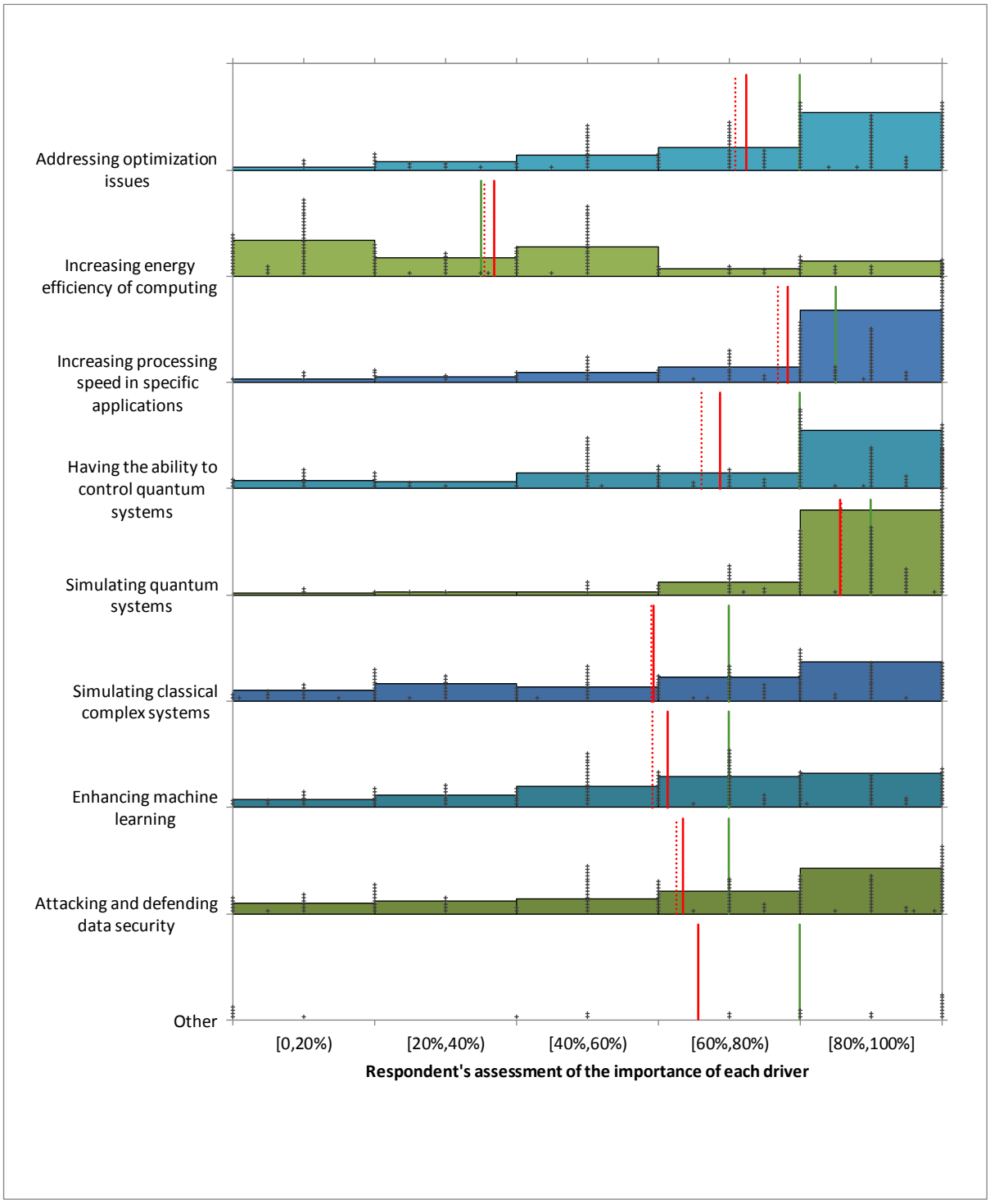


Fig. 2.1 Main reasons for quantum computing to be useful

median | mean | weighted mean | individual responses, stacked vertically

artificial intelligence in general. Although we had intended to address such specific applications only later in the questionnaire, participants started raising them here. Also mentioned were quantum sensing, communication and imaging, although the survey concerns only quantum computing; some other participants commented on this.

For all the drivers except energy efficiency, the distributions are skewed to the high end, with medians exceeding means, and some answers where the participant rated the driver at 100%. There are only small differences between means and confidence-weighted means, except for category of the "other" drivers, where some participants had made suggestions but had noted that they were less confident in them. We received several specific comments regarding the drivers, which are cited below. The participants did not strictly separate their suggestions for other drivers from their comments, and they are not separated here.

Table 2.1 Main reasons for quantum computing to be useful

Application	**No. of responses**	**Mean**	**Median**	**IQR**
Addressing optimization issues	121	72.4%	80%	35%pts.
Increasing energy efficiency of computing	117	36.8%	35%	40%pts.
Increasing processing speed in specific applications	120	78.3%	85%	30%pts.
Having the ability to control quantum systems	117	68.8%	80%	40%pts.
Simulating quantum systems	121	85.6%	90%	20%pts.
Simulating classical complex systems	116	59.3%	70%	50%pts.
Enhancing machine learning	116	61.3%	70%	30%pts.
Attacking and defending data security	118	63.5%	70%	40%pts.
Other	23	65.7%	80%	-

Notes on plots and statistics
The plots show, for each driver, histograms on 20% point bins, with the mean (red bar), weighted mean (dotted red bar) and median(green bar) . Responses on the borderline between two bins are assigned to the higher bin, values of 100% are assigned to the [80%, 100%] bin.
The individual responses, indicated by crosses, are shown to give a more complete picture of the distribution. They tend to be at multiples of 5 and 10%, rather than randomly distributed over the percentiles.
Distributions are asymmetric and highly non-normal, as is typical of real-time Delphi studies. The responses are not independent, by the design of the method, so no confidence interval can be calculated. The median and the interquartile range are the most usually quoted statistics; the smaller the interquartile range the greater the degree of consensus. For the "Other" responses, there are fewer data points, so the detailed statistics are less meaningful and only the median and mean are shown.

Similar schemes are used in subsequent questions.

Sub-question 2.1: Suggestions for other drivers and general comments

Optimization

1. "They may be useful for optimisation- but unclear if they can do well on their own (without accurate representation of the optimisation problem) and even if the optimisation can be sped up- initialisation to run the problem may be even harder than the optimisation problem."
2. "Optimization is more useful [than simulation]- but the speedups are typically more modest."

Energy Efficiency

3. "Energy efficiency may become more relevant if the cooling issue can be resolved - robust QC at room temperature (not with current scheme- though)."

Processing speed

4. "Looking at the interests of commercial players- the overlap between quantum computers and high performance computing (increasing 'processing speed' of currently intractable problems) is the most significant."
5. "Unclear what specific applications processing speed could really be improved and whether speed is the actual issue - what about data and enabling access to a vast amount of data?"

Quantum control

6. "Quantum information processing can be very powerful for controlling and characterizing quantum systems and this is an important- and underappreciated application."
7. "Control and linked to that simulation of quantum systems may be most relevant for a QC- for obvious reasons."

Quantum simulation

8. "The priority in quantum computing development efforts seems to be naturally returning to Feynman's original proposal of using simpler quantum information manipulation construction to simulate Hamiltonians of rather complex and exotic quantum systems. This is one of the most plausible directions that promise significant benefits in the near future. All areas are in need of new specific quantum algorithms demonstrating clear advantage over existing classical counterparts."
9. "Quantum simulation- at present- is the best application that we have for quantum computing in the near term. Security applications- while important- will become less important as quantum resistant crypto becomes used."
10. "In my opinion the most appealing feature of a quantum computer is the ability to mimic quantum systems in a programmable way- simulate their evolution and final state. This feature has unpredictable consequences but it will mean a major breakthrough in the way we simulate chemical reactions and novel material design."
11. "Quantum simulation is also seen as commercially important- but value proposition remains unclear."

Classical simulation

12. "Classical complex systems rely heavily on partial differential equation solving and there may not be much QCs can do."

Machine learning

13. "Quantum machine learning is in its infancy and while enormous advantages can be found for quantum data the speedups for existing problems are at best quadratic."
14. "Quantum simulation and quantum machine learning approaches use specific solutions that are rather close in terms of ideology and technological implementation. This cross-fertilization promises to speed up the development of quantum machine learning."
15. "I'm more optimistic on the machine learning side in terms of special purpose hardware being able to learn things akin to current artificial neural networks (deep or otherwise) as it doesn't require the full gate model."

Data security

16. "In my opinion the most practical application of quantum technology will be defending data security and various aspects of cryptography."
17. "Question needs more definition. What does it mean to be 'useful'? Is the death of public key cryptography 'useful'? Highly significant- but probably not useful. Over what time scales is this question interested? "
18. "Re. data security- the problems are not related to quantum- but humans- so building an even bigger wall that no one has to jump over to access the information in other ways is not useful."

Other

19. "I'm still expecting real applications to come from elsewhere once engineers can get hold of the technology to solve practical problems."
20. "They should tackle real-live problems in society like cancer- climate change- new drugs- etc... The list up there is too specific. Maybe to be able to solve the real goals one need all of the above things."
21. "I think the efficiency of machines in general should be added to the list (not just computing). A lot of the comments about climate change biological systems etc. fit under the category of simulating classical complex systems. There is also the important aspect of tackling fundamental questions which is ENTIRELY lacking here. Quantum computers can assist in testing for new fundamental theories."
22. "People will use the new technologies and create applications."
23. "I believe that the whole community (not only myself) is quite uncertain of which applications will be useful. This needs further- focussed research to develop and test new algorithms."
24. "All reasons are important- however in different domains. For example simulating could be very useful for certain applications- and not ML for those; and reverse for others.'"
25. "My opinion is skewed by the kinds of things researchers talk to me about - a function of what they think the public is interested in."
26. "Being involved in academia within Europe for the past 5 years- and being involved in many conferences and discussions with experts in the field I am confident of the reasons and priorities I have indicated. I can be selfish and ask to prioritise more theoretical and fundamental research which is what I do. Whilst I do wish that more fundamental research is funded- as a European taxpayer- I think our wisest investment for the betterment of our society is to prioritise in the areas indicated."
27. "More confident in the 'Main reasons' answer because of my own motivation to achieve successes in areas that can offer significant benefit to people's lives through medicine or technology- over any timeframe. Less confident in the 'Funding priorities' answer because this will be decided by others with more political agendas I suspect."

Sub-question 2.2: Which do you think would be the priorities for public funding support?

Figure 2.2.1 show the histograms of the priority levels assigned to each driver by the respondents. For this sub-question, the participants were not asked to indicate their own numerical value, only their preferred order. The topics seen as most important to fund publicly are optimization, increasing processor speed for specific applications, and quantum simulation. There was little enthusiasm for funding data security applications, which is quite surprising given that, elsewhere than in this RTD, they have been advocated as amongst the most important. These conclusions remain unchanged if the respondents' confidence in their own answers is taken into account (Figure 2.2.2).

Fewer comments were received to this second sub-question. Two comments were received regarding data security: a participant who ranked it at 6th priority said:

> "It is not clear that quantum computers can defend data security- on the other hand the mere threat that they could break security is already there. It is not clear that there is a commercial interest in cracking security but defending against their attacks is critical and has been for some time."

Two participants commented that military and security funding would be major sources, one saying they would be interested in cryptography.

Two participants commented that control of quantum systems as a key application to fund.

Three respondents stressed the importance of machine learning.

With regard to what was appropriate for public as opposed to private funding two respondents commented:

> "a lot of these have clear business-cases and will be funded regardless. Some require a longer development track- and hence should be focused on by public funding. PRIMARILY Funding should be looked at from a global strategic context. No need to fund what we cannot ever competitively win as Europe."

> "Public funding should be directed towards applications with the greatest societal gain. Hence- applications in increasing energy efficiency and simulating quantum [systems] should be given high priority for public funding. Applications in optimization and machine learning have applications in business and finance- and are more appropriate for support by private investment / industry. Having the ability to control quantum systems is important from a basic science perspective- and as a underpinning element of the other applications."

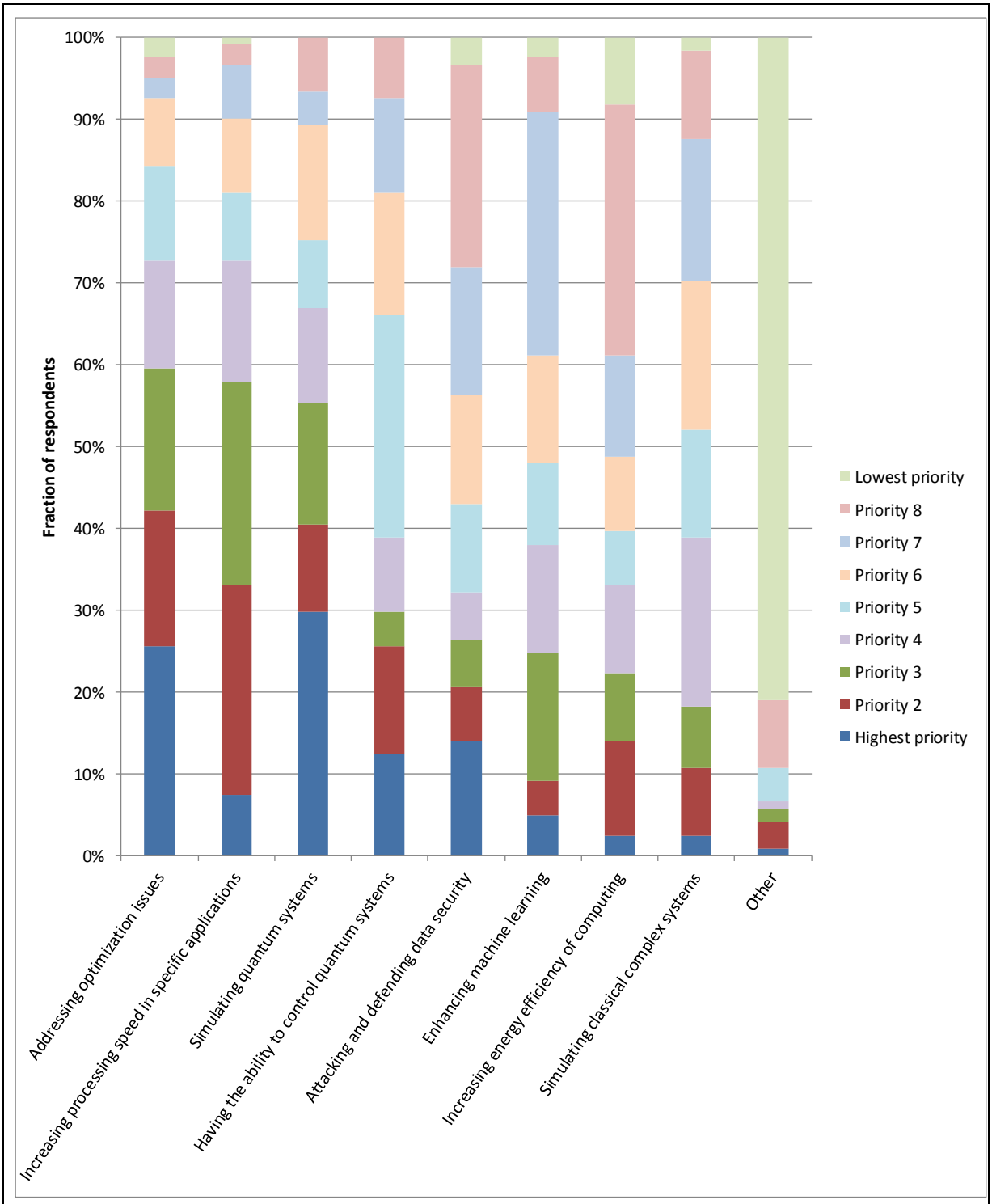


Fig. 2.2.1 Respondents' priorities for public funding support

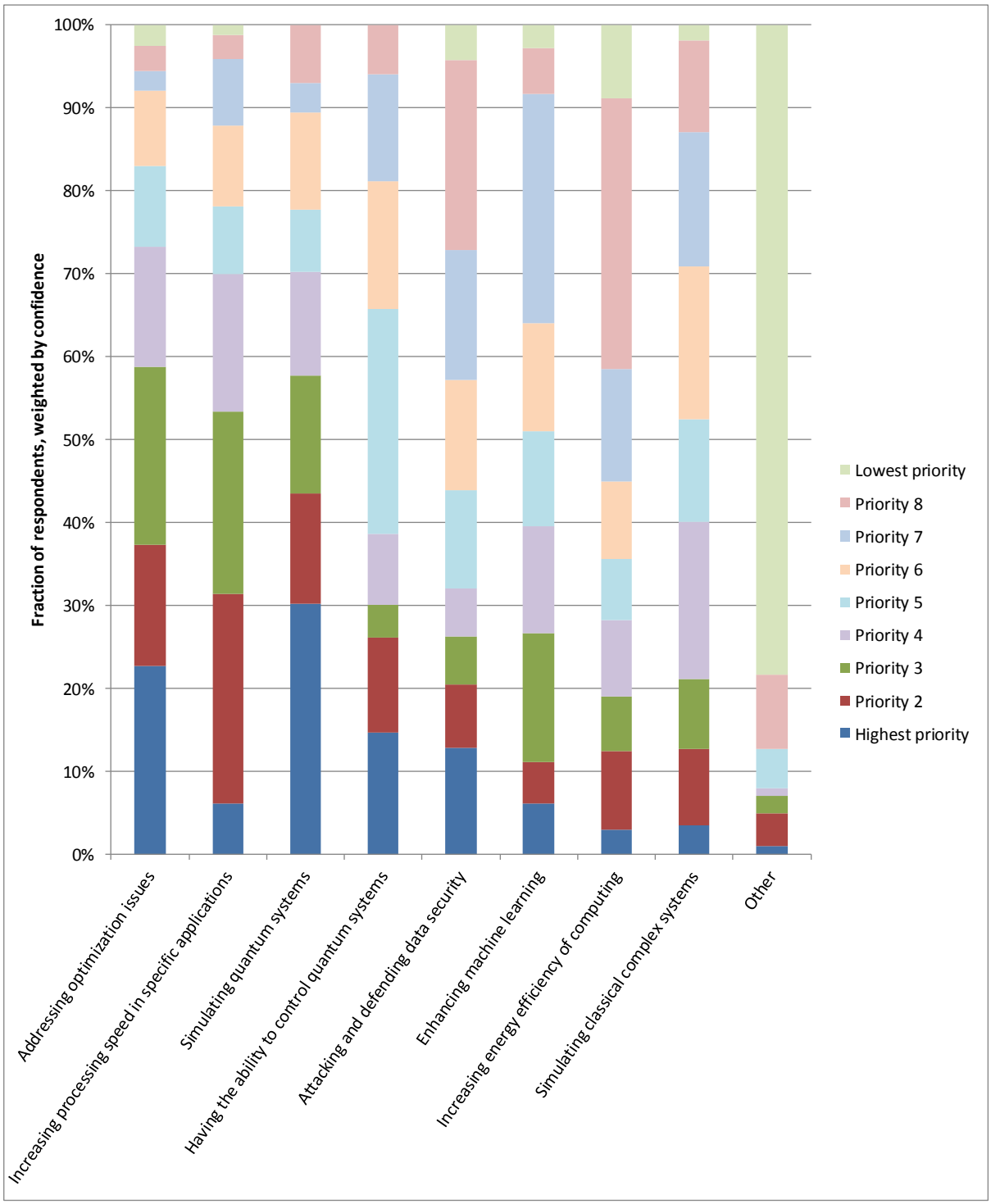


Fig. 2.2.2 Respondents' priorities for public funding support, weighted by the confidence they expressed in their own answers.

Question #3 Technical aspects, IT applications

Please indicate how important you think quantum computing may be for IT applications, and the timeframe.

High speed search of large databases
Optimization
Increase safety of cloud computing systems
Breaking current cryptographic protocols
Machine learning
Pattern recognition
Other (please specify in the textbox after "Submit")

Sub-question 3.1: Importance for applications. Please rate on a scale of 0 to 100 the importance you think quantum computing could play for the following applications (from 0=not important, 100=extremely important)

Sub-question 3.2: Timeframe. Please indicate the expected time scale in years for validation in a relevant environment (i.e. to achieve Technology readiness Level 5), for the indicated applications

Sub-question 3.3: Level of confidence. Please insert a number to indicate your level of confidence in your own answers to the questions on "Importance for applications" and "Timeframe". (from 0=not confident at all to 100=extremely confident)

Motive

This question is intended to examine the issues of question 2 in more detail, focusing on the IT applications which are cited as possibly suitable for quantum computers.

Sub-question 3.1: Importance of quantum computing for IT applications

The responses in Figure 3.1 and Table 5.1 show a lack of consensus, with optimistic, pessimistic and intermediate views all well represented and high interquartile ranges. The highest scores are for optimization.

High speed search also scored high. Two participants noted that Grover's algorithm has no advantage for search of classical databases. This is well-known but did not discourage other participants from giving positive opinions.

Table 3.1 Importance of quantum computing for IT applications

Application	No. of responses	Mean	Median	IQR
High speed search of large databases	101	61.1%	70%	55%pts.
Optimization	102	74.6%	80%	20%pts.
Increase safety of cloud computing systems	99	49.4%	50%	40%pts.
Breaking current cryptographic protocols	100	65.1%	70%	40%pts.
Machine learning	99	66.2%	70%	40%pts.
Pattern recognition	96	64.6%	70%	34%pts.
Other	19	71.1%	80%	-

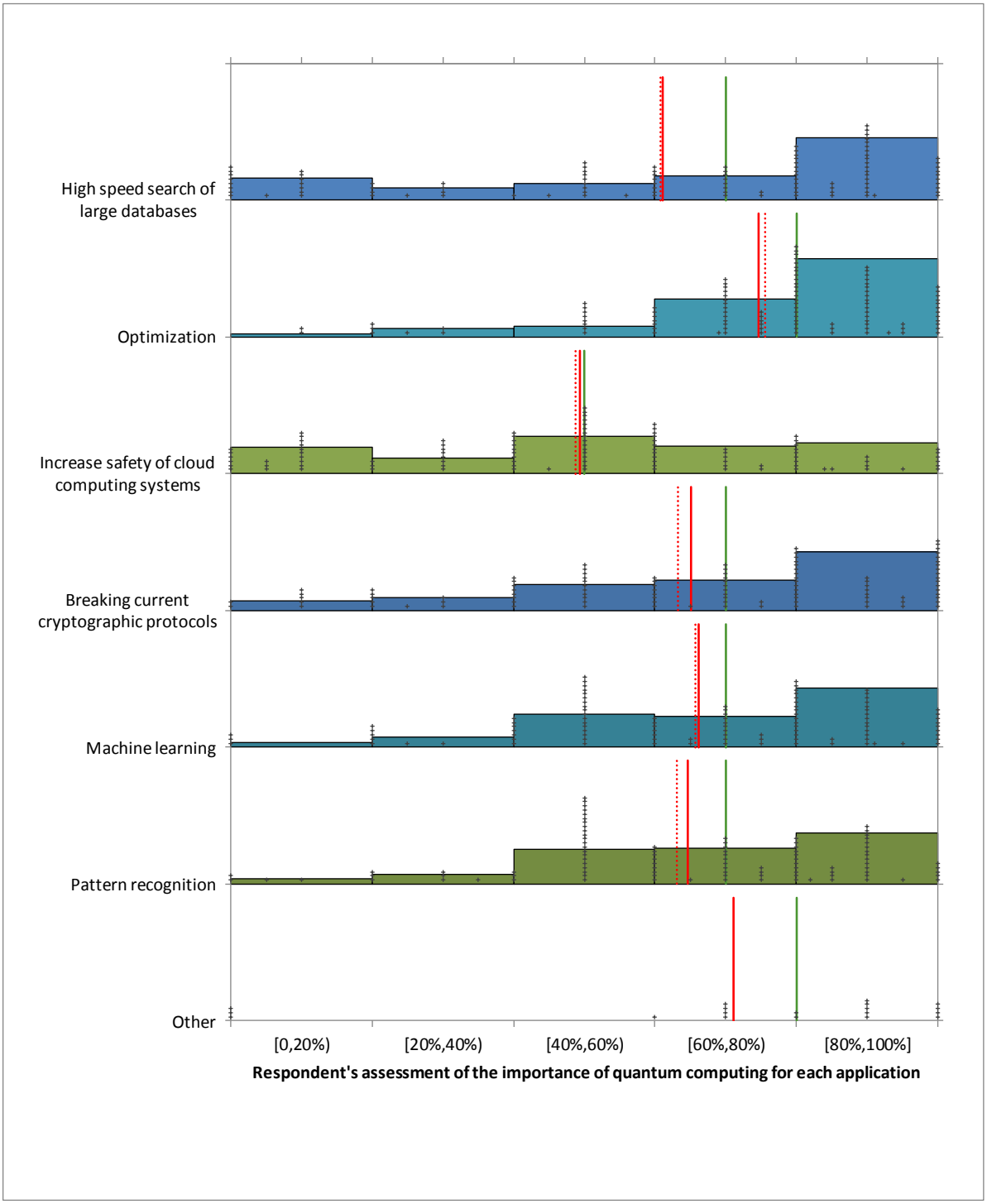


Fig. 3. 1 Importance of quantum computing for various IT applications

median | mean | weighted mean + individual responses, stacked vertically

Comments

Search

1. “There is the common misunderstanding that Grover search can be applied to classical databases. In fact- it is slower than classical search for that. There is also no demonstration of a quantum speedup in any real optimization problem.

2. Grovers' search will have no impact on the ability to search large data bases because the database has to be stored in quantum memory. The remaining numbers reflect previous responses.”

3. “Database search is not a likely application because the database has to be held in quantum memory and needs to be unsorted- which few databases are.”

4. “Pattern recognition and database searches are the same algorithm family. They are the exact same application”

Cryptography

5. “Same as previous sections- it depends of the application and our objective is not to break current crypto- but to protect against breaking.

6. “My answers are based on the potential for near-term devices. Although crypto could be a high-payoff application- I see it as a much longer term (several decades timeframe).”

7. “The ability to break encryption protocols is more of a driver for encryption that is robust to quantum computers.”

8. “I've not seen much in terms of encoding large datasets to give search or optimization applications access. QCs won't make anything in the ‘cloud’ safer as it's not the core problem. Cryptographic codes may be in trouble- even if the usefulness is less than the risk (but maybe it will push another technology to replace current cryptographic protocols). Machine learning in terms of building specialist hardware- not QC as such- could highly benefit. Pattern recognition may be simpler than search as it's usually on a stream of data rather than having access to a large set of data; see machine learning. “

9. “The ability to break encryption protocols is more of a driver for encryption that is robust to quantum computers.”

Machine learning

10. “Data processing including Security and ML are to be extensively impacted by Quantum computing”

Other

11. “Coordination in distributed systems- network applications.”

We also received 14 comments which concerned non-IT applications, apparently because we had not made it clear that they would be addressed in another question. We have included them in the discussion of question 4.1.

Sub-question 3.2: Timeframe

Discussion

Very notable is that the median response for all applications was less than or equal to 15 years, so optimistic views are in the majority, although there is no consensus. Overall, the estimated time scales are consistent with the ratings of importance expressed in the previous sub-question: applications thought important were also the ones for which it was thought that a quantum computing solution would be quickly achieved.

For all applications, several participants replied that quantum computing would never be important. These replies were included for the purpose of calculating the median, but excluded when calculating the mean and weighted mean, there being no obvious way to include them.

Notes

The responses to sub-question 3.2 are shown on a scale with maximum 100 years, which spans almost all the responses received for expected timescale, except those for which it was "never". One participant gave an expected time scale of 900 years and one 470 years, for increased safety of cloud computing. There was one reply indicating 200 years, for high speed search of large data bases, and one of 200 years for breaking current cryptographic protocols. These four data points are not shown, to avoid compressing the scale, but they affect the statistics, making the mean much greater than the median.

Comments

Predictive

1. "There is much interest in Big Data and Data analytics and I think that this will foster the use of quantum algorithms in the near future (5 years or less)."
2. "The Grover Family- (database searched and pattern recognition) have large differences. Alike encryption breaking (RSA very easy- Elliptic Curve a little harder- and other harder) etc. but RSA is dead by 2020."
3. "The time scales will be governed by the practical development of quantum computers being 10-20 years."
4. "The moment IBM achieves quantum supremacy (they expect it this year) they will need to use their own hardware to make the new quantum technology steps. Chemical and physics simulation applications currently used would already greatly benefit from 100 qubit systems. Assuming that some technologies are stable enough to make simple error-correction with 300 qb- this will be reached by 2020/2021 already."
5. "Given that we can already have highly non-trivial simulations for quantum chemistry with just 20 qubit quantum computers- I think that advancements in quantum chemistry for some simple models can be achieved in the next decade."
6. "Some forms of quantum neural net training can be performed on quantum annealers at present. This debatably makes the technology available at present. For quantum algorithms for making this apply to realistic tasks- we will likely need to wait years for a fault tolerant quantum computer."
7. "Breaking current cryptographic protocols requires a rather large gate-based quantum hardware. This is still a distant goal. Quantum annealers are almost ready for practical optimization tasks."

Uncertain

8. "No idea when a fault tolerant quantum computer will emerge from research programs."

9. "I don't believe anyone is certain of the answers to these questions. More focussed research is needed to identify and test applications."
10. "It seems like a guessing game at this point- with available information skewed by the need to garner research funds."
11. "As I am not an experimentalist I have indicated the timeframe based on what I read and hear from colleagues. So my timeline is at best an optimistic one."

Other

12. "Validation in a relevant environment" seems a flawed question to me: only because it can be demonstrated to work & be built as a product- doesn't mean it's economically viable. For example it may be overall cheaper to run a large cluster of normal CPUs for optimisation than one costly quantum annealer."

Table 3.2 Timescale for validation of quantum computing in a relevant environment, for various applications

	No. of responses	**Mean**	**Median**	**IQR**
		years	years	years
High speed search of large databases	93	24.1	15	22.5
Optimization	93	14.5	8	10.0
Increase safety of cloud computing systems	88	36.4	11.5	20.75
Breaking current cryptographic protocols	91	22.9	15	23.0
Machine learning	90	16.9	10	14.0
Pattern recognition	89	16.7	10	14.0
Other	18	10.4	10	-

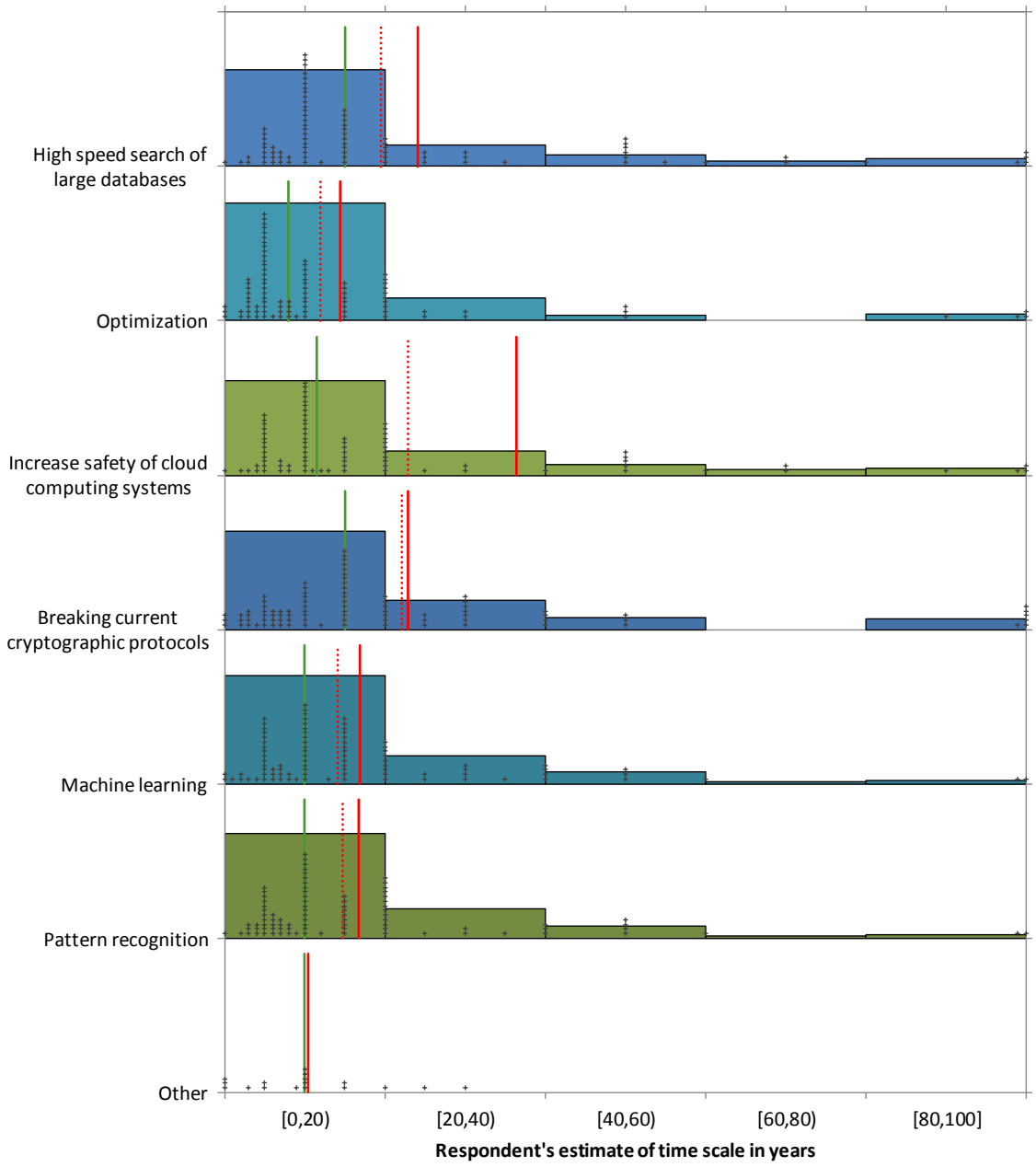


Fig. 3.2 Expected time scale for TRL5 - validation in a relevant environment, for the indicated applications

median | mean | weighted mean + individual responses, stacked vertically

Question #4 Technical aspects, scientific and engineering applications

Please indicate how important you think quantum computing may be for scientific and engineering applications and the timeframe, for specific applications.

Material science

Molecular simulations / quantum chemistry

Aerospace

Other fluid dynamics, e.g. climate modelling

Exoplanetary research

Economics and finance

Simulation of smart cities

Software validation

Other (please specify in the textbox that opens after you click "Submit")

Sub-question 4.1: Importance for applications. Please rate on a scale of 0 to 100 the importance you think quantum computing could play for the following applications.

Sub-question 4.2: Timeframe. Please indicate the expected time-scale in years for validation in a relevant environment (i.e. to achieve Technology Readiness Level 5), for the following applications.

Sub-question 4.3: Level of confidence. Please insert a number to indicate your level of confidence in your own answers

Motive

This question continues the enquiry of the previous one, broadening to other science and technology areas for which quantum computing has been advocated. Eight classes of application were proposed in the question (shown in Fig. 4.1) with an option to suggest others. All but one of these are things which are of clear and obvious economic importance to Europe.

Sub-question 4.1: Importance for applications

Discussion

Participants rated quantum simulation for materials and chemistry as the most promising application, several people also said, in comments, that physics simulation would be important. Many other applications were mentioned: pharmaceuticals, artificial intelligence and logistics, pure and applied mathematics, atomtronics, cosmology, biophysics, block-chain mining and quantum internet. However, not everyone accepted all of these. One participant strongly promoted quantum metrology, but did not elaborate on the connection with quantum computing.

Comments

1. "Modeling complex quantum systems leads to better control of cumbersome quantum effects in basic physics research and to building quantum materials with new properties."
2. "Modelling physical systems is also a significant application (many-body physics-decoherence- quantum-to-classical transition)."

3. "Understanding the failure of quantum computation is important for many areas of quantum physics."
4. "Simulation provides clear exponential speedups. The remaining areas are speculative and can only give quadratic advantages."
5. "Sorry- but most of this is wishful thinking. Material science and molecule/chemistry simulation seem highly relevant. The rest is too remote from what we are likely to be able to actually achieve to be considered. Links to medical and semiconductor technologies applications are missing."
6. "As far as I'm aware- all the significant advantages are in simulating quantum systems (like materials science or chemistry) and not classical ones (like climate- stock markets- or fluid dynamics)."

(As said above, some of these comments were received in reply to sub-question 3.1.)

Table 4.1 Importance of quantum computing for scientific and technical applications

Application	**No. of responses**	**Mean**	**Median**	**IQR**
Material science	95	81.3%	80%	25%pts.
Molecular simulations / quantum chemistry	95	86.8%	90%	20%pts.
Aerospace	93	46.4%	50%	50%pts.
Other fluid dynamics- e.g. climate modelling	90	48.3%	50%	55%pts.
Exoplanetary research	89	30.8%	25%	40%pts.
Economics and finance	93	48.7%	50%	48%pts.
Simulation of smart cities	89	37.3%	39%	40%pts.
Software validation	90	35.5%	35%	36%pts.
Other	12	65.8%	75%	-

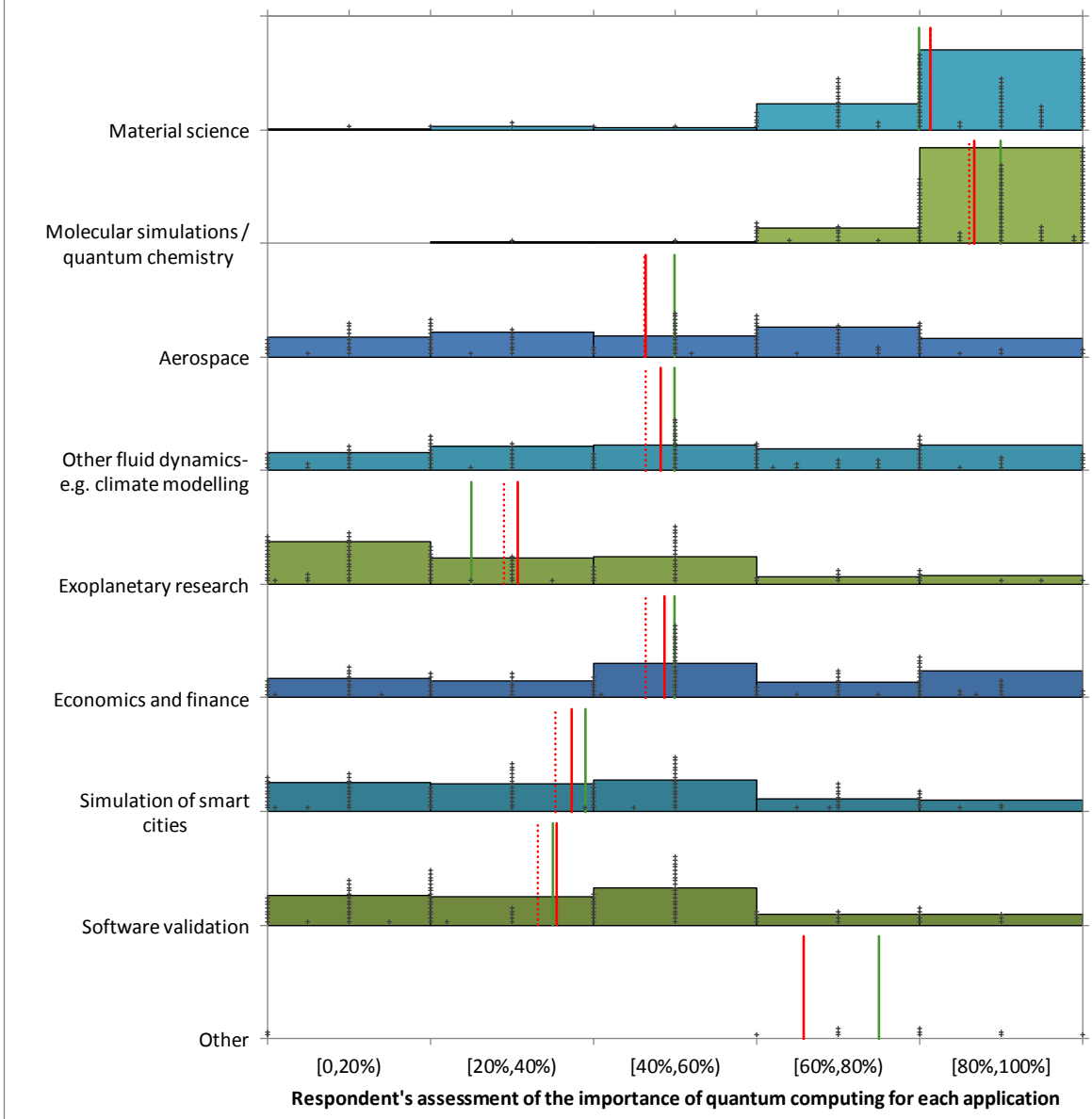


Fig. 4. 1 Importance for scientific and engineering applications

median | mean | weighted mean + individual responses, stacked vertically

Sub-question 4.2: Expected time-scale for validation in a relevant environment (TRL5)

Expected timeframes are again shortest for those applications also deemed most important: in this question material science and molecular simulation. Economics and finance is also seen as an application which might be addressed quickly, with a median response of 15 years.

For all remaining suggested applications, the expected timeframes are longer, with medians greater than or equal to 20 years.

Other scientific and engineering applications suggested by the participants were, with timescales in years in brackets:

Nuclear physics (5);

Many body physics/condensed matter systems (10 or 15);

Decoherence/quantum-to-classical transition (15);

Atomtronics (15);

Particle physics (20);

Cosmology (20);

Biology and biophysics (25);

Table 4.2 Expected timeframe in years for validation in a relevant environment (Starting from May 2017)

Application	No. of responses	Mean (years)	Median (years)	IQR (years)
Material science	90	14.6	10	11.3
Molecular simulations / quantum chemistry	90	11.8	10	10.0
Aerospace	88	26.6	20	37.50
Other fluid dynamics- e.g. climate modelling	85	27.0	20	30.0
Exoplanetary research	81	32.8	25	87.5
Economics and finance	86	25.2	15	28.3
Simulation of smart cities	81	31.8	20	40.00
Software validation	83	32.9	20	50.0
Other	14	13.5	12.5	-

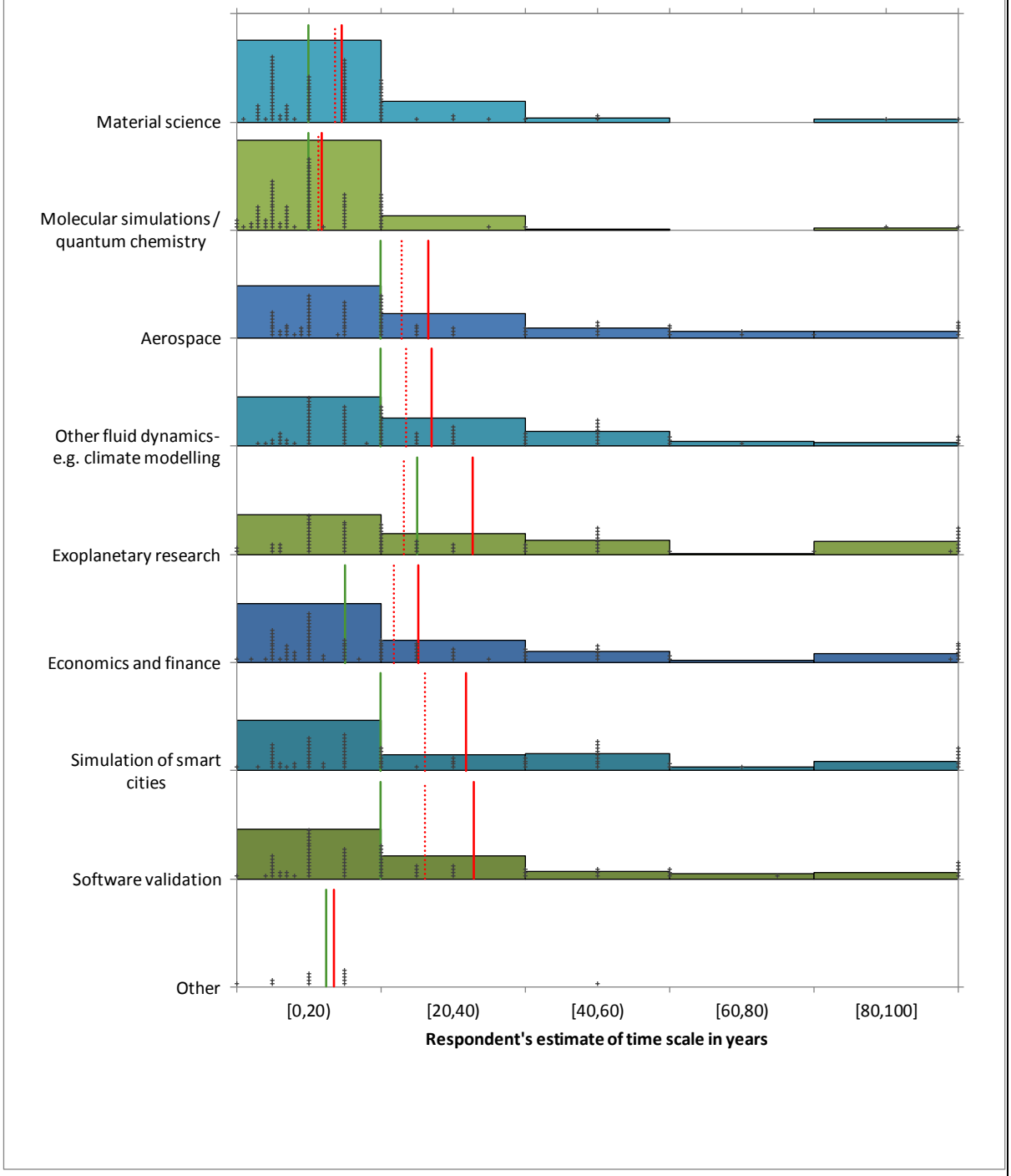


Fig. 4.2 Expected timeframe for validation in a relevant environment (TRL5)

median | mean | weighted mean + individual responses, stacked vertically

Both for the IT applications of question 3 and the scientific and technical applications of question 4, there was a correlation between the deemed importance and the expected timescale: respondents tended to expect the applications which they considered to be important to be addressed in a shorter time scale (Fig. 4.2.1). It is not clear from the participants' comments why this should be the case. One explanation is that the participants expected that resources would be concentrated on important applications and therefore they would be realized more quickly. Another is that the participants regarded the two factors as being inherently correlated i.e. they attached greater importance to things they expected to happen more quickly. (The two factors were intentionally separated into different sub-questions so as to allow other interpretations.)

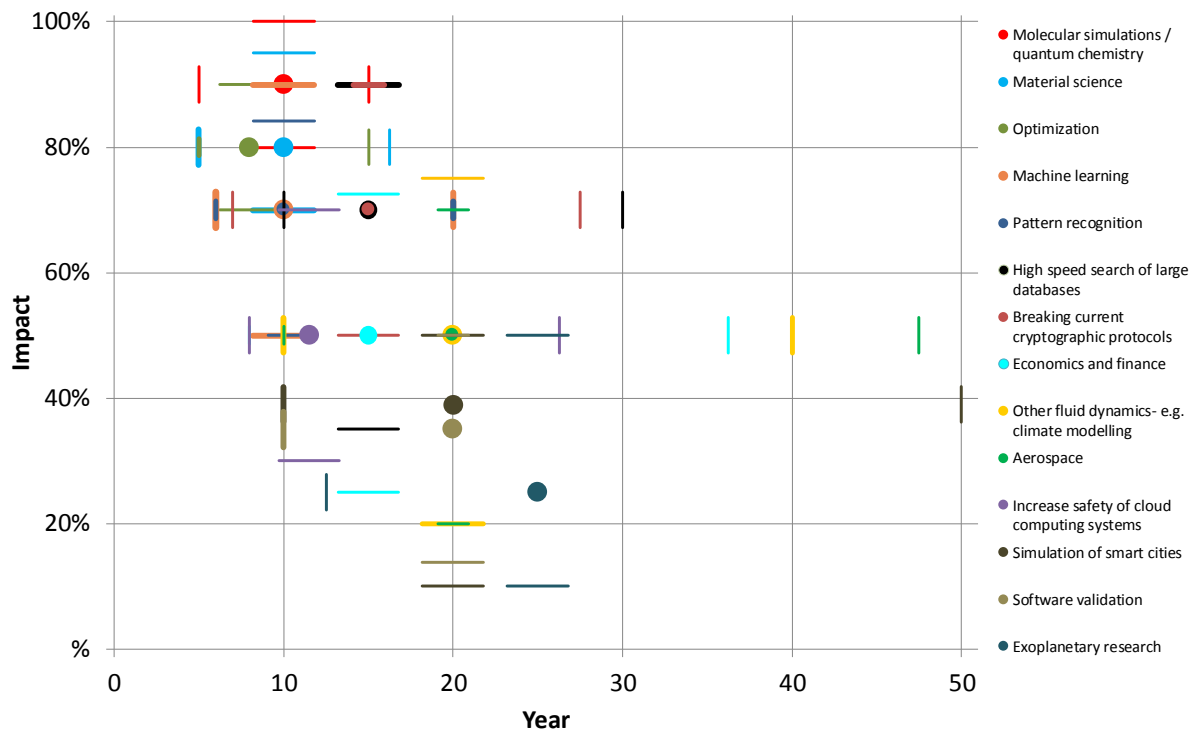


Fig. 4.2.1 Deemed importance of quantum computing for various applications, versus the expected implementation time scale.

Applications with higher expected impact are also expected to be realized sooner. This (anti)-correlation is quite strong: Spearman's rank correlation coefficient ρ = -0.87.

Medians are shown as circles, quartiles are shown as vertical and horizontal fences. (The upper quartiles in time for software validation, 60 years, and exoplanetary research, 100 years, are omitted only to avoid compressing the graph).

Question #5 Social aspects

Potential implications of quantum computing, when it is operationally available

Sub-question 5.1: Impact on society. Please indicate your opinion about the potential benefits and risks of quantum computing to society at large.

From -100=very harmful to 100=very beneficial;

From -100=very dangerous to 100=very safe

Sub-question 5.2: Areas of benefit. Indicate how the listed areas could be affected by quantum computing.

Basic knowledge

Applied Science

Health

Security

Education and training

Finance

Quality of life (e.g. job-satisfaction, work/leisure balance)

Other (please add in the textbox after "Submit")

Sub-question 5.3: Potential regulatory implications. Please indicate your judgement about potential regulatory implications

Few drawbacks and no special controls needed

Requiring some regulation to control abuse, based on incremental development of existing IT law

Requiring rigorous control and restriction to a limited number of trusted users and organizations

Be confined only to research, requiring only research-ethics controls

Other (please indicate after "Submit")

Sub-question 5.4: Certification. Is any certification specific to quantum computing needed – e.g. for security, privacy or quality? What kind? In which area(s)? Why?

Motive

In order to achieve foresight of the policy issues, on the relatively long scale needed for the subject, it was thought necessary to have a vision of the likely societal impacts. Also, responsible research and development should include not rushing to fund a potentially very disruptive technology without considering what the negative effects of such disruption might be.

Sub-question 5.1: Benefits and risks of quantum computing to society at large

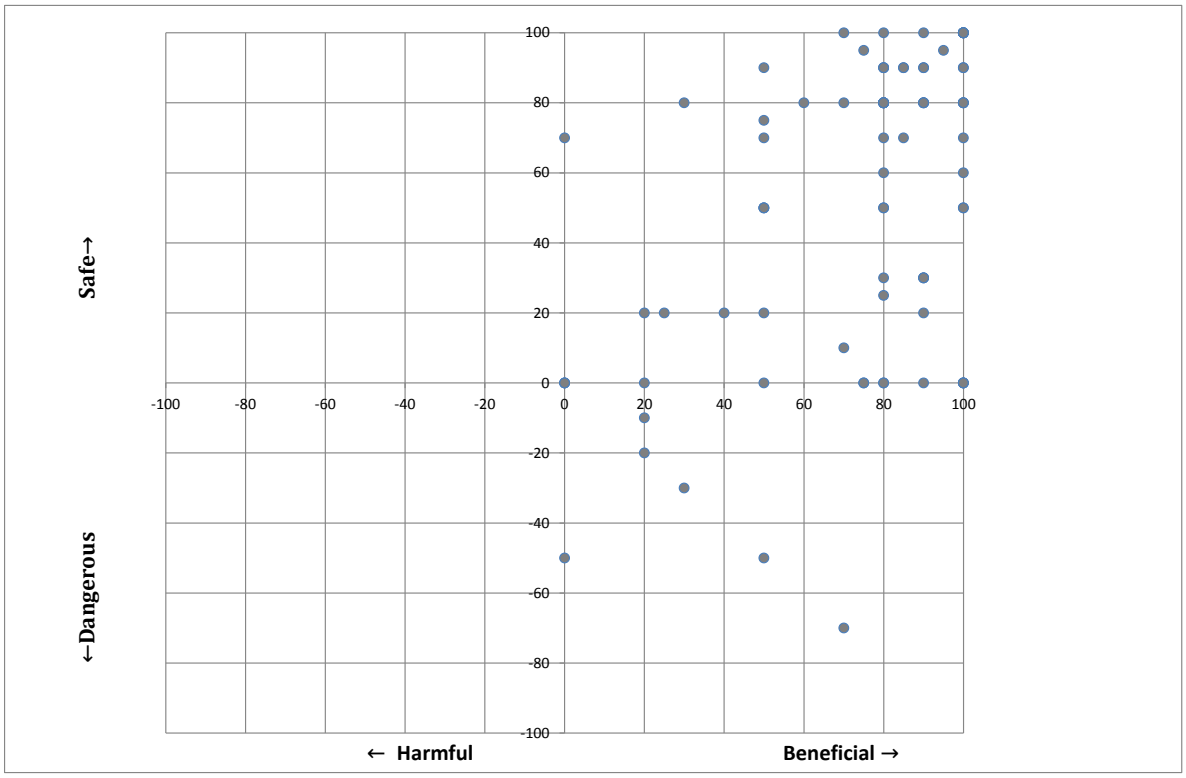


Fig. 5. 1 Benefits and risks of quantum computing to society at large
The expectations for the two factors are uncorrelated.
(Spearman's rank correlation coefficient ρ = 0.47)

Table 5. 1 Averages for potential effect on society at large

	No. of responses[6]	**Mean** (nearest integer)	**Median**
Harm or Benefit (-100 to +100)	92	+74	+80
Dangerous or Safe (-100 to +100)	90	+53	+72.5

The overwhelming majority of respondents consider quantum computing likely to be safe and beneficial. None considered it likely to be harmful. It is the strongest consensus on any question we asked.

The answers in the two dimensions are uncorrelated, as is seen from the graph and the low value of Spearman's coefficient i.e. the people who were more optimistic about the benefits of quantum computing were not necessarily the same ones who were more optimistic about its safety.

(6) Two participants responded for only the harm/benefit category. These are not shown on the graph, were ignored in calculating ρ and do not change the mean and median (+/- 1).

Comments

1. "Definitely beneficial- but it would be in-league with the current progression of technology and people's perception of it. It is not safe- not because of cyber-security etc. But because of the massive knowledge gap between technology and people. I fear society might distance itself from understanding something that controls (eventually) the majority of their lives."
2. "I'm not sure I can answer this – for example- if quantum simulation turns out to be very useful for discovery of new materials then it could be very beneficial but in the wrong hands it could also be very harmful – it is not that technology is 'neutral' but that the way it is developed and appropriated reflects underlying social structures.'"
3. "Depends on the decision making process and several factors which are very difficult to predict. This only means that an strong and parallel ethical control should be established."
4. "Quantum computing is fundamentally so much more powerful than classical computing that its benefits to the society at large are not in doubt. There is nothing dangerous about the technology itself. Only people who use it may be dangerous."
5. "Knowledge is always beneficial and it opens unexpected doors for new applications- which become inaccessible without such knowledge.
6. "On the other hand security- privacy etc. can be a great danger if this technology is not used in a controlled way"
7. "Highly dependent on policy framework- test- validation and preparation by governments. If those things are carried out properly- I don't see much additional threat to the world (which is already under considerable strain- for other reasons)."
8. "benefits will be for immediate users- and only with the passage of time for society at large. The employment of new- powerful computing options always creates risks- such as misuse- or imbalances of power between military users."
9. "Not more or less harmful or beneficial than any other technology and can be used for good or bad. It depends what we choose to do with it. I don't see any specific safety issues compared to current technologies in use and generally seems safe (if we put nuclear energy at 0)."
10. "Any technology in the right hands can be very beneficial and fairly safe. In the wrong hands it can be the opposite. It depends on the state of affairs of the world and on politicians really. "
11. "The answer depends on a multitude of factors such as- who will the device be accessible to etc."

Sub-question 5.2: Effect of quantum computing on specific areas:

Basic knowledge
Applied Science
Health
Security
Education and training
Finance
Quality of life (e.g. job-satisfaction, work/leisure balance)
Other (please add in the textbox after "Submit")

Discussion

Although the great majority of participants see quantum computing as beneficial for all areas listed, there is not a strong consensus on the degree of benefit, the data showing a wide spread and large standard deviations.

It is very notable that basic Knowledge and applied Science are the areas seen as benefiting most, with fewer respondents confident of the benefits to health, security, education and training, finance and economics and quality of life. This suggests that quantum computing is seen as an emerging scientific tool, and not, at least yet, something poised to have dramatic impact on life in general.

The only specific "Other" area mentioned was better clocks, which we had considered outside the scope of the questionnaire[7].

Comments

1. "In the longer run I see massive benefits from health- and applied sciences. Basic knowledge will not grow until quantum-natives enter the workplace. This takes at least 12 years."
2. "Again it's hard to say what will be 'beneficial'. For example in 'Security'- QC might break existing security but also provide ways to identify security threats (and QKD etc. to address them directly)."
3. "In the (very) long run quantum computing will have a great positive impact on all parts of the society."
4. "It could lead to the cracking of crypto algorithms we rely on but I don't believe it would be that difficult to develop new quantum resistant algorithms. Advantages in high frequency trading and its negative effects could be another negative impact."
5. "There may be a harmful impact to financial markets if expensive quantum technologies give rich financial institutions an advantage that skews the market."
6. "I have given a zero where the risk/benefit is entirely dependent on the method of adoption- e.g. policy framework- and level of planning. I believe benefit to applied science is more significant than fundamental- but only marginally. "
7. "It would be a matter of pure belief to say that more-advanced technology is purely beneficial (cf. privacy- community- equality of opportunity- etc.). "

(7) See the earlier report from this study [Lewis, 2017] for a discussion of the topic.

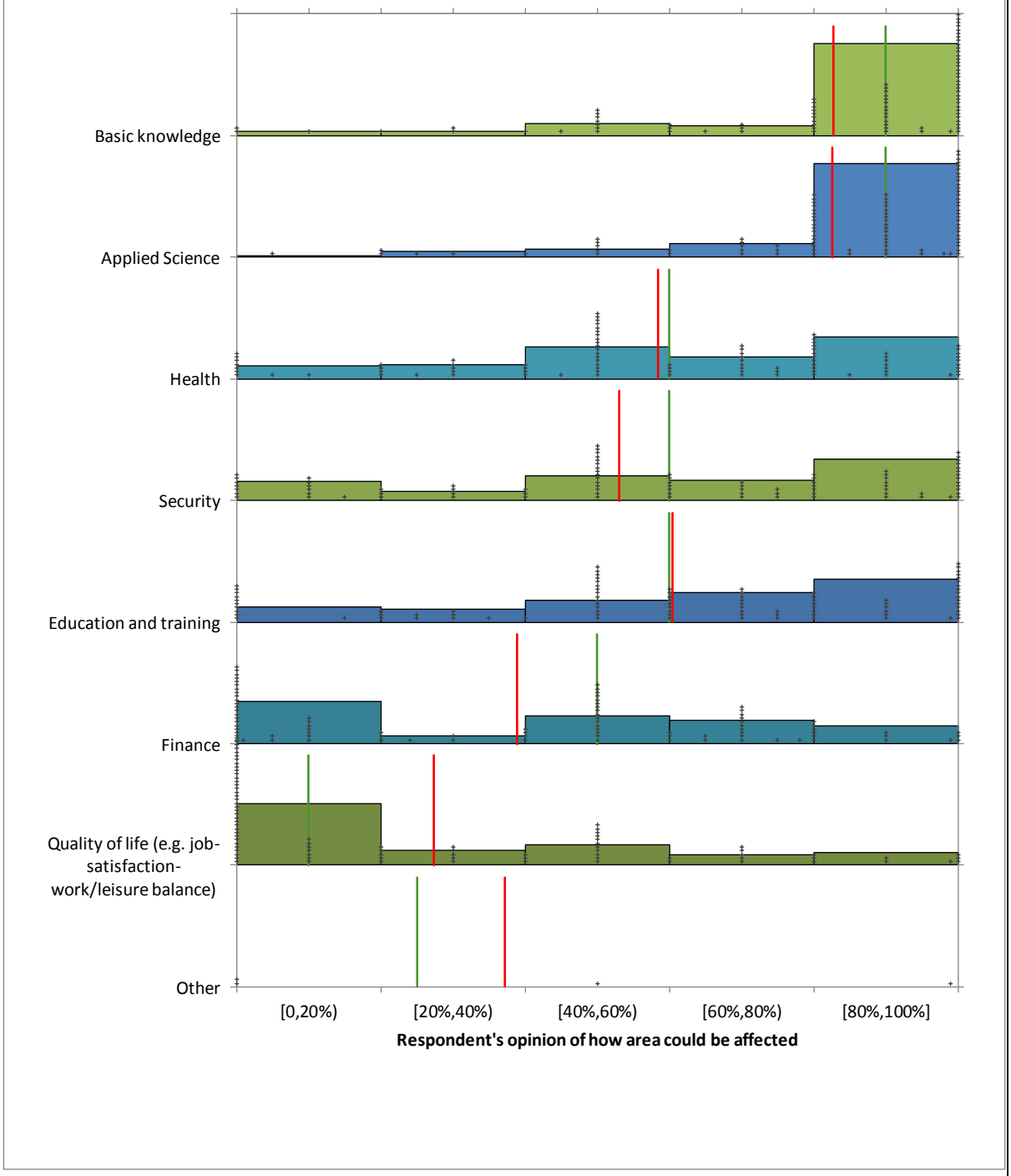


Fig. 5. 2 Effect of quantum computing on specific areas

median mean + individual responses, stacked vertically

Table 5.2 Effect of quantum computing on specific areas

Application	No. of responses	Mean	Median	IQR
Basic knowledge	91	82.7%	90%	20%pts.
Applied Science	90	82.6%	90%	20%pts.
Health	88	58.5%	60%	40%pts.
Security	91	53.%	60%	70%pts.
Education and training	88	60.4%	60%	40%pts.
Finance	89	38.8%	50%	70%pts.
Quality of life (e.g. job-satisfaction-work/leisure balance)	83	27.4%	10%	50%pts.
Other	4	37.3%	25%	87%pts.

Sub-question 5.3: Potential regulatory implications

For this sub-question, the participants were asked simply to indicate which one of the options they considered the best. A total of 87 participants responded.

Table 5.3 Potential regulatory implications

Option	Few drawbacks and no special controls needed	Requiring some regulation to control abuse, based on incremental development of existing IT law	Requiring rigorous control and restriction to a limited number of trusted users and organizations	Be confined only to research-requiring only research-ethics controls	Other (please indicate)
Fraction of participants selecting	36.8%	51.7%	8.0%	0	3.4%

The second option—requiring some regulation—was preferred by an absolute majority.

Although 3 participants said that they would prefer other options, they did not provide details.

Comments

1. "I'm not sure that 'regulation' is the right way to address the social implications - good and bad - from QC. So in that sense the question is irrelevant. The question might also be moot- if QC is only available to research and big corporations - assuming we trust them to behave responsibly. It's hard to see how anyone will be able to do physical damage with QC- but maybe one day either QC could be used as a threat to critical infrastructure- or- conversely- will be so fundamental to critical infrastructure that it will require its own protection."
2. "The regulation should be based in the foresight done when more information and impact could be estimated. It is clear that there should be an important previous effort to advance some responses but now it is too early to pre-suppose an answer."
3. "Wide availability ensures greater development- performance and equity between all potential users"
4. "Laws and regulations will have to be reviewed- as usual- but no special approach is required. Unlikely- though- that these will catch up with actual capabilities and what is possible will be done- and build- no matter the law or the funding."

Sub-question 5.4: Certification

Overall, there was no consensus on the requirements for certification.

Relatively few participants chose to reply.

46 answers were received, which may be grouped as follows.

Table 5. 4 Requirements for certification

Response group	Fraction of participants selecting
No, specific certification not needed	20%
Not yet, or too early to say	15%
Yes, specific certification needed	20%
Certification of genuine quantum character needed	11%
Certification for security and/or privacy purposes needed	17%
Requirements same or similar to certification of conventional IT	17%

Several responses referred to ongoing efforts to establish standards, security models and certification in quantum cryptography, which is somewhat out of scope but, given the early stage of development, a hard and fast distinction between certification of quantum communications technology and certification of quantum computing technology perhaps cannot be made yet.

Question #6 Economic aspects

Implications of quantum computing, when it is operationally available

Sub-question 6.1: Potential economic implications. Please indicate your judgment of the potential economic implications of quantum computing, on all sectors of the economy. Assume a scenario in which conventional computing ceases to evolve in cost and performance as it has done whilst Moore's law has remained valid. The economic effect of quantum computing could be:

Greater than that which conventional IT has had.

Similar to that which conventional IT has had.

Smaller than that which conventional IT has had.

A net loss.

Any of these, it is too uncertain to say.

Sub-question 6.2: Concentration. Please indicate your opinion about the potential effect of quantum computing on the IT sector generally. It will:

Lead to a near-monopoly in IT.

Tend to concentrate control of IT in the hands of a fewer major players.

Have no effect on the concentration of the sector.

Tend to make the sector somewhat more diverse.

Lead to a highly diverse market in which no company can dominate even a small part.

Sub-question 6.3: Future job market. What will be the impact of quantum computing on the job market? Insert a number to indicate the likelihood of each expected outcome. (From 0=not likely to 100=very probable)

Quantum computing will have a disrupting impact on employment, destroying many existing jobs.

Quantum computing will always be limited to a small niche for very highly skilled, specialized experts.

A new generation of computer programmers will arise for developing quantum software.

Applications and satellite activities enabled by quantum computers will generate significant concomitant employment.

Other (enter explanation in the textbox that will appear after "Submit").

Motive

Quantum computing is potentially highly disruptive of the IT sector, which is of central importance to the economy, now and in the future. We recognized that it is premature to attempt an economic prediction, but hoped to achieve some foresight of likely effects on key areas. The impact of quantum computing had to be judged against the background of the expected development of the sector. We chose one possible scenario (end of Moore's law), thinking that it would be the one where the advent, or non-advent, of quantum computing, would have the greatest significance. We recognize that other scenarios are possible for classical IT. In asking the third question, we were conscious of the special importance given to employment within EU policy, in Juncker Priority 1: jobs, growth and investment.

Sub-question 6.1: Economic impact, assuming end of Moore's law

Only one option could be selected.

105 people opened the question. 90 selected an option, 15 did not.

Table 6. 1 Economic Impact

Impact	Fraction of respondents selecting this option, out of the 90
Greater than that which conventional IT has had.	20%
Similar to that which conventional IT has had.	38%
Smaller than that which conventional IT has had.	32%
A net loss.	1%
Any of these- it is too uncertain to say.	9%

Although there is consensus that the effect will be positive, the opinions differed as to the degree of impact. The positive responses are phrased in relation the economic impact which conventional IT has had, which is enormous, and the majority of the participants who responded thought that the impact of quantum computing could be as large or greater. This remarkably sanguine view is reflected in the comments received.

Comments

1. "Joint effect of Quantum Internet- Computing and AI will be bigger than the internet."
2. "It's not really a relevant question- because QC will always work alongside conventional IT. But QC might increase the already large economic implications of IT as a whole - perhaps by orders of magnitude. Do you mean- will QC overcome the limits to Moore's Law? No."
3. "Since quantum computing is fundamentally more powerful than classical computing- it is very likely that eventually its effect will be much greater to the economy than what conventional IT has had until now."
4. "Applications cannot be fully specified yet"
5. "Quantum computing is special purpose and its scope is more limited than classical computing's revolution was."
6. "Since quantum can have great impact in the two top trends if IT (data & security) the potential impact has to be greater"
7. "Impossible to say right now until you can see real examples of where quantum computers have advantages over classical. However- likelihood is that if quantum can help provide improvements to machine learning- search and optimisation- it is likely that- in time- their use may become as ubiquitous as that of classical

computers/electronics. Remember that it took classical electronics over half a century to become what we know if to be today."

8. "Classical computing continues to be required as the basis for an enterprise's operations; you will never send an email using a quantum computer (at least not for an economic reason). Quantum computers are likely to occupy a similar co-processor space as GPGPUs today- though have the potential to be larger than this particular existing market."
9. "We are still learning which applications a quantum computer might have. Currently the applications are limited to several algorithms (Shor,...) with ideas how to extend this to other areas (machine learning- simulation of chemical reactions- biological systems). At the moment it is still difficult to extrapolate the future impact."
10. "The leap to silicon-based processing has been more significant than the silicon to quantum leap will be. Applications and access will be more limited. There is little reason to think that developers and programmers working with current technology have left an enormous amount of untapped potential in information processing. The gains will be incremental- not step-change."
11. "The applications are not new- so QC as it is stated and referred to here is merely an adjustment of how we do IT- so it will not have a major impact at all- but could generally improve things a bit. More general quantum technologies may have more dramatic impacts- but unlikely on what we call IT at the moment directly."

Sub-question 6.2: Potential effect of quantum computing on the IT sector generally

Only one option could be selected.

105 people opened the question. 89 selected an option, 16 did not.

Table 6.2 Effect on IT sector

Impact	Fraction of participants selecting an option, of the 89
Lead to a near-monopoly in IT.	2%
Tend to concentrate control of IT in the hands of a fewer major players.	45%
Have no effect on the concentration of the sector.	34%
Tend to make the sector somewhat more diverse.	16%
Lead to a highly diverse market in which no company can dominate even a small part.	3%

There is no strong consensus but the larger group of respondents see quantum computing as tending to concentrate the sector. One argument for this is that quantum computing is by nature a less accessible technology than conventional IT. In this respect,

its effect would tend to reverse the effect of the microcomputing revolution which has made conventional IT extremely accessible, compared to the situation beforehand. This view is reflected in some of the comments received.

Comments:

1. "Quantum IT will (for this decade) be something for the large institutions- already ordering at a few large suppliers. Additional products will not really change in this way of working."
2. "Requiring large and resources and specialised skills- QC is likely to concentrate ownership. However- not necessarily in the current big corporations - new ones might emerge. At the same time- new and specialised markets for QC-related products and services can be expected."
3. "Initially quantum computers will be expensive and accessible only to major players- but this will become less of a problem as the price comes down. The same process happened with conventional computing."
4. "The actual major hardware players will probably remain- and will be the ones building new quantum computers. So the risk is to end up without any European hardware player- and the quantum software to be dependent of non-European major players. in fact- reproducing / continuing the same situation"
5. "The development of a quantum computer requires significant technology development- similar like for classical computers."
6. "if successful- only large IT companies will be able to really develop large-scale quantum computers"
7. "Unless an immense breakthrough happens and we get silicon based QC- I am afraid this technology would be concentrated in the hands of a few major players"

Contrary viewpoints expressed were:

8. "New quantum computing companies are emerging and may grow to be large future players in this sector. Yet traditional IT companies are expressing great interest in quantum computing. "
9. "Quantum technologies have a very broad application area which creates opportunities for existing and new industries. Because of today's worldwide political situation- 'monopoly' will not happen."
10. "Players who will lead this revolution will take over the lead on the future of IT"
11. "On the assumption that the major players make it to market with competing offerings- this may create an initial diversity which may then resolve as the superior offerings and applications are discovered and drive economies of scale. However- a correctly abstracted ecosystem may maintain a diversity of players unified by architecture standards."
12. "It will be too small a niche to make a lot of difference- except possibly in the very long term"
13. "The benefit ultimately lies in the applications- so the hardware will not have a major impact on the concentration. Few hardware suppliers can be beneficial if they are controlled suitably. Traditional IT will also not actually go away- QC will just be another component in the mix."

Sub-question 6.3: Effect on the job market

The overall view of the effect on employment is positive, but with no strong consensus and dissenting views on all categories. Few respondents thought that quantum computing would have a disruptive effect and destroy many existing jobs. Since the majority of respondents in sub-question 6.1 took the view that quantum computing would have an economic effect greater or equal to that of conventional IT, which is generally believed to have destroyed existing jobs but also created many, the respondents seem to have interpreted question 6.3 as referring to the net effect. Indeed, some were explicit about this in their comments. There is greatest optimism about the possibility that a new generation of quantum programmers will arise. For the other two categories suggested, there was very little consensus.

Comments

1. "Other factors will influence the job market far more than quantum computing could ever. "
2. "Quantum technologies in general will create jobs because it is based on a lot of new enabling (classical) technologies."
3. "In the early days- the ability to program for QC will be a rare and valuable skill. If QC becomes a commodity- then either simple ways to program it will be developed- or else many more QC programmers will be need to be trained. Economies of scale and other parallel technologies such as AI- which might replace much of the 'street-level' programming - tailoring applications to meet the needs of companies- maintaining software- etc. - which is any case a slowly diminishing industry- and can be easily off-shored to the extent that it is done at all. I do expect industries around QC to be important economically- but not necessarily to employ very many people. But this is more or less a guess."
4. "No new technology will destroy jobs- it just transforms the inconvenient machine-like jobs to more convenient ones. Assuming the likely event that a large-scale quantum computer will be built- its effect will so large that it will create a great number of jobs in many different areas."
5. "Lump of labour fallacy does not apply to quantum computing just as it doesn't apply to other new developments i.e. it may make some jobs obsolete but it will create others."
6. "Strong chance that QC will provide satellite benefits and spinoff application. All other answers are highly speculative- and dependent on applications that we can't yet imagine."
7. "difficult to predict the impact on such long-term technology; however- machine-based tasks are already happening- it's not the quantum computing that will change it so drastically. on the other hand- new skills & competencies will be required"
8. "this is hugely speculative- especially without a timeframe for the question"
9. "Impact seems generally minor and won't be on the applications and IT overall referred to in this survey (they will still be there- even if powered by QC). Maybe we need less programmers (not being replaced by QC programmers)- as QC and related technologies offer alternative approaches- but AI is already doing part of that job now."

"I think that as Quantum computing grows- the advent of new skills would mean that jobs will grow concomitantly. I suspect there would be a transient period as Quantum computing starts to take over conventional IT- but i believe the labour market will eventually adjust accordingly. History has always shown us that it does."

Table 6.2 Effect on the job market

	No. of responses	Mean	Median	IQR
Quantum computing will have a disrupting impact on employment- destroying many existing jobs.	90	14.2%	8%	20%pts.
Quantum computing will always be limited to a small niche for very highly skilled-specialized experts.	89	48.1%	50%	45%pts.
A new generation of computer programmers will arise for developing quantum software.	90	71.6%	78%	39%pts.
Applications and satellite activities enabled by quantum computers will generate significant concomitant employment.	88	60.4%	60%	40%pts.
Other	5	30.0%	0%	-

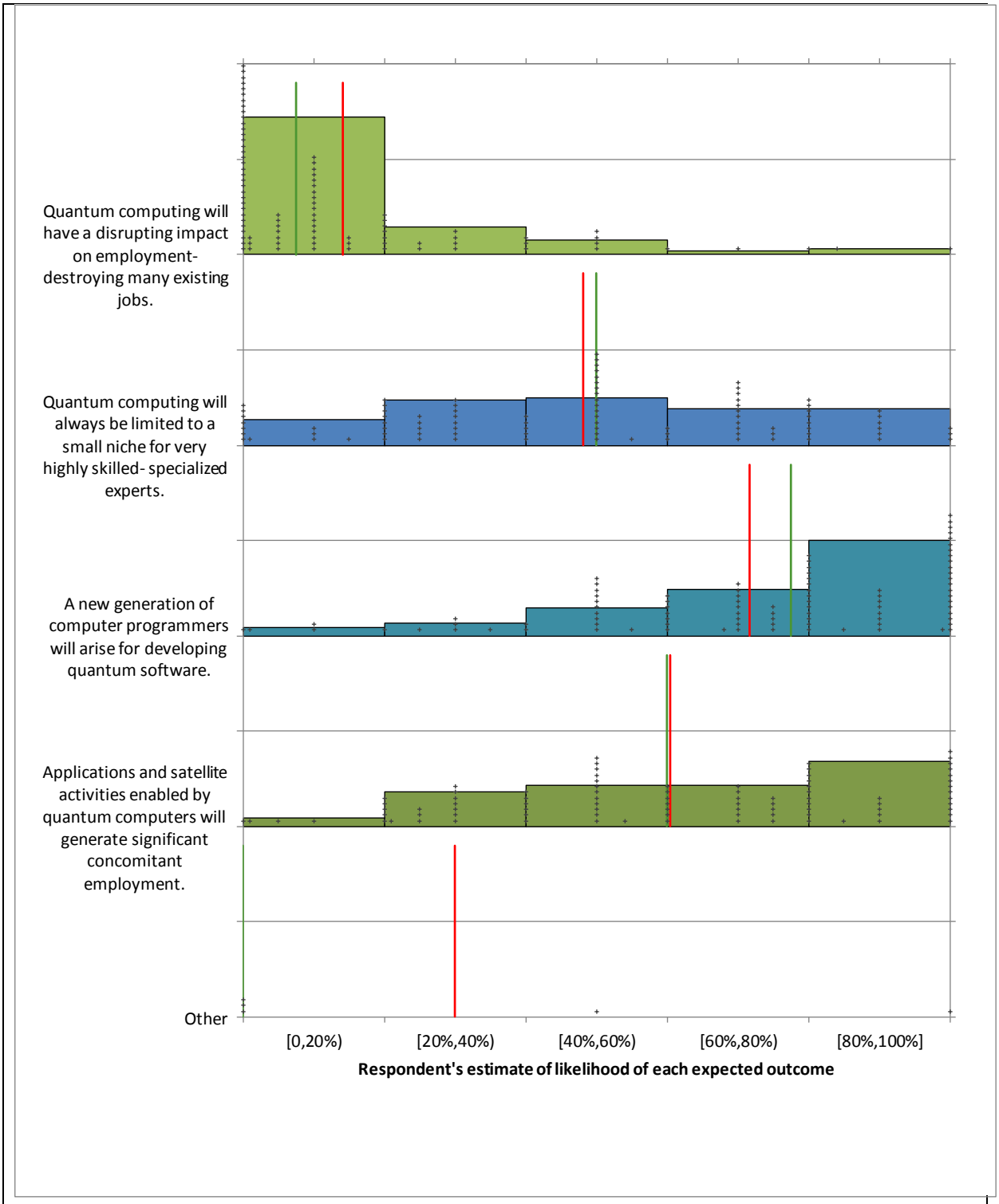


Fig. 6. 3 Effect on job market

| median | mean + individual responses, stacked vertically

Question #7 European Public Funding I

Please give your opinion about the priorities of European public funding for quantum computing hardware.

Sub-question 7.1: Public funding priorities. Please indicate which quantum computing hardware should European public funding give priority to.

> *Basic research, e.g. because it is premature to move ahead with technology development and the attempts being made to do so are misguided.*
>
> *Enabling technologies, which would increase the available options for a full-scale quantum computer.*
>
> *Solutions such as quantum simulation and adiabatic computing, which have a good chance of being useful in the medium term.*
>
> *Two or three credible candidate platforms, with an aim to produce full-scale computers.*
>
> *One chosen leading candidate platform, since only by focusing all available resources is there a reasonable chance of success.*
>
> *Other (please indicate in the textbox after "Submit").*

Sub-question 7.2: Reasoning for public funding. Please explain your response to the public funding choice

Sub-question 7.3: Level of confidence. Please insert a number to indicate your level of confidence in your own answers to the questions on "Public funding priorities" and on "Reasoning for public funding". (From 0=not confident at all to 100=extremely confident)

> *Level of confidence in public funding priorities*
>
> *Level of confidence in reasoning for public funding*

Motive

This question relates to European Future and Emerging Technologies (FET) Flagship in quantum technology (see https://ec.europa.eu/digital-single-market/en/quantum-technologies#Article). Questions 7 and 8 concern both the ongoing ramp-up phase under Horizon 2020, and the main phase, to take place under its successor research and technology development investment programme, called "Horizon Europe".

Sub question 7.1: European public funding for quantum computing hardware

Nearly half of the first priorities are for funding basic research. If the second and third priorities are considered, enabling technologies are preferred over basic research, and medium approaches next. No difference in this respect is seen between the unweighted and confidence-weighted data. There are some dissenting opinions, especially in favour of two or three credible platforms, but only two respondents were ready to recommend selecting a single favoured hardware platform for quantum computing. This is a key result of the RTD and has important implications for the organisation of the FET flagship. In order to retain the support of the quantum computing community it will be necessary to keep hardware options open well into the life time of the Flagship, and maybe throughout its life time, which implies dividing and diluting the funding. These issues were mentioned by many of the respondents in their explanatory remarks.

Given the need for debate on funding priorities, the respondents were especially encouraged to give explanatory remarks for this question by means of a specific sub-question. All the remarks we received are reproduced below in full.

In most (although not all) cases, they are consistent with the first priority selection made by the respondent, so they are categorised below accordingly.

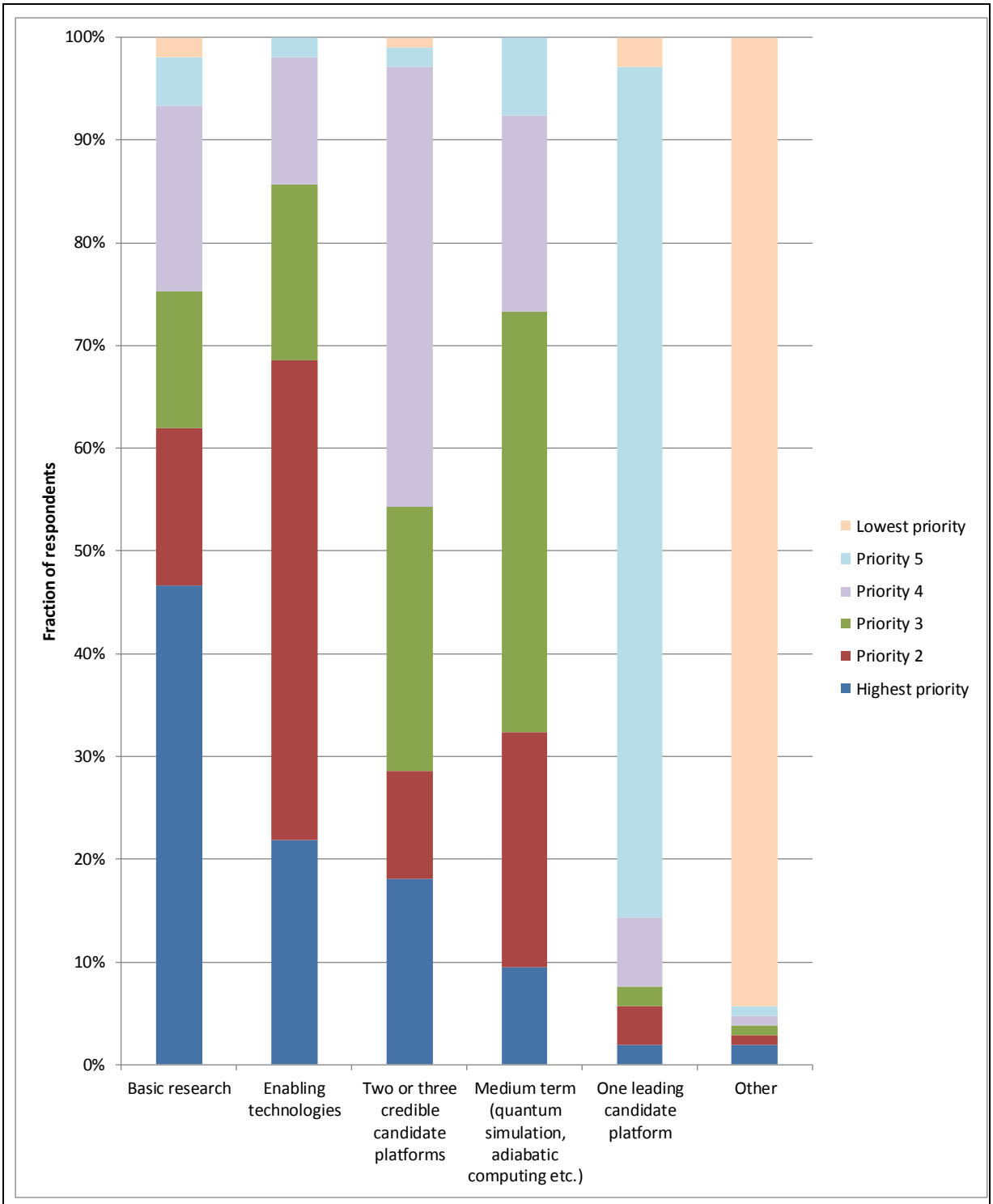


Fig. 7.1.1 Priorities for European public funding of quantum computing hardware

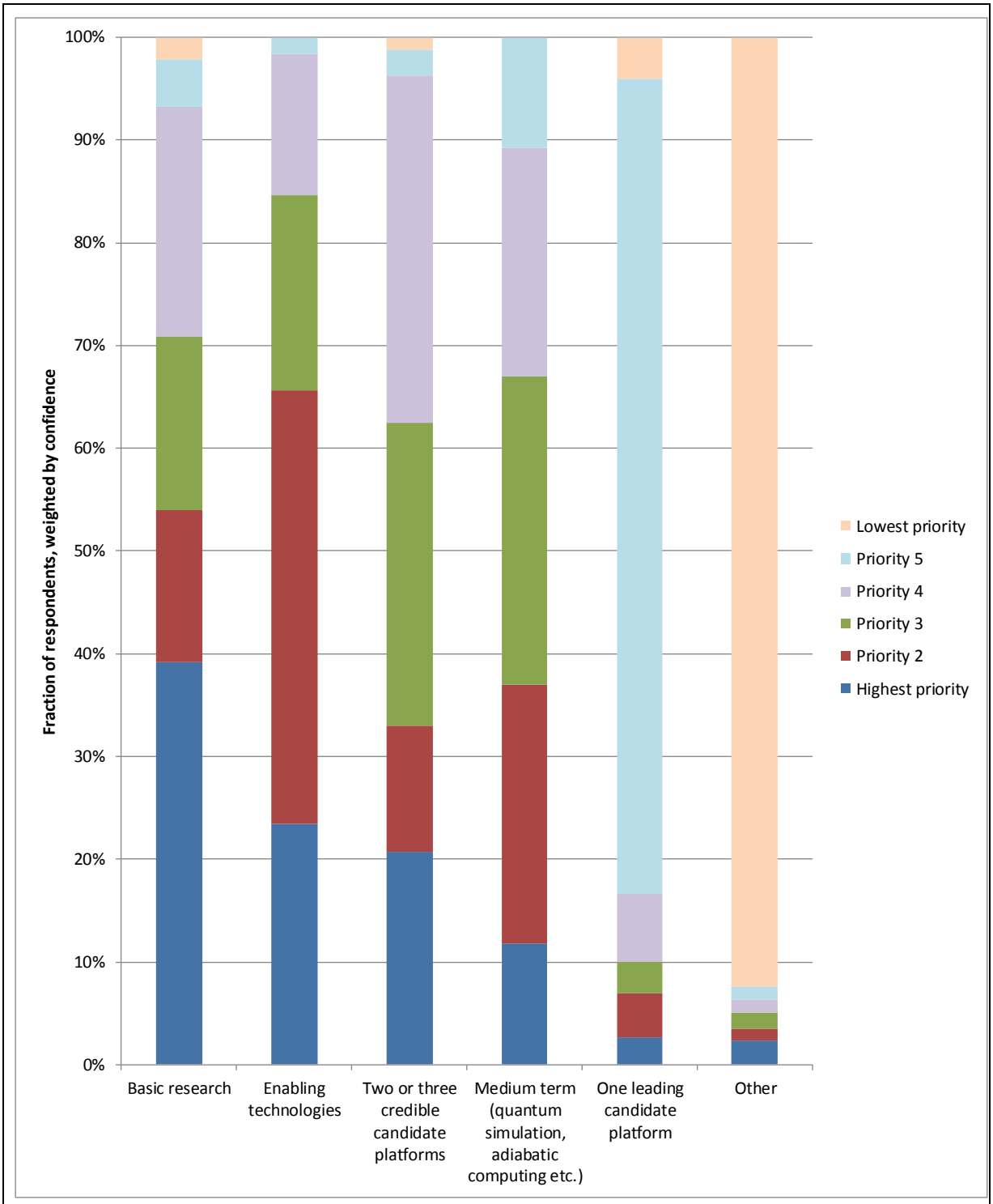


Fig. 7.1.2 Priorities for European public funding of quantum computing hardware, weighted by respondent's confidence in their own answer

Comments on reasoning, clustered by respondents' respective first priorities

Basic research

1. "Quantum technologies still need mainly research. Enabling technologies and demonstrations are important to verify or European progress."
2. "Quantum computing is still at an early stage and funding still needs to be given to basic research as well as studies on scalability."
3. "highest priority should be given the basic research with decreasing priority to more specialized approaches - there are only few candidate platforms so far and I think more basic research is required to find the optimum system"
4. "With a time frame typically between 15-20 years- it is hard to ignore the purpose and contribution of quantum research for basic science. Actual realization of a quantum computer will need a societal demand and push (e.g. warfare or railway problems in the case of conventional computers)."
5. "Both basic research and enabling technologies should work together towards developing one or two credible platforms."
6. "I think the status of the field at this point is at the level where basic research will prove to be most beneficial. The reason being it the many uncertainties: We do not know what quantum computing is good for- which platform would serve best potential applications."
7. "We're near the tipping point now. Getting the enabling technologies in place with a focus to real solutions will become more and more of a priority."
8. "Basic research is the most important thing for public sector funding of quantum computing. There are a number of basic questions about applications and platforms that still need to be addressed. We also vitally need to build the enabling technologies for verifying and validating quantum computers."
9. "I think it is a bad strategy to focus on one- two or three candidates only. For example- I think basic research is mandatory in fields like decoherence and quantum-to-classical transition."
10. "It would be wrong to choose one candidate and shower money on it- as there is not a clear frontrunner at the moment. All approaches so far show pros and cons to different extents. By funding basic research as well as enabling technologies- we keep our eyes open to new possible implementations while pushing forward the state of the art of the available implementations."
11. "Too early to say which technology will provide the quantum computer. It could be that it has not yet even been considered."
12. "Many approaches are still needed"
13. "Currently- Quantum technologies are not enough mature to focus on some specific platforms. As a consequence- a basic research about Quantum Computing and its applications is still necessary to face efficiently the second age of computing."
14. "All of those are applicable"
15. "Basic research in the field plus a few experimental platforms for implementing quantum simulations are the most realistic options."
16. "It is necessary to secure the continuity of the basic research and development of several platforms in this field as there is lot to be understood and accomplished before the quantum computing can be realised in large scale. Individual companies can make selection between platforms. The enabling technologies are

crucial for the development of scalability and production of the feasible technologies."

17. "At this stage it is too early to tell which platform will be feasible for building a quantum computer. Supporting too many platforms defocuses the available resources. Funding 2-3 (or 4) platforms seems reasonable."
18. "I think it's too early to choose- so fund the most promising platforms in a concentrated way. After the ramp-up- strategic decisions can be made on which efforts to strengthen and which to stop / slow down"
19. "The field still needs some basic research. Since an optimal candidate is not established yet- it would be prudent to keep funding several possible candidates. Then- it should 1st focus on some concrete result with the 1st generation quantum computer before moving onto optimization of the machine itself"
20. "Quantum simulation is the next application"

Enabling

21. "EU must hold itself on a global market. Let's face it- we are lagging behind tremendously on China and the American Corporations. The FET is booting up sluggishly- and other continents are taking over many of our resources. We cannot hope to be leaders in quantum computing hardware. We must look a step further and deal with the step after that. We should focus on what we are still leading in- (Quantum Software- Quantum Sensing and Quantum Internet)- large scale quantum computers will be a side-effect of these investments."
22. "Enabling technologies are the key to long-term success- they should certainly be prioritised."
23. "We do not know which technology will be the best for full-scale quantum computer. So- researchers shall continue working on all promising technologies. Full-scale quantum computer should be much more powerful than adiabatic computing. So- full-scale quantum computer has higher priority. At the same time adiabatic computing is already reality and we can hope to get useful adiabatic computer faster than full-scale quantum computer."
24. "I believe the full-scale integrated hardware will be mostly implemented by the private sector and there are several fundamental problems to solve in enabling technologies such as materials science."
25. "Enabling technologies is the fastest way to realize quantum computer. Basic research is very important- but it will not directly lead to the development of a real quantum computer."
26. "it is time to try and consolidate promising approaches. this will require substantial investment so choices will need to be made. already- it is clear that some platforms are not going to make it into a large-scale device."
27. "To support small- medium- and large companies to develop quantum technologies products- and applications."
28. "The topic (computing) is still at its fundamental stage- where a public funding could be more convenient. However- I would more support a public funding for the generic building blocks (technologies- architecture- algorithms) which could have an impact on other topics like quantum sensors- instead of a pure public funding focusing only on the quantum computing goal"
29. "Quantum technologies and enabling technologies still require a lot of research- we don't know the best candidate for a quantum computer."

30. "Enabling technologies should be made a priority- because there are many materials related problems that should be resolved before final choices on competing technologies can be made"
31. "We need a broad basis for potential approaches rather than narrow focus on a few options. We also must avoid focus on trying to simply come up with better solutions to technologies that are currently being used - it will only ever be a minor improvement."
32. "Most present day options are not scalable and considerable funding is needed for further enabling work. There is no single viable candidate and multiple options need to be explored"
33. "The main goal should always be the full scale quantum computer. However- since it is too early to say which platform might be the best- we should focus on two or three candidate platforms. Namely: Ion traps (on a chip), Solid state devices and of course photons as flying qubits"
34. "Small-scale quantum technologies and quantum simulators may be achievable in the short term. A full-scale quantum computer is a long way off. Basic research is always important."
35. "Current available approaches in quantum computing are rather primitive and will not lead to anything really useful in the near future. Current quantum computing paradigms and mostly following successful digital classical concepts that are not suitable for scalability and usefulness in quantum computing applications. Therefore- I think that basic research is still needed- not to follow or develop current paradigms but to propose and design still highly disruptive novel concepts in quantum computing. In between- solutions and advances involving current quantum simulation and adiabatic computing efforts are necessary. But this will be sooner or later replaced by novel disruptive quantum computing paradigms. Which? We are working on that and I will not display here my thoughts- just hear my talks and read my papers. It is also time to discard or put some pressure on quantum platforms that are not showing a path towards scalability or are just following primitive concepts that may not work. Digital quantum computing with quantum error correction is a path to failure in the next decades unless there is a technological breakthrough that is not happening and- apparently- not being sought. Analog quantum computing- including adiabatic or topological methods- is just a current fashion that will be sooner or later overcome by novel disruptive quantum computing paradigms."

Medium term solutions such as quantum simulation and adiabatic quantum computing

36. "First, is the most close today for application; second, is very important but usually forgotten by the political decider- who are not always the most clever ones."
37. "These seem to be the safest horses to bet on"
38. "Adiabatic computers and quantum walk simulators of complex Hamiltonians are almost ready for utilization. This will show some plausible outcome to the audience that is fatigued with never ending promise of general quantum superiority. Cold atoms and superconducting circuits are clearly two most promising technological solutions that require development. The basic research is needed to discover new useful applications- additional future computational platforms- and novel algorithms that outperform classical computation. The more spin-off technological applications will be produced the longer quantum computing will have a broad support of community. "

39. “It is futile to concentrate on overpolishing small-scale quantum devices or developing advanced quantum software for non-existent hardware. We should go full speed with developing \reachable\" quantum technologies- such as adiabatic quantum optimization- quantum sensing and simulation. This will bring about technology advances and theoretical methods- which will eventually enable the realization of universal quantum computing."
40. “I do not think that we know already which technology will be able to function as a scalable quantum computer. Thus- public funding will need to support the most promising ideas- but should not be focused only on one technology- yet. The craziest idea at the moment might make it in the end.”

Two or three credible candidate platforms

41. “Two platforms are reasonable at this point as both have a reasonable chance of success.”
42. “Basic research is always important- but for achieving QC- a balance will be needed - there is still quite a lot of ‘basic’ physics and engineering required to make this work. So this is not ‘basic’ in the sense of ‘curiosity-driven’ (good though that is) but also driven by the need to make something work."
43. “Currently leading edge technologies will enable the respective markets. A second generation of quantum computers will be more evolved and provide the necessary information to decide on the most promising architecture. Said architecture might be not even realized yet (see for instance the Majorana approach). All of that is based- and requires- fundamental research as a seed for new ideas, Adiabatic quantum computing is likely not going to be beneficial on the long run - neither for larger systems- nor for higher speeds- while it is too early to decide on a single platform yet.”
44. “It makes no sense to put all eggs in one basket at this stage- but a few frontrunners worthy of pursuit are emerging”
45. “A certain focus on a few platforms would lead to focus and critical technology and system oriented questions towards full-scale computers. This in turn will provide clear roadmap-oriented work and finally product definition. And potentially clear statements on the limitation of one technology over this other.”
46. “Many platform has shown extremely promising results. A current scalable architectures start to be within reach of current technologies.”
47. “Given the status of the development I see a combination of a focus on leading candidate platforms to gather with an enhancement of the basic research activity as the best route forward.”
48. “At the moment it seems to me that there are 2 or 3 viable alternatives. So I think it is wise to give each of them a chance. In addition- even if only one of the three candidates succeeds- the spin-off technology that will emerge would certainly be viable. In addition- we should look at the long term goal which is a fully integrated quantum infrastructure (quantum internet if you will) and this would require a successful marriage of several hybrid infrastructures (optics-condensed matter- silicon perhaps). It is therefore preferable to hedge ones bets on two or three good candidates in order to have the best gains in the long term.”
49. “I think that the technology is at the point where credible quantum computers are possible- but it's not obvious which technologies will be the best. Therefore supporting a range of options- and continuing enabling and basic research to produce more options is the best way forward.”

50. "Focus is required to ensure the Flagship has any impact. Flagship should aim high- so for the large-scale quantum computing."
51. "The fundamental building blocks of a trapped-ion quantum computer have been demonstrated to an exceptional level. While further improvements are required such as further increased gate fidelities- it is now important to push towards full-scale devices to bring sub-systems together and tackle the challenges that will undoubtedly be uncovered when scaling up. This is also the only way to remain competitive in an increasingly fast moving environment. Focusing on two or three credible platforms will allow for sufficient scope to encompass different promising approaches while providing the required focus to push ahead."

One chosen leading candidate platform

52. "building a large scale quantum computer is the greatest challenge with the greatest benefits. Hence we should aim for it seriously in Europe. The funding reserved for quantum computing is not so large that it would allow for a serious development of several distinct platforms. Thus we should primarily invest in the most promising one. Obviously- a lot of enabling technologies and basic science need to be developed as well but the actual quantum computer should have the greatest weight."
53. "Europe is not strong enough to cope with 2 or 3 quantum platforms in parallel."

Other

54. "It would be convenient to work on European initiatives of quantum basic infrastructure. European companies have to have quantum infrastructure to grow independently of non-European initiatives"

Subquestion 7.3

The median confidence in priorities was 80%.

The median confidence in reasons was 80%.

Most respondent's expressed the same confidence in their priorities as they did in their reasons.

Question #8 European Public Funding II

This question concerns the types of funding instruments which you consider useful for quantum computing, taking the ones currently used in Horizon 2020 as the starting point.

Please also indicate other possibilities which you think would be appropriate for quantum computing, using the second column.

Sub-question 8.1: Horizon 2020 instruments. Indicate you preferred distribution of funding among the following types of funding action, on a scale of 0 to 100%.

- *Research & innovation actions (RIA)*
- *Innovation actions (IA)*
- *Coordination & support actions (CSA)*
- *SME instrument actions*
- *ERA-NET Cofund actions*
- *Precommercial procurement (PCP) & Public procurement of Innovative solutions (PPI) actions*
- *European Joint Programme (EJP) Cofund actions*
- *Other (please explain in second column)*

Sub-question 8.2: Other instruments. Please indicate any other funding instruments which you think would be suitable, such as those from national programmes or previous European programmes.

Sub-question 8.3: Level of confidence. Please insert a number to indicate your level of confidence in your own answers to the questions on "Horizon 2020 instruments" and on "Other instruments". (From 0=not confident at all to 100=extremely confident)

- *Level of confidence in your preferred funding distribution among Horizon 2020 instruments*
- *Level of confidence in your indications of other instruments*

Motive

The current FET Flagship model has, for the main phase, a large "core project" playing a leading role for the whole duration of the initiative and a set of "partnering projects" [SWD 283, 2014].

The detailed governance model for the main phase of the FET Flagship on Quantum Technology has not yet been finalised. We felt that it would be helpful to take existing instruments many of the participants would be familiar with as a starting point for the discussion. Moreover, the ramp-up phase for the FET Flagship on quantum technology is taking place under Horizon 2020, using its standard funding instruments, so the answers to sub-question 8.1 are directly applicable. Sub-question 8.2 then invites participants to extend their recommendations to other types of funding instruments.

The types of actions used now are described in general Annex D of the 2016-17 Horizon 2020 work programme [H2020annexes, 2017]

Sub-question 8.1: Preferred distribution, based on H2020 instruments

A preference for the more research-geared, knowledge-generating actions Research and Innovation Actions (RIA's) was expressed, against the more development-geared, technology-generating Innovation Actions (IA's). This is consistent with the answers for sub-question 7.1, where a priority for basic research was expressed. The IA's were preferred over other actions, however.

Rather few participants want to see a concentration on Coordination and Support Actions, which could be out of concern that it would dilute the funding for their preferred actions, or out of a belief that the community is already adequately served in this respect. Two contrasting comments were made about this (see comments 4. and 5. below).

All the other instruments listed scored lower preferences. It is surprising, and perhaps disappointing, that this was true even of SME instruments, given that small start-ups are now appearing in quantum computing, especially in software.

Relatively few respondents answered this question, only 66 out of the 101 who opened the question.

Table 8.1 Funding instruments

Instrument	Mean	Median	IQR
Research & innovation actions (RIA)	40.7%	40%	29%pts.
Innovation actions (IA)	17.7%	19%	12%pts.
Coordination & support actions (CSA)	8.9%	8%	7%pts.
SME instrument actions	8.1%	10%	9%pts.
ERA-NET Cofund actions	9.8%	9%	11%pts.
Precommercial procurement (PCP) & Public procurement of Innovative solutions (PPI) actions	5.4%	4%	9%pts.
European Joint Programme (EJP) Cofund actions	5.8%	5%	11%pts.
Other	3.6%	-	-

The call for proposals of the ramp-phase of the Quantum Technology Flagship was issued on 31 October 2017 and closed on 20th February 2018. The allocation of funding was: RIA 87.8%, ERA-NET 6.8% and CSA 5.4%, no other instruments were used. These figures refer to all branches of quantum technology. Of the 141 proposals received, only 10 were for quantum computing systems but some of the 87 proposals received for fundamental science were orientated towards quantum computing.
http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/fetflag-03-2018.html

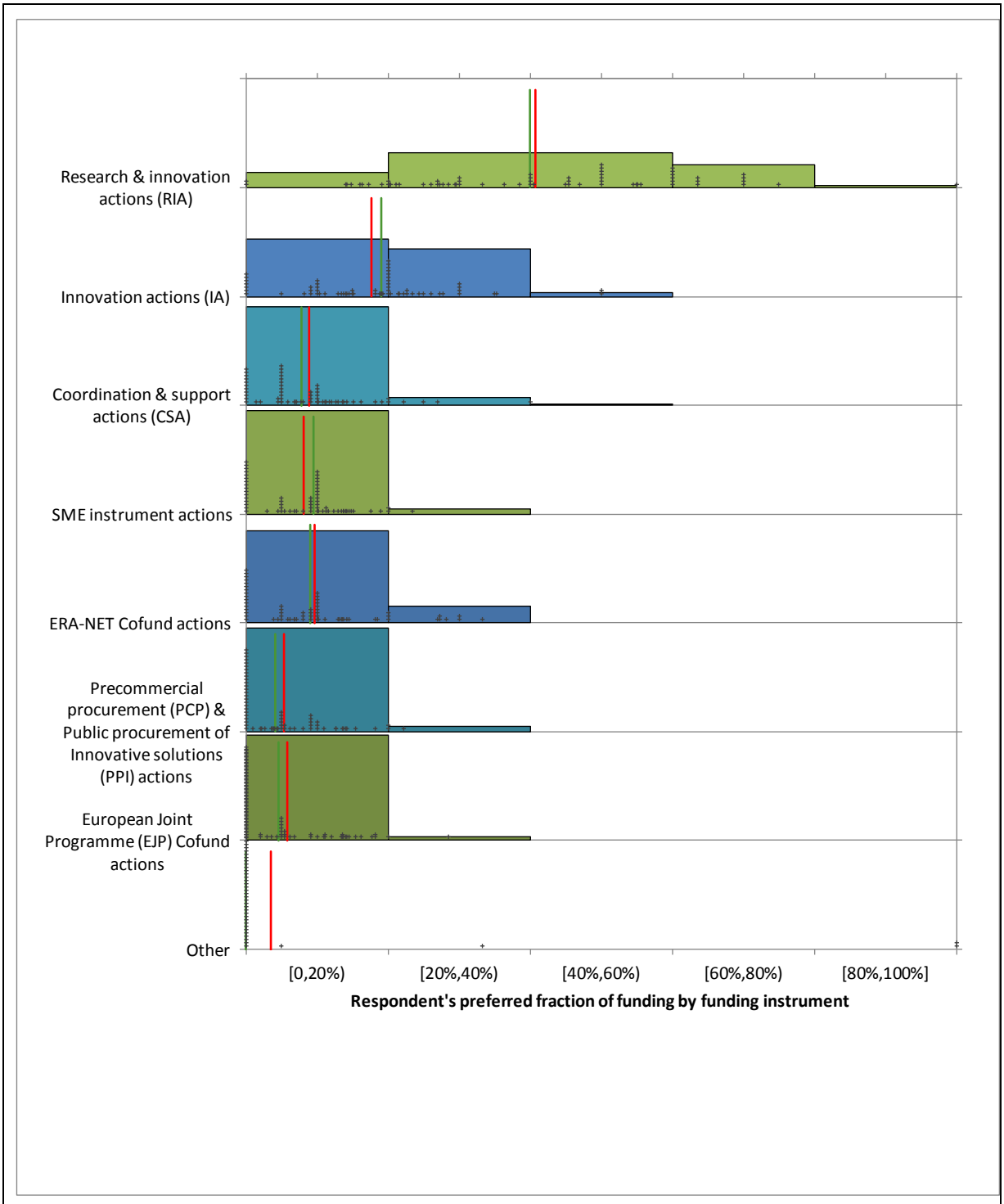


Fig. 8.1 Preferred distribution of EU public funding, based on H2020 instruments

median mean + individual responses, stacked vertically

Comments

1. "Large demonstration programs as planned in the Quantum Flagship".
2. "Quantum research should still remain primarily as a curiosity driven program. "
3. "Focus should be on funding research- with some support for applications and commerce to enable creating links and bringing in new ideas for problems to look at."
4. "I have given a high score to CSA because a few overview projects- each quite small- could greatly improve the focus and impact of the Flagship. I don't really have an opinion on the PCP etc. actions- but- as the research progresses- involvement of industry and especially SMEs will be important"
5. "Eliminate Administration and coordination spending within big European wide funding projects. Researchers are perfectly capable of coordinating themselves. This is just a giant hole to waste public money in. I am in favour of having the majority of funds be European wide but the current state of affairs of how these are coordinated and funded (with different countries putting different money and trying to get more out of the pot than what they put in) is detrimental. Please make access to funding uniform and accessible throughout all European institutions regardless of which country they reside."

Sub-question 8.2: Other funding instruments

Only 19 participants replied with ideas to this sub-question. The replies could be categorised into six groups, and one less easily categorised reply.

Specific existing instruments not mentioned in 8.1

1. "national programs- national networks- IP and STREPS"
2. "National programs can be utilised but they should not be fully restricted to the QT Flagship roadmap. FET Proactive would be great instrument too."
3. "Academia is- to my knowledge- the ONLY sector where the idea of a Europe where people freely exchange ideas has worked 100%. I would encourage that more and more funding be consolidated into European funds. This would ensure a more uniform research network (lets not kid ourselves there is a large chasm between north and south in terms of cutting edge research)- free mobility of skilled workers and- if nothing- else would strengthen the European scientific community as a whole. So more Marie Curies- more mobility grants- more joint EU projects involving several research and development institutions from across Europe and less concentration of capital in one or another country. " "FET OPEN and Marie Curie networks"
4. "Would like to see greater funding into FET Open as a mechanism for small scale and highly innovative programs. Too much emphasis on flagships- clusters- hubs and the like- soaking up large funds- restricting the number of players and limiting the options"
5. " The Flagship should be run like IARPA but without the monthly reporting. Consortia consisting of whoever is needed (universities- industry- government,...) targeting clear 5-year goals. The Flagship runs the risk of being divided into many small pieces covering many subjects- in which case it will not have the impact it could have and Europe will have missed a huge opportunity."
6. "The quantum hub structure in the UK could be an interesting model to consider in a varied form."

Large projects within the Flagship

7. "Quantum Flagship which supports large demonstration projects"
8. "Quantum Flagship to support large projects. National programs to support small / SME-driven projects"

Education and training actions

9. "A specific education program on quantum technologies would be welcome in engineering schools"
10. "Research training networks for education of the next generation scientists in quantum information."
11. "Research training;"

Business-orientated actions

12. "Venture and angel investment"
13. "To foster shared initiatives between Research and Industry"

Coordination and Support Actions

14. "Networking programmes could help European institutions in creating suitable consortium to face this research challenge."

Basic research

15. "quantum computing is still a research question at heart- and funding should be concentrated on developing the science and not trying to push unready technologies into commercialisation.
16. "I think that basic research is mandatory in fields of many-body physics- decoherence and quantum-to-classical transition."
17. "Encourage basic research into quantum physics to look for new technologies. Regular grant schemes but with added funding. What I'll say is that quantum computing is still a research question at heart- and funding should be concentrated on developing the science and not trying to push unready technologies into commercialisation."
18. "The funding efforts of the flagship should include a true invitation to novel disruptive concepts- in theory and experiments- in quantum computing. I have not seen any EU funded personal (ERC or the like) or collaborative (Proactive or the like) projects that involve novel disruptive concepts in theory or experiments. Most earned EU grants are incremental or trivial horizontal advances of known previous misleading directions as is the case of digital quantum computing with error correction or simple advances of adiabatic or topological quantum computing paradigms. Support of truly risky novel concepts was never available or granted in the last years and decades. When these true advances are offered beyond the wording and are truly granted- quantum computing and quantum technologies will see the light of present and future."

General

19. "Responsive mode call and research projects; fellowships."

Question #9 External funding

Please give your opinion about the funding priorities for quantum computing from other sources.

Sub-question 9.1: Largest funding sources. What do you think should be the partitioning of funding for quantum computing over the next 20 years, excluding European public funding? (Your answers will be normalized to 100% total)

Civil private sector

Research institutions (non-publicly funded)

Defence (non-publicly funded)

Donations

Venture capital

National governments

Other (please indicate after "Submit")

Sub-question 9.2: Private sector. Please indicate which quantum computing hardware you believe the private sector will give priority to. If your rationale differs from that suggested, use the textbox to explain it.

Basic research, e.g. since it is premature to move ahead with technology development and the attempts being made to do so are misguided.

Enabling technologies, e.g. since they would increase the available options for a full-scale quantum computer.

Interim solutions, such as quantum simulation and adiabatic computing, e.g. since they would have a good chance of being useful in the medium term.

Two or three credible candidate platforms, with an aim to produce full-scale computers.

One chosen leading candidate platform, e.g. since only by focusing all available resources is there a reasonable chance of success.

Other (please explain in the textbox after submitting).

Sub-question 9.3: Non EU-institutional public funding. Please indicate which quantum computing hardware you believe the public sector, excluding the EU institutions, will give priority to If your rationale differs from that suggested, use the text box to explain it.

Basic research, e.g. since it is premature to move ahead with technology development and the attempts being made to do so are misguided.

Enabling technologies, e.g. since they would increase the available options for a full-scale quantum computer.

Interim solutions, such as quantum simulation and adiabatic computing, e.g. since they would have a good chance of being useful in the medium term.

Two or three credible candidate platforms, with an aim to produce full-scale computers.

One chosen leading candidate platform, e.g. since only by focusing all available resources is there a reasonable chance of success.

Other (please explain in the textbox after submitting).

Motive

We asked this question because we realised that EU funding was part of a wider financial system which could be used for quantum computing research and technology development.

Note that the first sub-question intentionally asked the participants to express their own preference, while the second and third concerned their assessment of what others would do.

Sub-question 9.1: Preferred partitioning of non-EU-public funding

The replies show a fairly low level of consensus, but overall a preference for the largest share to come from national governments, and the next largest from the civil private sector and non-public research institutions. Most also would like to see substantial contributions from venture capitalists and the private defence industry.

The desire to see a substantial fraction of the investment coming from the private sector is not compatible with the preference for basic research expressed in earlier questions, and suggests a lack of realism in the aspirations of the community.

Only 71 people replied to the question out of the 102 who opened it.

Table 9.1 Preferred partitioning of non-EU-public funding

Funding source	**Mean**	**Median**	**IQR**
Civil private sector	18.4%	17%	16%pts.
Research institutions (non-publicly funded)	19.1%	17%	12%pts.
Defence (non-publicly funded)	10.9%	10%	12%pts.
Donations	5.2%	5%	9%pts.
Venture capital	13.0%	10%	15%pts.
National governments	31.4%	30%	22%pts.
Other	2.1%	-	-

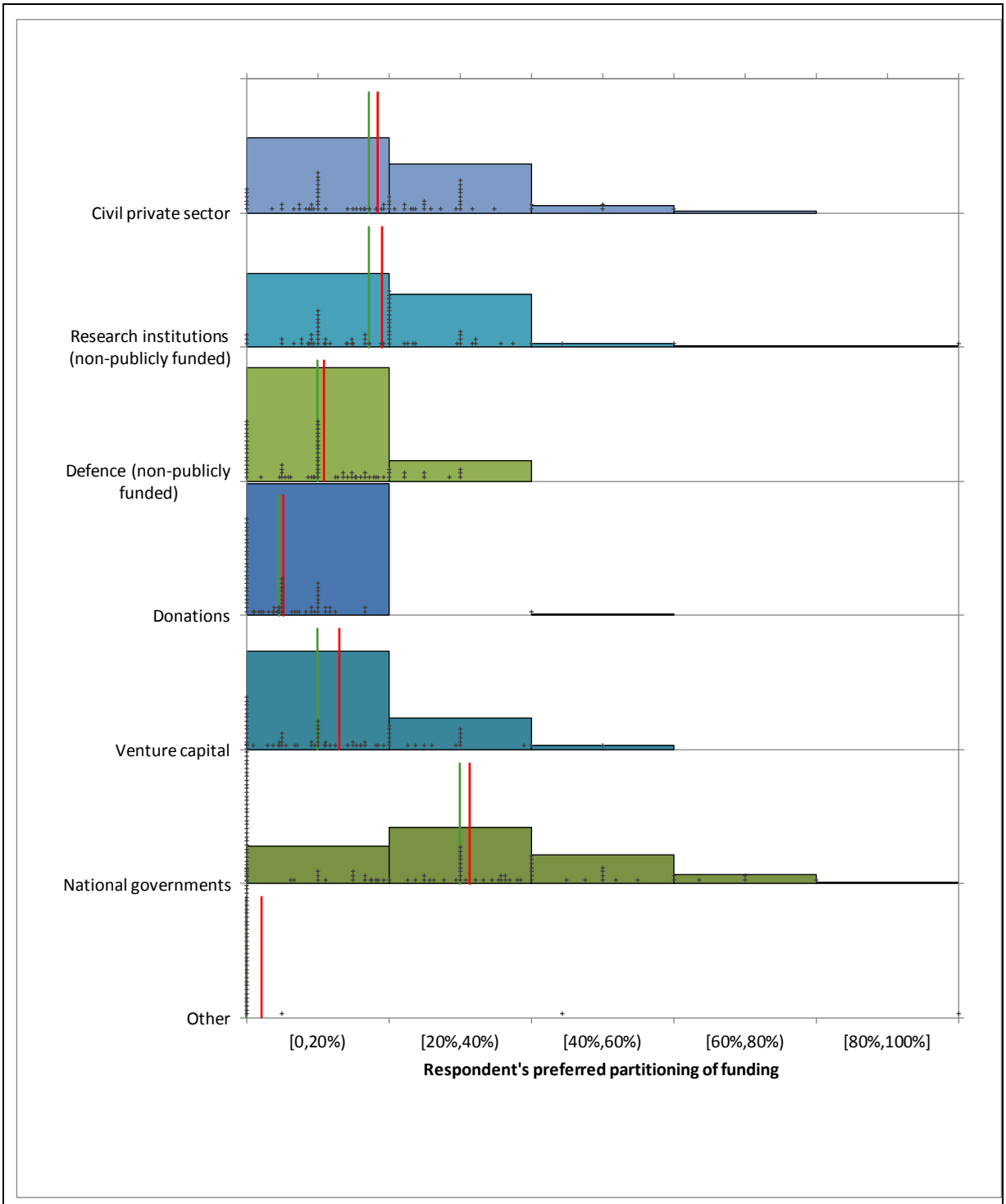


Fig. 9.1 Preferred partitioning of funding, other than from EU public sources

median mean + individual responses, stacked vertically

Sub-question 9.2: Expected priorities of private–sector for QC hardware

The expectations of many of the participants regarding the funding priorities of the private sector are even more surprising. 40% of respondents thought the private sector would give top priority to basic research, although their motive for doing so is unclear. In some respects, the responses appear to be contrary to what is already visible. Most participants expect interim solutions based on quantum simulation, adiabatic computing etc. to be only third or second priority but the only commercial device now available falls into this category. It is widely known that Google have committed heavily to one platform (superconducting qubits) as have Microsoft (topological qubits) but few participants expect the private sector to commit to a single platform. It is possible that this is a matter of interpretation i.e. that the private sector as a whole will not commit to just one platform, diversity will come about from different companies favouring different platforms: one comment (7.) was received to this effect.

Comments

1. "Large scale industry / academia projects (up to 5 years) which demonstrate the state of the art."
2. "I have given the same answers as for European funding as this is what the private sector 'should' fund. It also makes the most long-term sense for the sector as a whole. However I suspect that in reality they will pick and choose short-term winners."
3. "Private sector will be in it for financial benefits and hence should try to build the quantum computer- enabling technologies- and intermediate solutions."
4. "Private sector will prefer fast solutions."
5. "Based on my experience in private sector- most companies will prefer near term deliverables."
6. "I think basic research is mandatory in fields like many-body physics- decoherence and quantum-to-classical transition. "
7. "Question is difficult to understand. Each company will choose one option- but that option may differ between different companies (therefore between all of them 'industry' will have chosen 2-3 options. Answers are not mutually exclusive- companies will choose 1 technology- but look for quick payback of investment. There will be a trade-off between how long companies are prepared to wait- and the size of the prize."
8. "important to have research and industry working together."
9. "I'd hope focus is on interim solutions. Likely and sadly some will focus on specific platforms- but hopefully keep options open instead of choosing too quickly. Unlikely they see basic research as relevant and enabling technologies may also be overlooked."
10. "Unfortunately this is what i believe they will fund. I stress that this is NOT what I want them to fund."

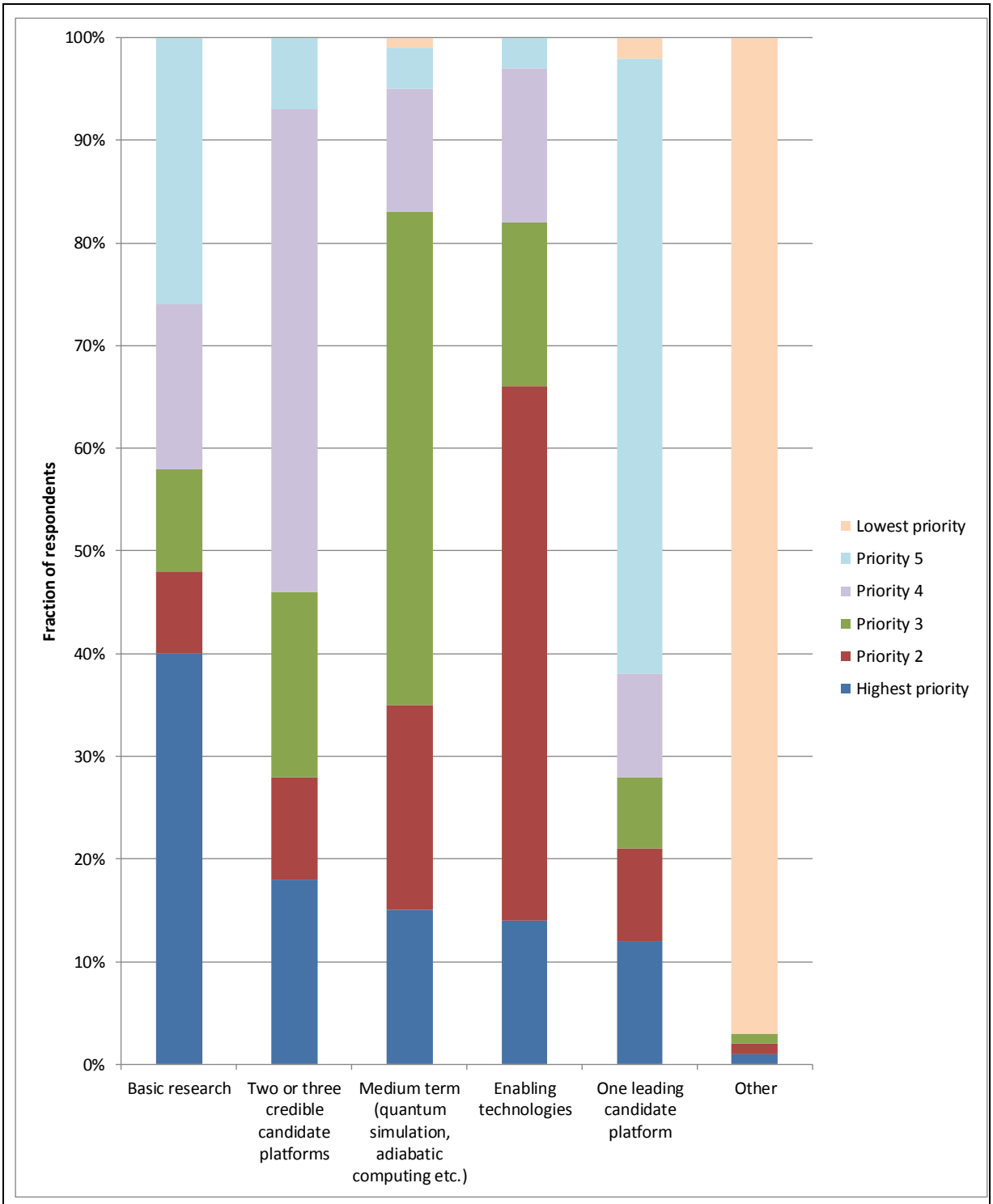


Fig. 9.2 Expected priorities of private–sector

100 people replied to the sub-question.

Sub-question 9.3: Expected priorities of non EU-institutional public funding

The expected distribution is in line with the participants earlier expressed preferences i.e. many respondents are optimistic that public authorities, other than the European Commission and other EU institutions, will agree with their own priority for basic research. Enabling technologies are expected to be strongly supported, as second priority.

Of the existing European national programmes, the UK programme is focused on a single chosen platform (trapped ion with photonic interconnect), while the Netherlands QuTech programme is much less focused at the moment, with work on superconducting qubits, electron spin qubits in quantum dots, spin qubits in diamond, topological qubits and enabling technologies, including basic research. Moreover, most national funding in the EU at present is not grouped into dedicated quantum technology programmes and many different approaches are financed, each on a smaller scale.

Comments

1. "It is usual to suggest public funding for things that the private sector can't or won't fund. However- in the case of Quantum- this is relatively close-to-market- and clearly application-oriented- so in terms of what to fund- the interests are the same- but with a clear willingness from the public to fund more cutting-edge and risky approaches."
2. "Public sector excluding EU has relatively small projects and hence is suited best for basic research and enabling technologies."
3. "Public funding should be allocated to offset the biases inherent in the private sector."
4. "Public and Private priorities are completely different"
5. "important to have research and industry working together."
6. "Hope they see the use of interim solutions and enabling technologies towards future solutions that still remain very unclear."
7. "Again- unfortunately- I see the public sector of governments moving along the same lines as the private sector (short to medium term goals). What I would like is for the public sector to fund precisely the things the private sector does not, that is focus more on funding fundamental research- or research whose output is more on the long term. Private and Public research should go in tandem... The public always funded the riskier more blue sky research....and it should because those that work eventually get picked up by the private sector."
8. "Public sector funding should be more focused towards basic research as this is less likely to be funded by the private sector"

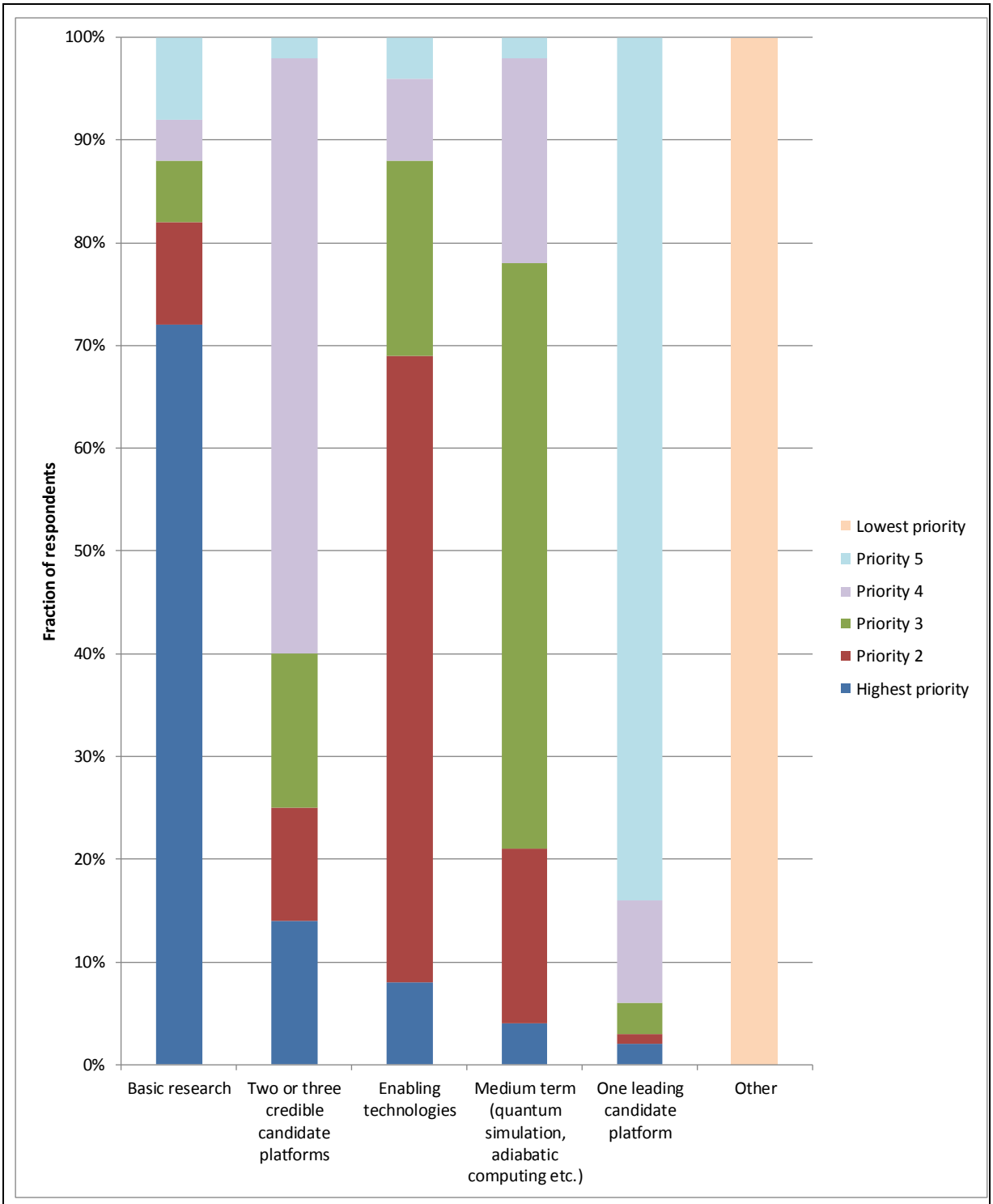


Fig. 9.3 Expected priorities of non EU-institutional public funding

100 people replied to the sub-question.

Question #10 Quantum computing software and hardware

Please indicate your opinion on how the quantum computing software and hardware might evolve

Sub-question 10.1: Software and hardware development. Consider the following statements about the relationship of software and hardware for quantum computing and check those that you think are likely to be true:

- *Quantum computing software and hardware will always need to be developed together.*
- *A quantum software industry will emerge independently from hardware developers.*
- *Quantum computer programming will always require major specific competences distinct from conventional programming.*
- *A general purpose language will emerge, suitable for running any task on a quantum computer.*
- *Quantum computers will always run specific algorithms only.*
- *Software and hardware development will reinforce each other's development.*
- *Other (please explain in the textbox after "Submit").*

Sub-question 10.2: Explanation. What might the future of quantum computer software and hardware development be?

Sub-question 10.3: Level of confidence. Please indicate your level of confidence in your own answers to the questions on the future of the quantum computing hardware/software relationship. (From 0=not confident at all to 100=extremely confident)

- *Level of confidence for "Software and hardware development"*
- *Level of confidence for your "Explanation"*

Motive

Since the introduction of quantum computing requires a re-examination of fundamental computer science questions, it is necessary to re-think the relationship between hardware and software. Because many aspects of the relationship between the two are taken for granted in classical information technology, there is a risk of assuming without question that they will be the same for quantum computing. Question #10 invites participants to break with such habitual thinking.

Sub-question 10.1: Specific aspects of the hardware/software relationship

It was possible to select more than one statement, and propose other statements.

Responses were received from 76 participants.

Table 10.1 Hardware/software relationship

Statement	Fraction of participants agreeing with statement	Fraction agreeing, weighted by expressed confidence[8]
Quantum computing hardware and software will always need to be developed together	49%	49%
Quantum software industry will emerge independently from hardware developers	45%	46%
Quantum computer programming will always require major specific competences distinct from conventional programming	66%	60%
A general purpose language will emerge, suitable for running any task on a quantum computer	39%	43%
Quantum computers will always run specific algorithms only	32%	34%
Software and hardware development will reinforce each other's development	80%	70%

There was strongest agreement for the last question: "Software and hardware development will reinforce each other's development". For all other questions there was little consensus, which lends support to the view that these issues are indeed open, and need to be further debated. For most questions, weighting by the participants' expressed confidence did not change the balance very much, i.e. positive views were as strongly held as negative ones.

Other statements proposed:

1. "Initially the two will develop jointly reinforce each other- eventually the competencies will spread to separate industries. Jointly with AI developed application. No general purpose language will emerge- but perhaps a compiling platform."
2. "Well written software is never hardware independent. We just agreed on writing software in a particular way that the compilers and interpreters manage to translate efficiently onto a standardised hardware architecture. This may or may not be the way for QC. Likely QC will not have a programming language as automated control can do a lot better than humans and maybe we can set very high level targets (as current computers already head towards as well - see 'web programming'). But QC will not be like a traditional computer in any sense (alone from the fact the even the gate model is more like an analog computer instead of discrete logic gates). "

(8) The responses where the participant did not agree were taken into account:

Fraction, weighted by confidence = 50% +

½(Sum of % confidences where box checked -Sum of % confidences where box not checked)/no of responses

Sub-question 10.2: Explanations

This sub-question collects the comments given by the respondents after question 10.1 on the specific aspects of the hardware/software relationship. They are very useful both for a better understanding of the results of question 10.1 and for a more general view on the envisaged future of Quantum Computing. The comments address three specific aspects: 1) importance of the hardware development; 2) mutual dependence or independence between hardware and software; 3) architecture of a Quantum Computer and its integration in classical environments.

Hardware development is still seen as a fundamental step. Only limited platforms are now available, and no single one is perceived as the "winning" one. Good representatives of such reflections are comments number 5 and 26 with comment 21 as a good synthesis, while comment 16 states that it is premature to make any prevision about the mutual development of quantum hardware and software.

Since the hardware platforms now available are limited, the debate on the mutual independence or dependence between hardware and software is open. This is a crucial point, seen in the choice of big companies, like Atos, to start the development of quantum software based on simulators while waiting for the construction of a hardware platform. Comments in favour of the independence between hardware and software are 11, 19, 14, 15, 24. Comment 25 goes further by advocating the development of a new "applied computer science" discipline. Comment 5 expresses some doubts about the possibility of adapting current quantum software to a future hardware platform, while comments 7, 18 and 26 are for a strong dependence between quantum hardware and software.

A specific set of comments deals with the integration of the quantum computer, when realised, in classical environments. So hybrid environments both for hardware and software (for example comment 8) are envisaged. The comments addressing this point are: 3, 10, 13 and, with a stronger position, 17. Comment 4 is interesting for the complete (long-term) change in perspective between quantum and classical architectures.

Finally, comments 2, 6 and 20 link the progress of artificial intelligence, using the quantum computer, to the production of software for it. Comments 22 and 23 are generic comments, possibly made while reading the others' comments.

Comments

1. "Due to the disruptive character of the field- this will grow exponentially and needs to grow together especially during the early stages."
2. "Moore's law for quantum computing (Leo's law). Software will start from 100% human developed to about 65% AI developed and 35% human developed by 2035."
3. "Soft and Hardware development will get integrated into traditional environments. Eventually- an application programmer does not have to care what will run on quantum or classical hardware."
4. "It is possible that in the far future (>70 y)- the technology that we develop for the quantum computer will become so energy efficient that power-consumption-wise also classical logic is economical to be run on a quantum computer. Thus it may be that classical and quantum computing will merge and hence quantum computers will not be limited only to a small set of algorithms. This obviously needs also a new computing paradigm which may be found. A general purpose language would be likely to emerge here."
5. "The main current problem is development of quantum hardware. When quantum hardware is developed it will be not so difficult to write appropriate quantum

software. Quantum software already exists. It is not clear to me whether this software will well fit future quantum hardware. "

6. "Probably- some form of quantum algorithms designed by quantum machines"
7. "Selecting efficient algorithms + hardware always depends on understanding the limitations and strengths of the hardware. These decisions could eventually be made by software however. "
8. "Hybrid algorithms that leverage the strong points of each."
9. "Compilers will be needed in the short term to execute quantum algorithms beyond a few dozen gates. Also this will be needed to validate existing quantum algorithms- which are likely to have minor bugs in them that will not become apparent until testing."
10. "Interfaces between quantum sensors and classical computers. the problem of decoherence will always be there."
11. "Since the operating principles of a quantum computer are known the software development can proceed."
12. "Quantum algorithms to perform better analysis of data"
13. "Hybrid classical-quantum computers could be more than an intermediate step- it could be a good idea to conceive both together- and use best of each. The target is not to replace everything by quantum technologies- but to use it when classical reach a limit- and complement it. Also- there are probably brand new way of proceeding not discovered yet- where in this case- it should evolve independently."
14. "A quantum software industry will emerge independently from hardware developers. Quantum computer programming will always require major specific competences distinct from conventional programming. A general purpose language will emerge- suitable for running any task on a quantum computer. Software and hardware development will reinforce each other's development."
15. "Quantum hardware might evolve independently from quantum software. Quantum software could be created in an independent way from the specific quantum hardware. "
16. "far too early to predict."
17. "hardware: trapped ions / superconducting qubits- maybe hybrid systems (memory in one system- processing in the other) software: at the moment most people think in terms of the circuit model with gate operations = sequence of qubit manipulation operations- however- I think we will develop a more general system similar to a von Neumann architecture for classical computers- maybe even with control programs in quantum memory"
18. "They will develop together. "
19. "Initially hardware and software will proceed together but general programming methods will emerge with time- and software development becomes independent."
20. "Control- learning and AI. Humans largely only set the target to be achieved- in particular if quantum algorithms are one huge unitary operator. This is not that different from how most people program traditional computers. Maybe we need to invent a new narrative what the machine is doing- different from the one used for traditional computers. Maybe- hopefully? we don't need that narrative at all anymore."

21. “In the first decade the development of hardware will be the most important and time/money consuming effort. When hardware becomes available- software will get more important. In fact a bit the same as classical IT developments.”
22. “I have no clue but i am excited for it”
23. “These are very over ambitious statements”
24. “Retargettable compilers for quantum software based on flexible intermediate representations of quantum algorithms.”
25. “To make hardware successful a few select hardware platforms need large support. Hardware for a quantum internet needs to look beyond QKD: building faster QKD systems is a problem of enhancing a product that is already commercially available which is not the objective of a flagship. Quantum software development urgently needs the development of applied quantum computer science- with a radical shift in mindset from the theoretical approach to quantum computer science used now.”
26. “In the next decades- it is impossible to foresee an independent development of quantum software without involving quantum computing platform specification. To think the opposite is equivalent to superstring theory. Wonderful universal solutions to problems we do not have- we cannot test- and nobody else cares beyond the elite associated scientific networks. The difference is crucial- superstring theory is an intellectual endeavour- while quantum computing is meant to generate a technology that should provide solutions to practical problems.”

Question #11 Quantum computation's future place

Please give your opinion on the place of quantum computing in the future computational landscape

Sub-question 11.1: Future computing scenarios. What do you think the place of quantum computing will be if and when it becomes established? (Chose the one scenario you think is the most likely to be true)

- *Quantum computing will be the only form of computation in the future.*
- *Quantum computing will coexist with other computational methods, but will be the most important.*
- *Quantum computing will be only one among a number of coexisting computational methods of similar importance.*
- *Quantum computing will be important only in a limited number of applications.*
- *Quantum computing will be abandoned, replaced by a new paradigm.*
- *Submit*

Sub-question 11.2: Potential synergies. Which areas could develop in tandem with quantum computing, to their mutual benefit? Indicate with a numeric value your assessment of potential synergies. (From 0=no synergies at all to 100=extremely important synergies)

- *Nanotechnology*
- *Electronics*
- *Materials science*
- *Chemistry*
- *Engineering*
- *Other (please add in the textbox after "Submit")*

Sub-question 11.3: Explanation. What might the future computing landscape be?

Sub-question 11.4: Level of confidence. What is your level of confidence in your own answer to the question of the three previous columns? (From 0=not confident at all to 100=extremely confident)

- *Level of confidence for "Future computing scenarios"*
- *Level of confidence for "Synergies"*
- *Level of confidence in your own "Explanation"*

Motive

This question was motivated by a desire to obtain foresight regarding the significance of quantum computing for EU information technology policy and research and technology development policy. How will quantum computing fit into these bigger pictures?

Sub-question 11.1: Most likely scenario

82 responses were received.

Table 11.1 Scenarios for quantum computing's future place

Statement	Fraction selecting	Fraction, weighted by expressed confidence
Quantum computing will be the only form of computation in the future.	0%	0%
Quantum computing will coexist with other computational methods- but will be the most important.	23%	27%
Quantum computing will be only one among a number of coexisting computational methods of similar importance.	56%	55%
Quantum computing will be important only in a limited number of applications.	21%	18%
Quantum computing will be abandoned- replaced by a new paradigm.	0%	0%

This question was one of the few were there was any complete consensus: which was that neither the extremely optimistic nor the extremely pessimistic scenarios were likely. The results fall into an approximately symmetric triangular distribution between the three intermediate scenarios. Weighting by the participants' expressed confidence made little difference to the overall picture.

Sub-question 11.2: Which areas could develop in tandem with quantum computing, to their mutual benefit?

The majority of respondents perceive synergy in all categories, especially nanotechnology, electronics and materials science. It is surprising that the score for chemistry was somewhat lower, given that quantum simulation was seen as a promising application.

These results change little if the respondents' confidence is taken into consideration, nor are there significant differences between mean and median answers. For all categories, some sceptical opinions were expressed, but were in a clear minority.

Other areas
Only one suggestion was made for synergy with other areas: quantum coherence may help in the understanding of biological processes.

Comments

1. "Material science will be important in optimising the materials used for the technology. Engineering will be important much later when manufacturing is volume"
2. "Physics- Biology- Material Science- Information Theory"
3. "Some arbitrary numbers... of course they could all benefit. Who knows..."
4. "Instrumentation! communication!"

Two participants also said they found sub-question 11.2 hard to understand, but did answer it.

Table 11.2 Areas with synergy with quantum computing

Technology area	No. of respondents	Mean	Median	IQR
Nanotechnology	75	76.4%	80%	40%pts.
Electronics	77	70.9%	75%	40%pts.
Materials science	77	75.2%	80%	25%pts.
Chemistry	77	61.9%	60%	40%pts.
Engineering	77	69.9%	70%	40%pts.
Other	4	37.5%	25%	-

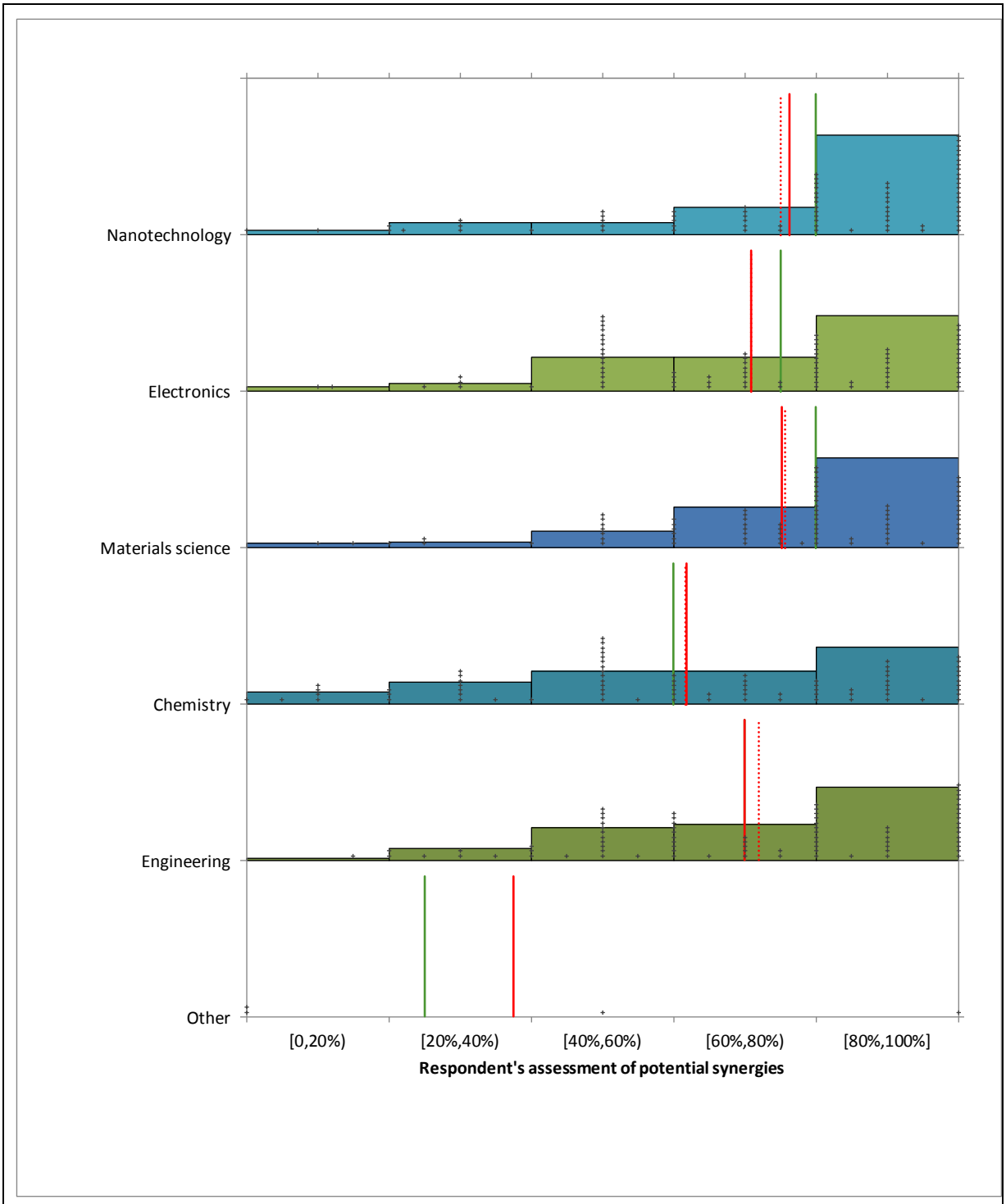


Fig. 11.2 Areas which could develop in tandem with quantum computing, to their mutual benefit

median | mean | weighted mean + individual responses, stacked vertically

Sub-question 11.3: Future computing landscape

Although 96 participants opened the question, only 32 provided narrative answers. Those answers are clustered below by the respondents' respective answer to Q.11.1.

Respondents who think quantum computing will coexist with other computational methods, but will be the most important:

1. "We are only scratching the surface on possible applications."
2. "A mix of CPU- GPU's- QPU's and AI solutions."
3. "On the short-medium term- quantum computing and classical computing will both be used for dedicated applications. With future developments- QC will take more and more tasks dedicated to classical computation."
4. "Eventually- quantum computers (or the technology being developed for quantum computers) will likely become the most important computational tool due to its fundamentally more powerful algorithms and need to reach extreme regimes of physical systems."
5. "very complex and varying."
6. "New paradigm in Data processing and management."
7. "going through artificial intelligent using quantum technology."
8. "Merging Quantum Technologies with Artificial Intelligence."
9. "Quantum computers take care of the high end of computing tasks- but there is need for various other solutions at the low end."
10. "Fully functioning quantum computers would be owned by a handful of computing companies around the world with other key industries renting computing time on the machines."
11. "I have no crystal ball. Can anyone seriously answer this? We still need to investigate multiple options- from which something clearer will emerge."
12. "People will own classical devices- which outsource problems to quantum computers in a cloud whenever this might be advantageous."

Respondents who think quantum computing will be only one among a number of coexisting computational methods of similar importance:

1. "A mixture of classical- quantum and cognitive."
2. "For long time ahead quantum computers will be used for specific problems only- but gradually they will grab larger and larger portion among computing devices."
3. "The coverage area of quantum computing will grow with algorithms and hardware development. The breadth of problems will be ranging from optimization of multiple processes in technology and society to the simulation of complex Hamiltonians and novel materials design. At the same time you don't want to use a complex quantum machinery where a simple conventional computer will suffice."
4. "We will see quantum computing emerging as a cloud resource sitting alongside other diverse computing platforms that are used for different workloads."
5. "I think that the problem of decoherence (quantum-to-classical transition) will be always present- making a lot of difficulties in the practical implementation of many quantum computing ideas."

6. “hybrid world with classical and quantum computing- together with other technologies. At the same time- quantum computing has to think differently- and not just reproducing the same 'old' logic and (only) running it quickly.”
7. “Quantum computing cloud services with emerging standards for programming interfaces.”
8. “An interplay between classical and quantum computing- each playing its strengths.”
9. “quantum computers will be larger centralized machines (due to isolation from environment and complexity of control); we will still carry around classical computers for standard applications (smartphone- ...).”
10. “A mixture between a number of coexisting paradigms- within this quantum computing will be used to solve special tasks.”
11. “Lots of hills that have different heights depending on who is looking at them.”
12. “An inhomogeneous system comprising quantum computers- classical computers- high performance computing systems- and other beyond von Neumann machines.”
13. “Quantum computing will coexist forever with classical computing paradigms. There is no necessity for fully and purely quantum facilities. The fact that any quantum computing effort has to be transformed in classical information for being useful by macroscopic human brains is a rationale of the above statement.”

Respondents who thought quantum computing will be important only in a limited number of applications”

1. “Quantum and classical computing platforms will coexist on one platform.”
2. “It will probably resemble the current landscape- with the addition of very task-specific machines.”
3. “Conventional computers will keep going strong- but quantum machines will shine in certain specific areas.”
4. “Classical will be dominant and quantum for specialised applications.”
5. “I would see quantum computing power as an available on-demand resource in the cloud- not available locally ‘at home’ "
6. “Conventional computing will keep its position as the main method of information processing. Quantum computing will be used in specific applications- which could be vast and important.“
7. “Replacing super computer clusters in Research and Defence environment and being used for companies doing a large amount of data processing”.

Question #12 Quantum computing physical platforms

Please give your assessment of the possible physical platforms that can be used to build a quantum computer, and evaluate how Europe is positioned in each of them with respect to international competitors.

Superconducting qubits

Trapped ions

Photonics

Semiconductor qubits

Topological qubits

Other (please indicate after "submit")

Sub-question 12.1: Intrinsic strength. Which are the most promising platforms on which to build a large-scale quantum computer? (From 0=not promising at all to 100=extremely promising)

Sub-question 12.2: European positioning. Please assess the European potential for developing these platforms into a fully operational machine give the capabilities of European universities, research centres and industry.

Sub-question 12.3: Self-assessment. What would you consider to be your own level of expertise in each of the following areas? (From 0=very low to 100=very high)

Motive

This is the most important purely technological strategic question for quantum computing research and development and is motivated especially by its importance for EU RTD policy, including the FET flagship. Which platforms emerge as superior and which fall out of favour will determine a host of issues for the quantum computing roadmap, especially with regard to the enabling technologies required to support a future quantum computing industry. The question also has ramifications for devices such as memories and interconnects, which might be applicable in communications, sensing or timing as well as in computation.

Sub-question 12.1: quantum computing physical platforms: intrinsic strength

The highest median score was for superconducting qubits (80), followed by trapped ions, phonics and semiconducting qubits (50) with topological qubits somewhat lower (40).

Other technologies mentioned were nitrogen vacancy (NV) centres in diamond (4 respondents) and cold atoms (3 respondents) and hybrids of superconducting and optical/photonic technique (1 respondent). Advocates of devices using NV centres pointed to them having advantages for a quantum internet. Cold atom advocates mentioned optical lattices for simulation, and Rydberg atoms.

The interquartile ranges are large and each of the five best established platforms has supporters and sceptics. The results do not constitute a strong case for committing for or against any of them now. They are consistent with the earlier expressed view that basic research should continue to be funded.

The results are significant for the FET Flagship, for which it will be necessary to decide whether or not to focus on one or more approaches, and if so, when.

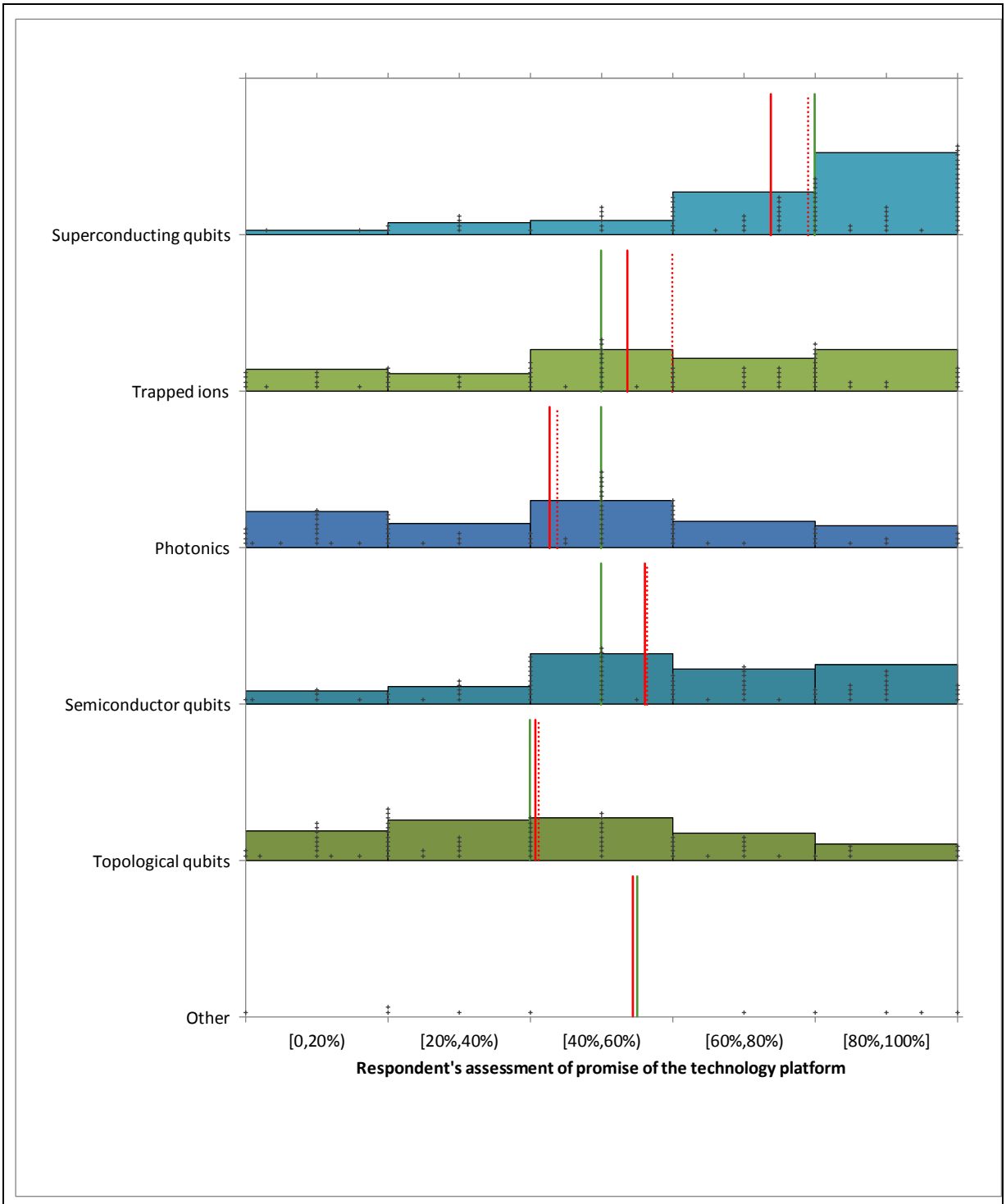


Fig. 12.1 Quantum computing physical platforms: intrinsic strength

median mean weighted mean + individual responses, stacked vertically

Table 12.1 Potential of technology platforms

Platform	No. of responses	Mean	Median	IQR
Superconducting qubits	76	73.8%	80%	39%pts.
Trapped ions	71	53.7%	50%	50%pts.
Photonics	70	42.8%	50%	40%pts.
Semiconductor qubits	71	56.2%	50%	40%pts.
Topological qubits	69	40.8%	40%	40%pts.
Other	10	54.5%	55%	71%pts.

Sub-question 12.2: Quantum computing physical platforms: European potential

These results broadly follow the intrinsic strengths (see Figure 12.1.2), but with the lead of superconducting qubits over trapped ions much less marked in Europe, a result which reflects the strong activity in superconducting approaches in North America.

Some of the participants who had replied to 12.1 on intrinsic strengths did not reply to 12.2--mostly people based outside Europe, as would be expected.

Table 12.2 European potential

Platform	No. of responses	Mean	Median	IQR
Superconducting qubits	68	66.9%	70%	34%pts.
Trapped ions	63	61.%	60%	40%pts.
Photonics	63	51.9%	50%	55%pts.
Semiconductor qubits	63	52.1%	50%	40%pts.
Topological qubits	60	45.0%	50%	50%pts.
Other	6	55.8%	58%	-

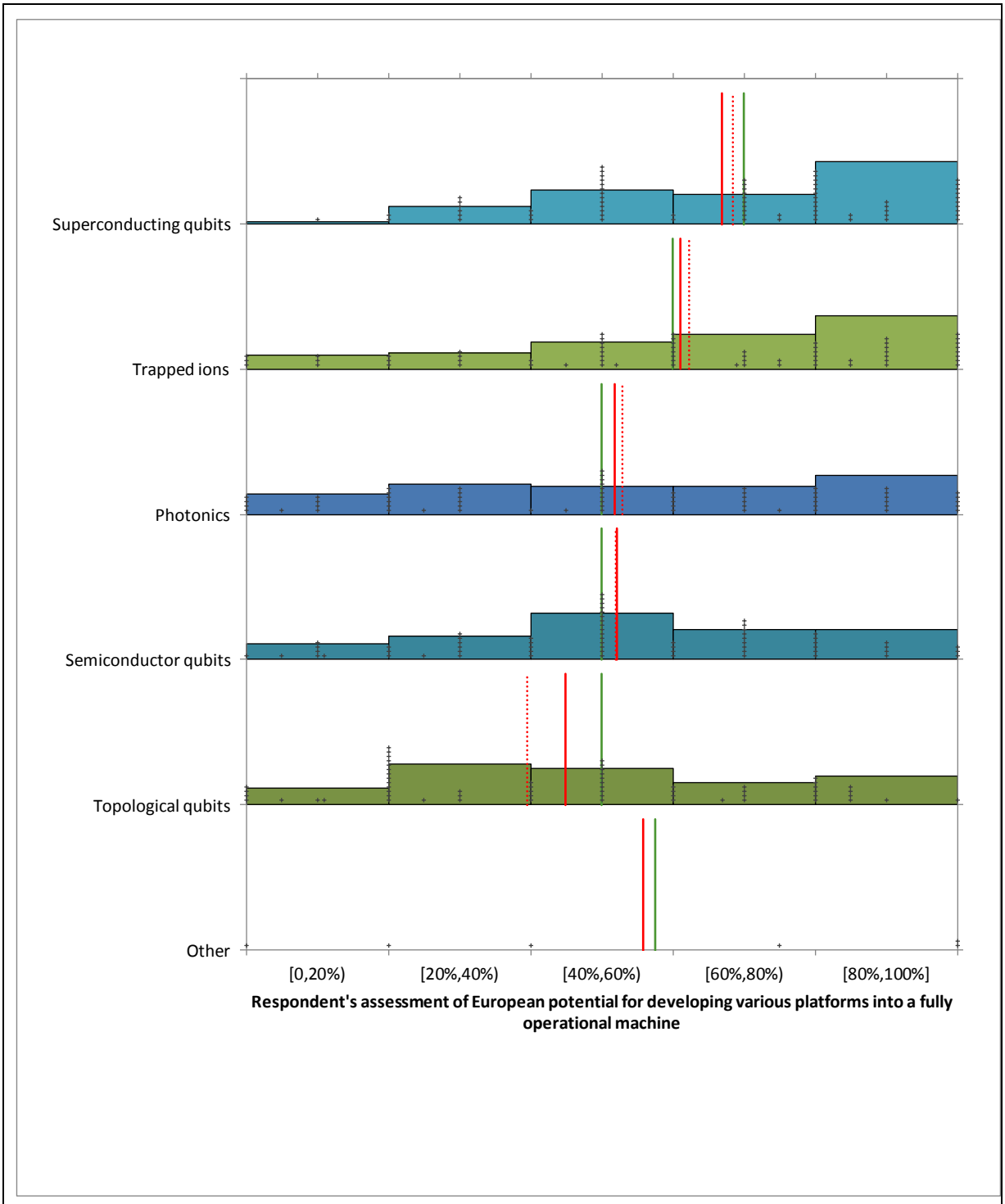


Fig. 12.2 Quantum computing physical platforms: European potential

median mean weighted mean + individual responses, stacked vertically

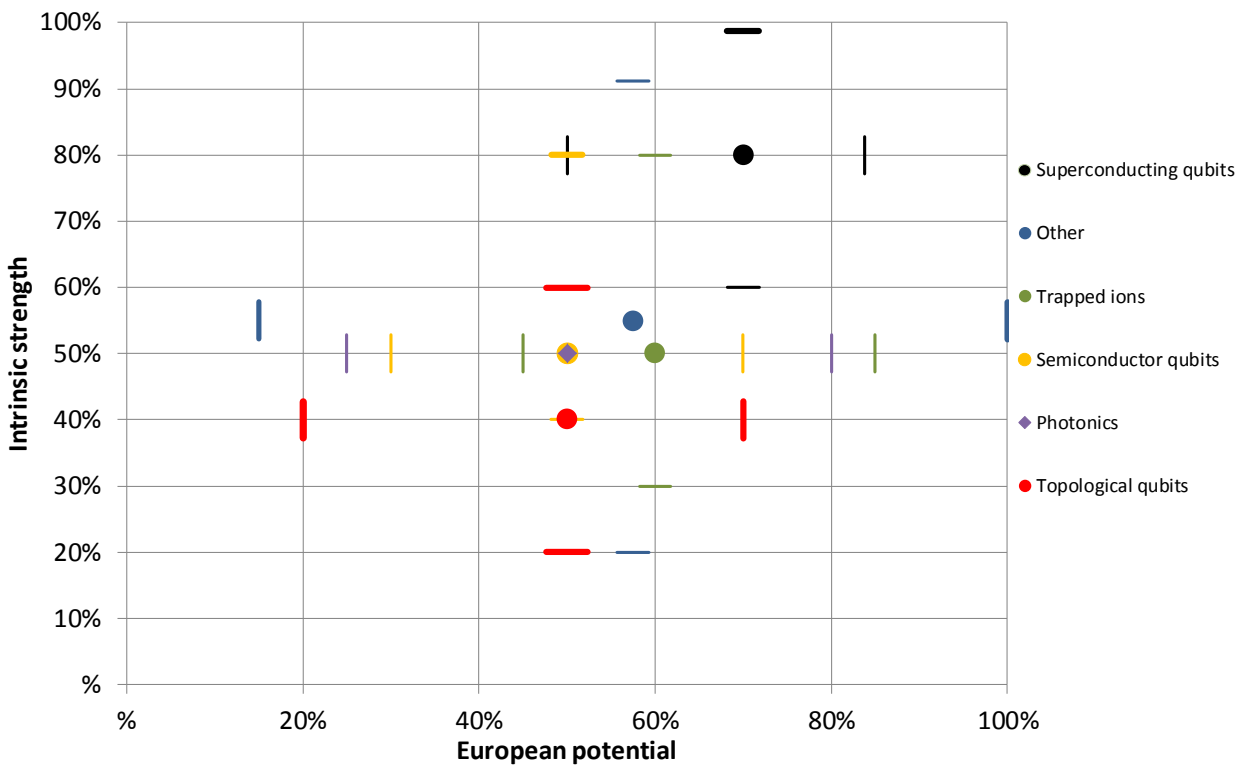


Fig. 12.1.2 Quantum computing physical platforms intrinsic strength versus European potential.
Circles : median values. Vertical and horizontal fences: quartiles.
Spearman's rank correlation coefficient ρ = 0.74

Comments

1. "Superconducting qubits are very promising. However- there is little infrastructure at the industrial level to foresee quick and costless applications in a near future. On the superconducting side- Europe benefits from several assets (from wafer processing to control electronics) but it is lacking integration."
2. "I don't have the expertise to say- but the USA appears to be ahead in superconducting."
3. "Superconducting quantum computers are currently the only ones that have been demonstrated to be truly scalable and Europe has many strong laboratories in this field. Thus Europe has great potential in building such a quantum computer."
4. "Having serious efforts in this area around the world makes also chances of European success higher. Europe has also strengths in trapped ions and semiconducting qubits (especially in spins in silicon) which have a reasonable chance of succeeding but need much more basic development."
5. "European labs are leaders in superconducting qubits- trapped ions- and (depending on whether 'European' now includes the UK)- photonics. So they're as likely to build quantum computers as any place."

6. “Superconducting qubits are promising- but maybe not for Europe alone. Semiconductor qubits- trapped ions and photonics may be better for Europe.”
7. “Europe has numerous excellent and large-scale nano fabrication facilities which would be ideal for the development of quantum computing hardware- as well as deep expertise in the design- testing and measurement of prototype systems.“
8. “Europe including UK could build such a computer. However it needs a greater effort in basic research- whether Microsoft’s investments yield a viable technology is an open question.“
9. “European businesses and research is not set up at present in a way to be able to build the large scale quantum devices needed. The one area I am more confident in is topological quantum computing because of the investments Microsoft has made in groups in Delft and Copenhagen. But apart from Europe's expertise in photonics- I am not convinced that the infrastructure is in place to build quantum computers in Europe at present (especially in a post-Brexit environment).”
10. “I guess- topological qubits are supposed to be e.g. majorana states in solid state. I think in any of these systems (trapped ion or superconducting qubits) we will need to use topological quantum error correction.”

Question #13 European Strengths

Is there a specific aspect of quantum computing for which Europe seems to enjoy some competitive advantages in the international landscape?

Sub-question 13.1: Hardware and software. In which field is Europe better positioned? (From 0=extremely weak with respect to competitors to 100=very strong in the global landscape)

Processors

Memories

Communications and interconnect

Fundamental algorithms

Software for quantum simulations

Firmware for hybrid classical-quantum hardware components

User interfaces

Other (please indicate after "Submit")

Sub-question 13.2: Level of confidence. Which is your level of confidence in each of the answers to 13.1? (From 0=not confident at all to 100=extremely confident)

Sub-question 13.3: Please indicate other quantum computing areas in which Europe might have a competitive advantage or conversely structural weaknesses.

Motive

This question is also intended to give useful information for designing research and technology programmes. The results could be used to develop a programme based on playing to strengths, or for one which sought to correct weaknesses. No indication was made about which approach will be taken; the results are relevant either way.

Table 13.1 European strengths in quantum hardware and software

Quantum computing area	No. of responses	Mean	Median	IQR
Processors	59	57.2%	60%	40%pts.
Memories	58	52.8%	50%	41%pts.
Communications and interconnect	60	68.8%	70%	40%pts.
Fundamental algorithms	57	60.2%	60%	35%pts.
Software for quantum simulations	56	60.3%	60%	34%pts.
Firmware for hybrid classical-quantum hardware components	54	49.8%	50%	40%pts.
User interfaces	49	40.1%	35%	28%pts.
Other	2	80.0%	80%	-

Discussion of all sub-questions

According to the quantitative data in Table 13.1, Europe is seen as:

- strong in interconnect and communication
- weak in user interfaces.

The first reflects the fact that quantum communications have been commercialised first in Europe, and the second that most of the open platforms for experimenting with quantum computer programming have come from the USA.

In other respects, the distributions in Fig. 13.1 are relatively flat, with only a small indication of particular areas of strength and weakness, although a rather different picture emerges from the text comments to sub-question 13.3.

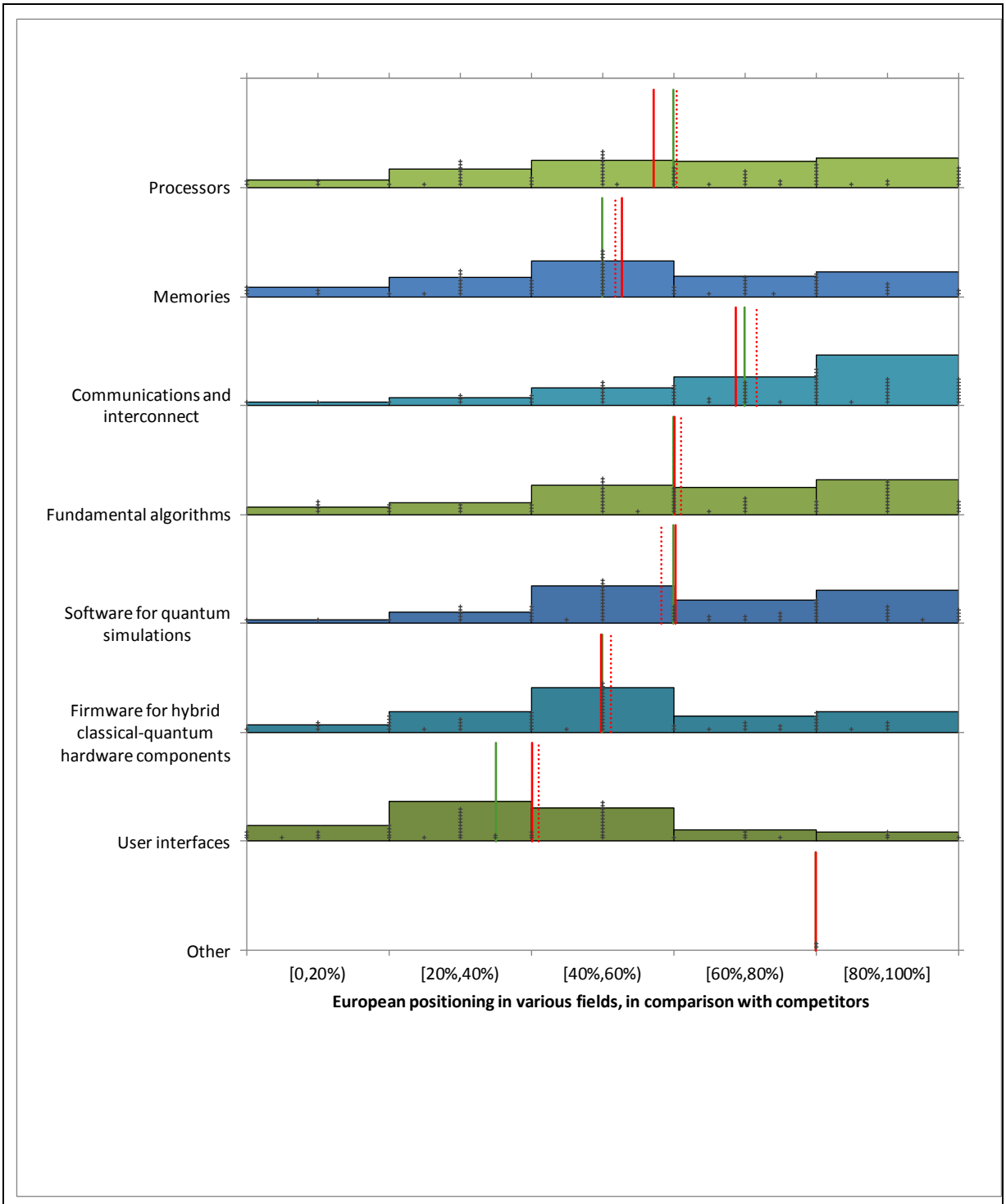


Fig. 13.1 European strengths – in which fields is Europe better positioned?

median | mean | weighted mean + individual responses, stacked vertically

Sub-question 13.3: Other quantum computing areas, European competitive advantages/structural weaknesses

1. "Strengths: Quantum Internet, General Quantum Software, Cryogenics, Weaknesses, Quantum computer development."
2. "The greatest weakness is the missing silicon industry which is required to build a quantum computer. The advantage in Europe is the high level of knowledge on quantum people have - even in industry."
3. "Advantages in utilization of controllable dissipation, heat management at the quantum and chip level, cryogenics."
4. "Interfacing stationary and flying qubits is rather weak."
5. "Europe leads quantum simulations with ultracold atoms and ions."
6. "Europe leads the area of cold-ions platform for general gate-based quantum computing. The superconducting computing research has been at the forefront in the past but needs rejuvenation to catch up with resent significant private industry efforts in North America. The quantum simulation using multiple quantum physical platforms is under active development in many parts of Europe but the pressure from quantum annealing simulators is very strong. "
7. "New quantum resistant cryptographic algorithms (AES was developed in Europe)."
8. "Europe is very strong in optics which makes it well suited for communication-interconnects and quantum cryptography. It has strengths in quantum computer science but lacks the large institutions that North America has to back these people up. Europe could help gain an edge in these areas. Also if Europe wishes to build a large scale quantum computer it will need to engage the private sector more."
9. "Difficult to say at the present time- perhaps- semiconductors."
10. "Very difficult to state as a dominant technology has not emerged. Strong in atoms/ions- topological and semiconductors weaker in superconductors."
11. "Quantum Computing for Artificial Intelligence."
12. "Competitive advantage: cryogenic technologies (including low-temperature electronics) as enabler of quantum computing."
13. "Strength is the scientific advantage in solid-state experimental physics and ion traps. weakness is the lack of hardware companies."
14. "Definitely in metrology (3 very strong theory groups and several experimental groups)."
15. "Europe is excellent at solid-state and at ion traps- so well positioned in the leading platforms."
16. "Biological and medical applications.", "Quantum simulators", "cryptography"
17. "Proposing- creating- and developing novel disruptive quantum computing paradigms- in theory and experiments- beyond the fashionable paradigms that are condemned to failure in the next decades: i) digital quantum computing with error correction and ii) topological quantum computing- and iii) adiabatic quantum computing."

Question #14 Education

What are the education aspects impacted by quantum computing?

Sub-question 14.1: Educational value. What is the educational value of a small scale quantum computer in each of the following (4) contexts? (From 0=no value to 100=extremely high value)

Platform on which software developers can learn

Means to train quantum engineers

Unknown yet

Other known educational value (please indicate what, after "Submit")

Sub-question 14.2: Awareness level. What is the awareness of quantum technology among (5) different targets? (From 0=no knowledge to 100=high awareness)

Physicists

Chemists

Engineers

Computer scientists

Others (please specify after "Submit")

Sub-question 14.3: Training. How important is it to train new quantum computing specialists in the categories listed in sub-question 14.2? (From 0=of no importance to 100=extremely important)

Sub-question 14.4: Adaptation. Which aspects of education should be adapted and how (e.g. promote training, finding jobs etc.)

Motive

This question directly concerns European programmes which have an educational character or aspect e.g. Erasmus http://ec.europa.eu/programmes/erasmus-plus/ and Marie Skłodowska-Curie https://ec.europa.eu/research/mariecurieactions/.

Further, allocating some of the FET Flagship resources to education is proposed in the [Quantum Manifesto, 2016] and has been raised in subsequent discussions, including the Berlin workshop of 10th November 2016 and the Malta workshop of 17th February 2017. The High Level Steering Committee for the Flagship went as far as saying that projects should always contain an educational and training aspect [HLSC Final report, 2017].

Sub-question 14.1: Educational value of small scale quantum computer

Response rates were quite low, 72 of 99 who opened the question.

The respondents mainly agreed that a small scale quantum computer would be a suitable platform on which software developers could learn and as a means to train quantum engineers, and there was also some support for seeing its educational value as unknown yet.

Other known educational areas specifically suggested were:

1. "General training in STEM subjects".
2. "Interdisciplinary training".
3. "Develop a 'quantum way-of-thinking' in the brain of the future scientists and engineers".
4. "Education in quantum processes and quantum chemistry".
5. "more than just training software developers to use quantum computers- they should also think differently. probably a new range of mathematic- on top of software engineering".

Table 14.1 Educational value

Context	No. of responses	Mean	Median	IQR
Platform on which software developers can learn	72	71.2%	80%	24%pts.
Means to train quantum engineers	71	82.0%	80%	29%pts.
Unknown yet	40	54.0%	60%	50%pts.
Other known educational value	6	35.0%	25%	-

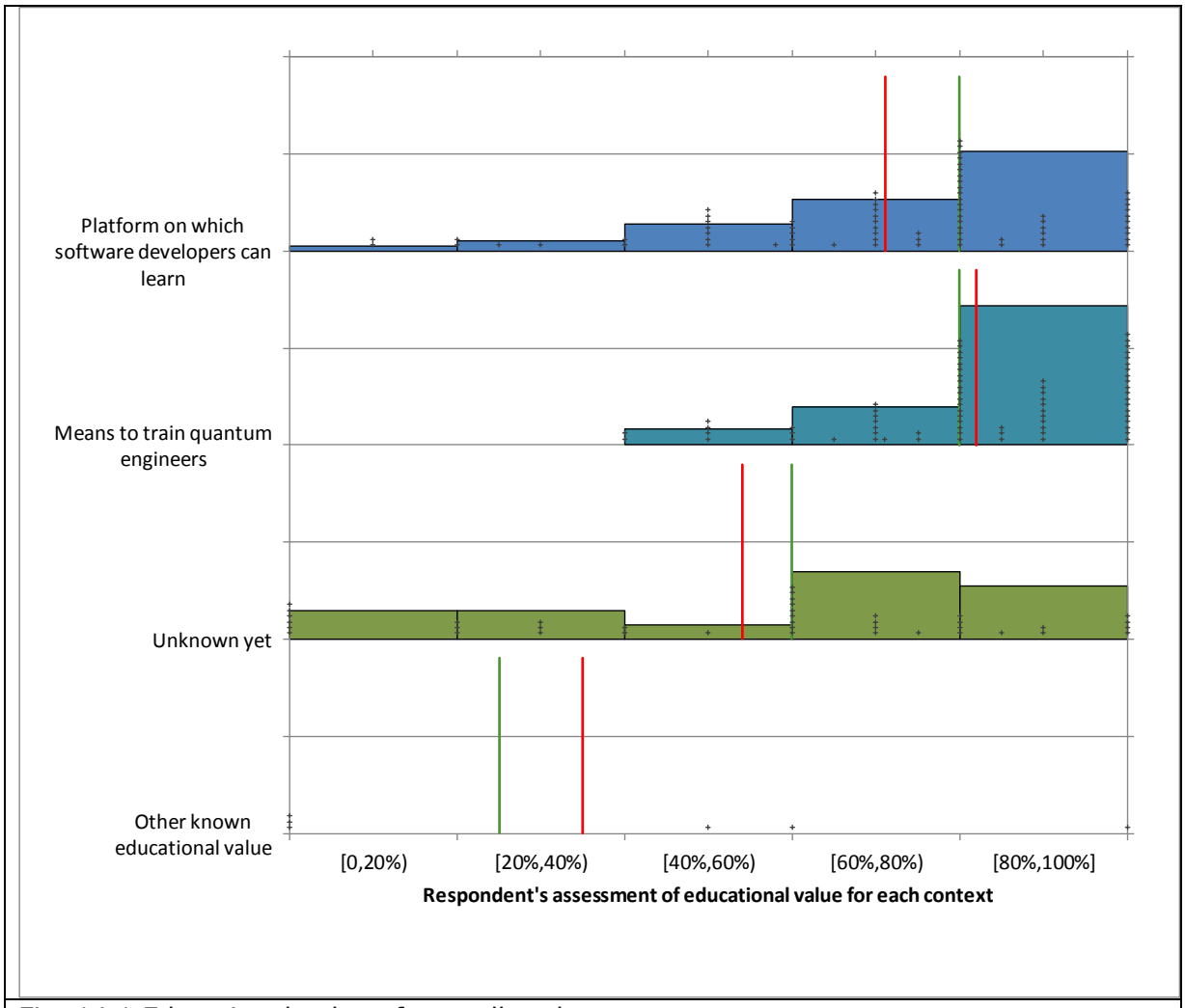


Fig. 14.1 Educational value of a small scale quantum computer
median mean + individual responses, stacked vertically

Sub-question 14.2: What is the awareness of quantum technology among different targets?

There is a good consensus that awareness of quantum computing is greatest among physicists, followed by computer scientists and less among chemists and engineers. The view stated in comment 3 below seems to be more pessimistic than the average regarding knowledge of quantum computing among computer scientists.

Only 4 respondents mentioned other categories of experts; one cited biologists and another, material scientists but no other disciplines were raised.

Response rates were also low for this sub-question, as for previous one.

Comments

1. "People learn the basics at university- but they are not well aware of quantum computing and its opportunities."

2. "I'm guessing here - if you want to find out- a better way would be to do a survey of these different groups. I suspect that most of these are aware of QC- but probably not of the potential or anything much about it."

3. "Well-known among physicists- not considered by computer scientists"

Table 14.2 Awareness of quantum computing among different specialists

	No. of responses	**Mean**	**Median**	**IQR**
Physicists	74	79.4%	80%	30%pts.
Chemists	71	49.5%	50%	30%pts.
Engineers	72	42.%	40%	40%pts.
Computer scientists	73	49.2%	50%	43%pts.
Others	4	22.5%	20%	40%pts.

Note: the respondents were not themselves necessarily specialized in these disciplines. The question concerns how aware they thought others were.

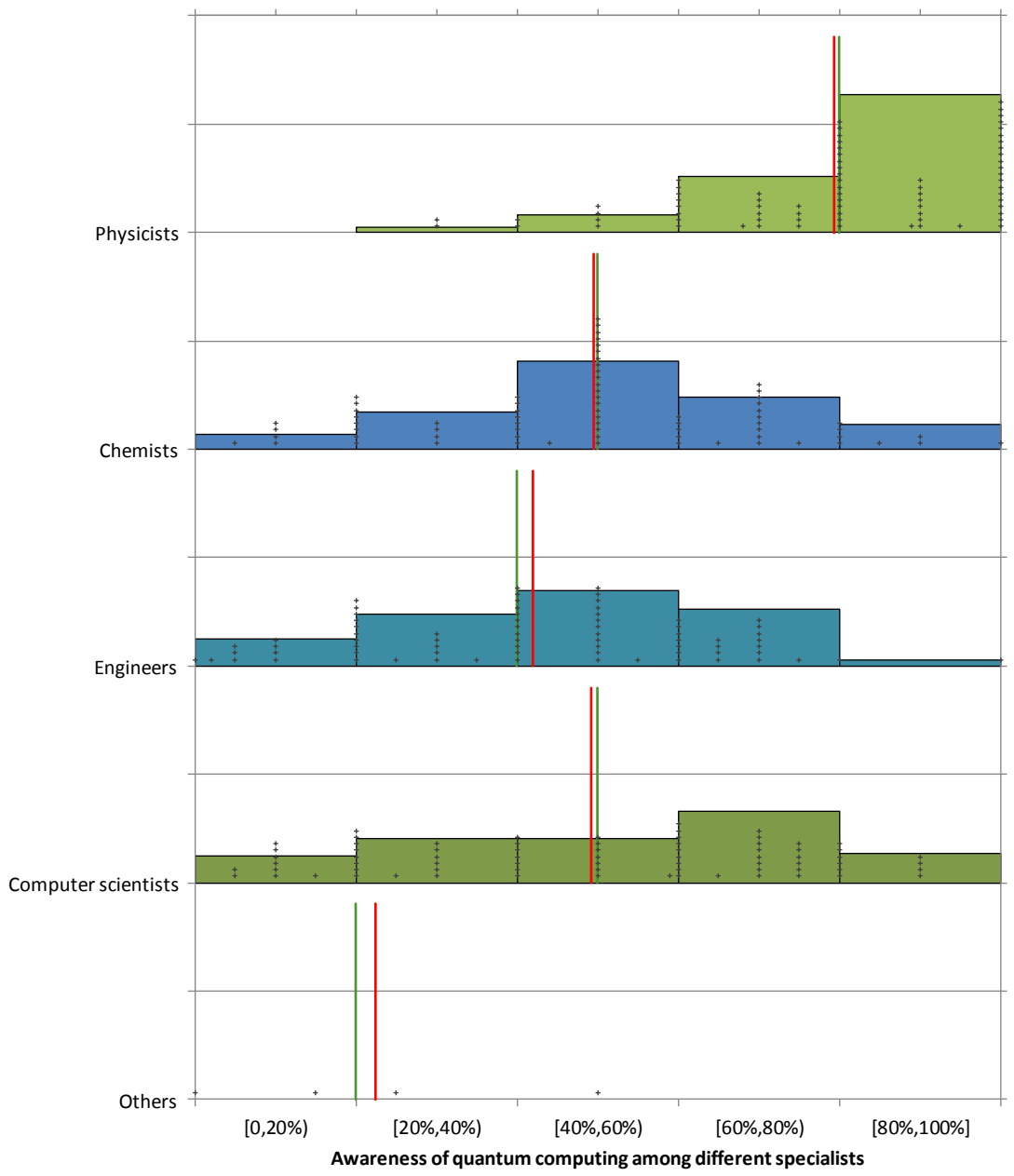


Fig. 14.2 Awareness of quantum technology

median mean + individual responses, stacked vertically

Sub-question 14.3: Importance of training new quantum computing specialists in different categories

There is a strong consensus on the need to train physicists, engineers and computer scientists in quantum computing with many respondents also thinking that it is important to train chemists in the subject. Together with the results of 14.2, these recommendations can be interpreted as meaning that the respondents perceive a need to correct a relative lack of knowledge of quantum computing among engineers and computer scientists, and some think chemists as well, but that it is also very important to continue to train physicists in the subject. Only four respondents recommended training other professionals, of whom one specified life scientists and the other software engineers.

Table 14.3 Importance of training different categories of specialist

	No. of responses	**Mean**	**Median**	**IQR**
Physicists	68	80.5%	81%	29%pts.
Chemists	69	64.6%	70%	30%pts.
Engineers	70	77.4%	80%	28%pts.
Computer scientists	70	81.3%	80%	30%pts.
Others	4	52.5%	60%	83%pts.

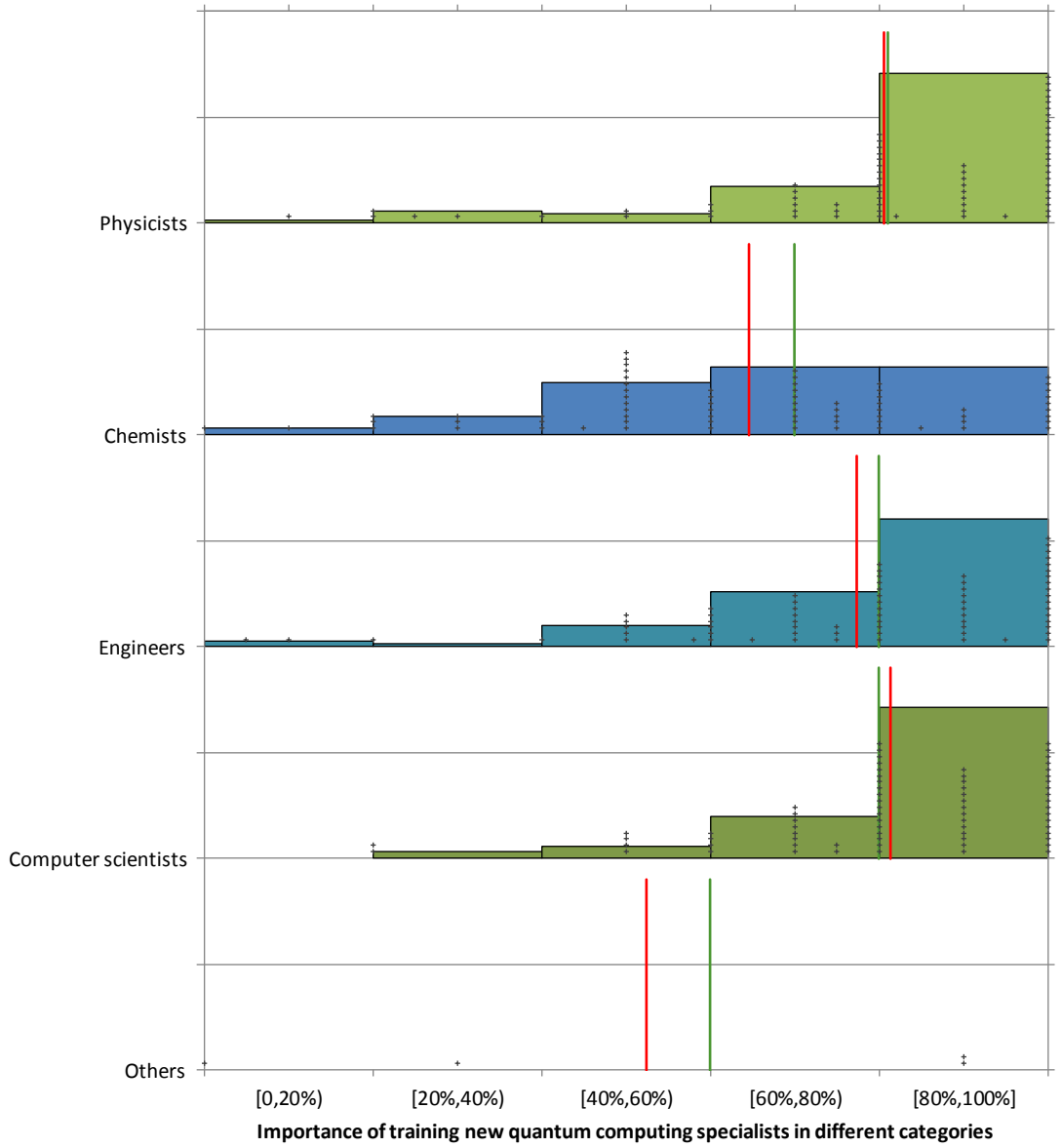


Fig. 14.3 Importance of training quantum computing specialists in different categories

median mean + individual responses, stacked vertically

Taking questions 14.2 and 14.3 together (see Figure 14.2.1), the high importance that the respondents attach to training for both more aware and less aware categories does lend support to the idea of using resources from the Flagship for this purpose. The numerical results do not indicate support for the counter argument: that training is already well-funded by other programmes which already ensure that there will be more trained people than the emergent European quantum computing industry is likely to need. No comments were received to this effect.

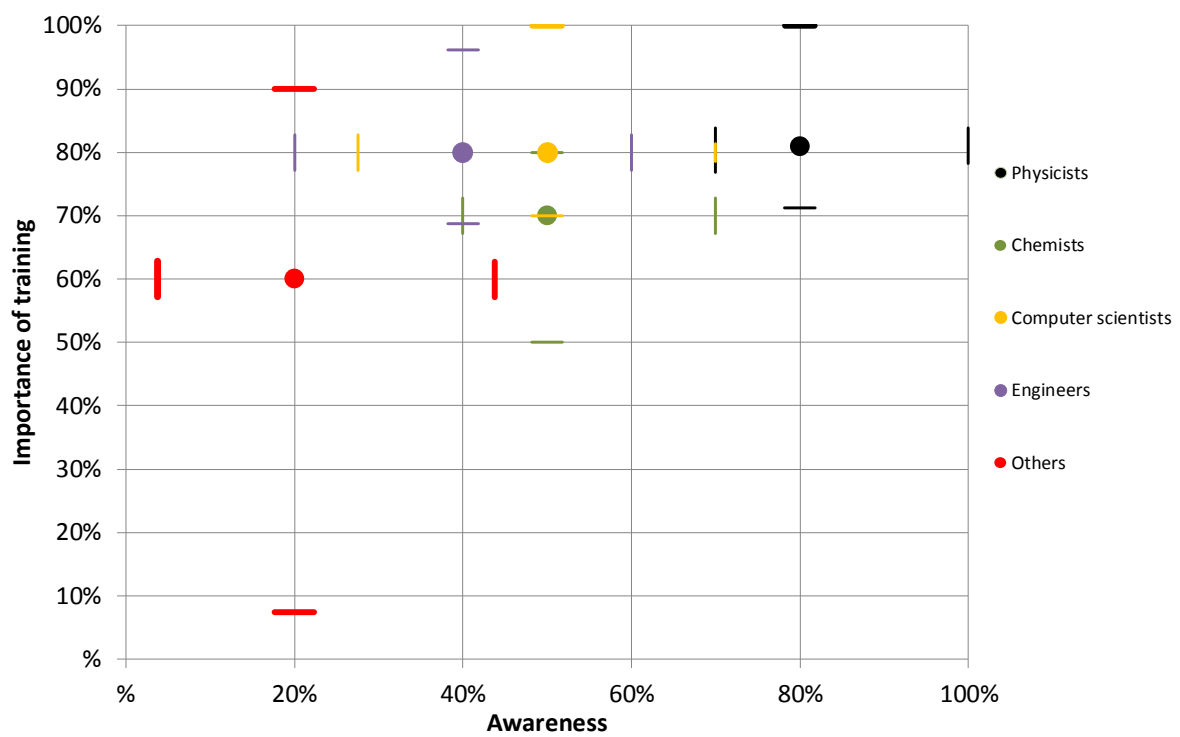


Fig. 14.2.1 Level of awareness and importance of training

Sub-question 14.4: Which aspects of education should be adapted and how?

Most of the recommendations received can be grouped into the first three groups below. The first group are to develop more courses in quantum computing, something which should be well within the capabilities of European universities. The second group concerns rather straightforward organisational and promotional issues. The third recommendation, to widen the diffusion of basic quantum physics education, is achievable in principle, although the goal of demystifying the subject is, of course, more challenging.

Overall, the path ahead for education and training in quantum computing seems clear.

Recommendations for quantum computing-relevant courses

1. "For the moment- perhaps it is enough to offer more undergraduate and graduate courses on quantum computing. Not so many universities offer such courses."
2. "Incorporating Quantum Programming into current physics- engineering and computer science programs via quantum simulators on classical machines."
3. "MSc and PhD programmes. Founding quantum technologies departments in the universities. We should remember that the success of the IT industry is correlated to the appearance in universities in the '60s - '70s of computer science departments & and training programs."
4. "Various high-quality MSc progammes in quantum technology would be needed."
5. "2 areas here: quantum hardware specialists need more physics. Quantum software specialists need define new areas in software engineering and mathematics. they need to understand the different approach- however they don't need to understand quantum physics."
6. "Definitely introduce quantum computing courses to a wider spectrum of students outside physics- computer science and chemistry. Depending on the level of development of the technology, I can also see a specialised quantum engineer course in the future as well."
7. "Special summer-schools for non-physicists."
8. "Post-graduate."

Recommendations for organisation and promotion of quantum computing training

9. "training networks- doctoral centres...are one nice way to train new scientists. Public awareness is also very important"
10. "Open Source tool-kits- principally the interfaces to which industry and academic offerings can be integrated. Underlying training and support for their adoption. Working groups. Standards committees."
11. "Cross-disciplinary education and training"
12. "promote information about opportunities to learn or train"
13. "promote training and r&d positions between industry and academia"
14. "Promote training."

Broadening elementary quantum physics education

15. “Basic physics education- starting in secondary schools. We'll never use the full potential of quantum technologies if every person starting in the field still coins it as 'weird'...”
16. “Teach basic quantum mechanics in secondary schools.”
17. “Basic quantum technology knowledge - people needs to understand the concept behind.”
18. “Explain quantum mechanics demystifying several issues (like collapse-measurement,etc) that provides many difficulties to students to get an intuitive understanding of quantum phenomena. Such type of explanations of quantum mechanics (beyond the orthodox one) exist and are very recommendable for students.“
19. “Education in all fields of science- computation- and engineer should include basics on quantum computing and quantum technologies.”

Other

20. “Creating jobs”
21. “Progress in quantum computing will depend on highly specialized laboratory equipment- materials and supply chains.”

Question #15 Status and evolution

Which of the following statements do you think reflect the current situation and the future evolution of quantum computing? (Enter a number from 0 to 100, with a higher score for the statements you are more confident of.)

Sub-question 15.1: Status and evolution of quantum algorithms

Quantum algorithms with proven performance enhancement with respect to classical ones will remain limited in number, and useful only in very specific tasks.

A growing number of useful quantum algorithms will be designed.

Already a significant number of quantum algorithms with proven performance enhancement with respect to classical ones have been found, and they can address computational tasks of practical use.

Performance enhancement of currently available quantum algorithms is still an open question but will be resolved in the next years.

Performance enhancement of currently available quantum algorithms is still an open question, and the situation will remain unsettled for the foreseeable future.

The quantum algorithms that have been found up to now do not provide useful solutions for computational problems of any practical importance.

Sub-question 15.2 Evolution of quantum hardware

Hardware for universal quantum computation able to perform tasks unfeasible for conventional computation will be developed in less than 5 years.

Hardware for specific quantum computations (e.g. annealing, simulation), decisively outperforming conventional computation, will be developed in less than 5 years.

Hardware for universal quantum computation able to perform tasks unfeasible for conventional computation will not be developed by less than 5 years from now but will be developed by less than 10.

Hardware for specific quantum computations (e.g. annealing, simulation), decisively outperforming conventional computation, will not be developed by less than 5 years from now but will be developed by less than 10.

Hardware for universal quantum computation able to perform tasks unfeasible for conventional computation will not be developed in less than 10 years from now.

Hardware for specific quantum computations (e.g. annealing, simulation), decisively outperforming conventional computation, will not be developed in less than 10 years from now.

Sub-question 15.3 Evolution of quantum computing architecture

Quantum processors will completely displace classical ones, without radically changing the computer architecture we know now.

Quantum computers will resemble today's supercomputers, running specific algorithms to solve targeted problems.

Quantum computers will resemble the mainframes of the sixties, with computing time sold in slots for general-purpose computations.

Quantum computers will resemble mini-computers of the eighties, with a few terminals for general-purpose computations.

Quantum processors will complement classical ones in hybrid architectures for general purpose applications.

Quantum processors will complement classical ones in hybrid architectures for specific scientific applications.

Motive
This question concludes the structured questions and represents a summary of the foresight obtained regarding technical issues.

Sub-question 15.1: Status and evolution of quantum algorithms
Overall, the results show optimism regarding progress more in quantum algorithms, but with quite a large spread and a significant number of pessimistic views. The greatest degree of confidence is that a growing number of useful quantum algorithms will be found, and the median value is somewhat greater than the mean, the latter being pulled down by a small number of dissenting views. Optimism is tempered by the fact that many participants had high or quite high confidence that quantum algorithms with proven performance enhancement would remain limited in number. Nevertheless, very few participants agreed with the most negative statement: that existing quantum algorithms do not provide useful solutions to problems of any practical importance.

Sub-question 15.2: Evolution of quantum hardware

Note that the statements 1, 3, and 5 concern universal computing hardware and statements 2, 4, and 6 concern hardware for specific problems. Not surprisingly there is more optimism about rapid development of the latter with greatest confidence in the timescale of 5-10 years, and some confidence for even shorter timescales. For a universal computer, then greatest confidence is for a timescale of more than 10 years. For all statements there is a wide spread of views, from 0 to 100%.

Sub-question 15.3: Evolution of quantum computing architecture

The weight of opinion is towards the picture of quantum computers as specialist machines, either resembling today's supercomputers or in a hybrid quantum-classical architectures for scientific applications. Some credence is nevertheless given to the idea of quantum computers being used for general-purpose computation, either in hybrid architectures and/or in mainframe-type, time-sharing configurations. There was a consensus against the picture of quantum computers in a mini-computer configuration. The idea of quantum computers completely replacing classical ones was considered implausible by the great majority of participants.

100 participants opened the question.

Table 15.1 Status and evolution of quantum algorithms

	No. of respondents	Mean	Median	IQR
Quantum algorithms with proven performance enhancement with respect to classical ones will remain limited in number- and useful only in very specific tasks.	71	46.8%	50%	50%pts.
A growing number of useful quantum algorithms will be designed.	73	72.3%	80%	30%pts.
Already a significant number of quantum algorithms with proven performance enhancement with respect to classical ones have been found- and they can address computational tasks of practical use.	69	46.7%	40%	48%pts.
Performance enhancement of currently available quantum algorithms is still an open question but will be resolved in the next years.	69	52.6%	50%	43%pts.
Performance enhancement of currently available quantum algorithms is still an open question- and the situation will remain unsettled for the foreseeable future.	66	29.3%	25%	40%pts.
The quantum algorithms that have been found up to now do not provide useful solutions for computational problems of any practical importance.	68	18.7%	10%	20%pts.

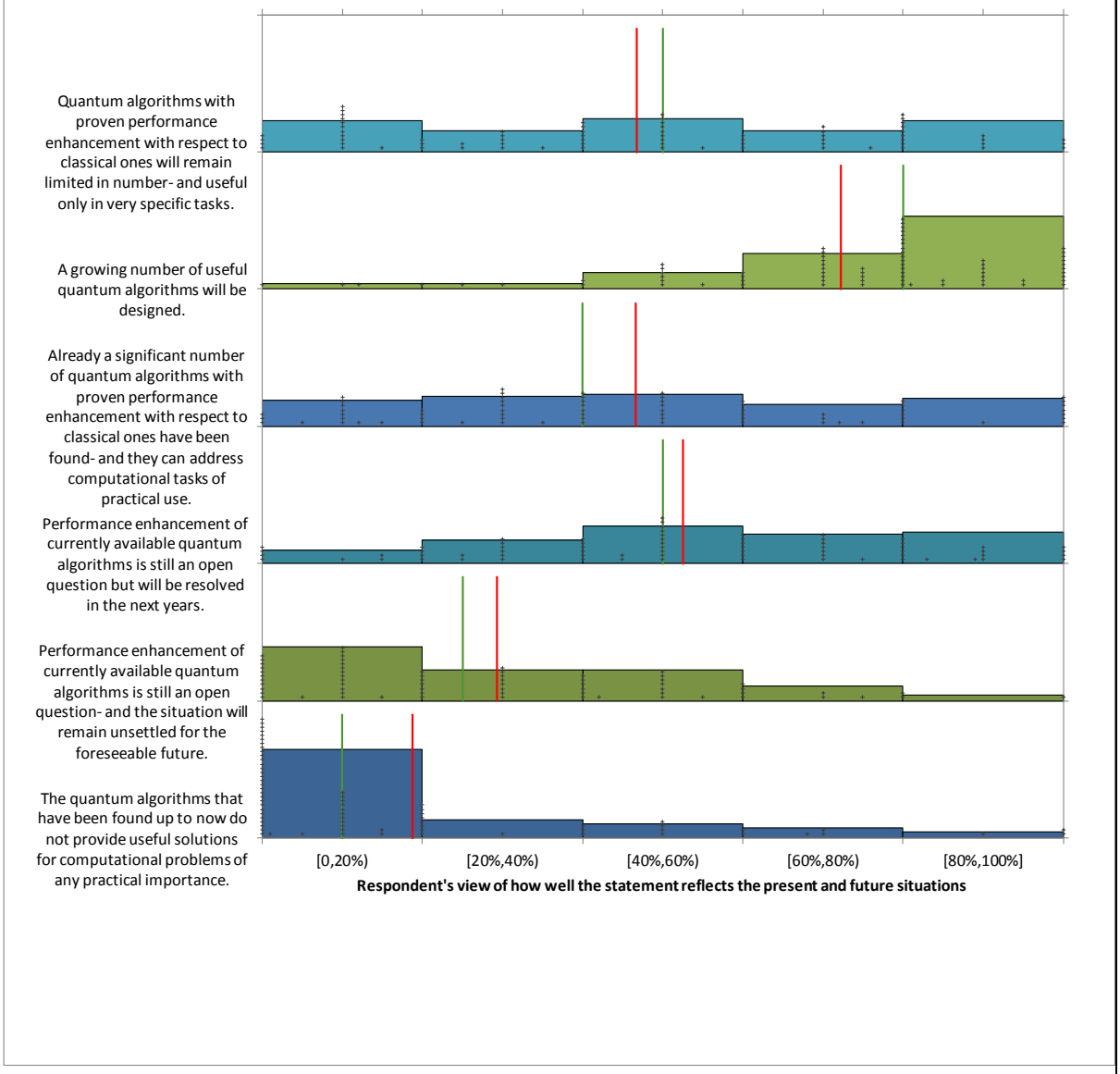


Fig. 15.1 Status and evolution of quantum algorithms

median mean + individual responses, stacked vertically

Table 15.2 Evolution of quantum hardware

	No. of respondents	Mean	Median	IQR
Hardware for universal quantum computation able to perform tasks unfeasible for conventional computation will be developed in less than 5 years.	69	30.6%	20%	35%pts.
Hardware for specific quantum computations (e.g. annealing- simulation)- decisively outperforming conventional computation- will be developed in less than 5 years.	72	52.7%	55%	55%pts.
Hardware for universal quantum computation able to perform tasks unfeasible for conventional computation will not be developed by less than 5 years from now but will be developed by less than 10.	69	42.1%	40%	40%pts.
Hardware for specific quantum computations (e.g. annealing- simulation)- decisively outperforming conventional computation- will not be developed by less than 5 years from now but will be developed by less than 10.	71	57.9%	60%	40%pts.
Hardware for universal quantum computation able to perform tasks unfeasible for conventional computation will not be developed in less than 10 years from now.	69	51.4%	60%	58%pts.
Hardware for specific quantum computations (e.g. annealing- simulation)- decisively outperforming conventional computation- will not be developed in less than 10 years from now.	67	32.2%	20%	40%pts.

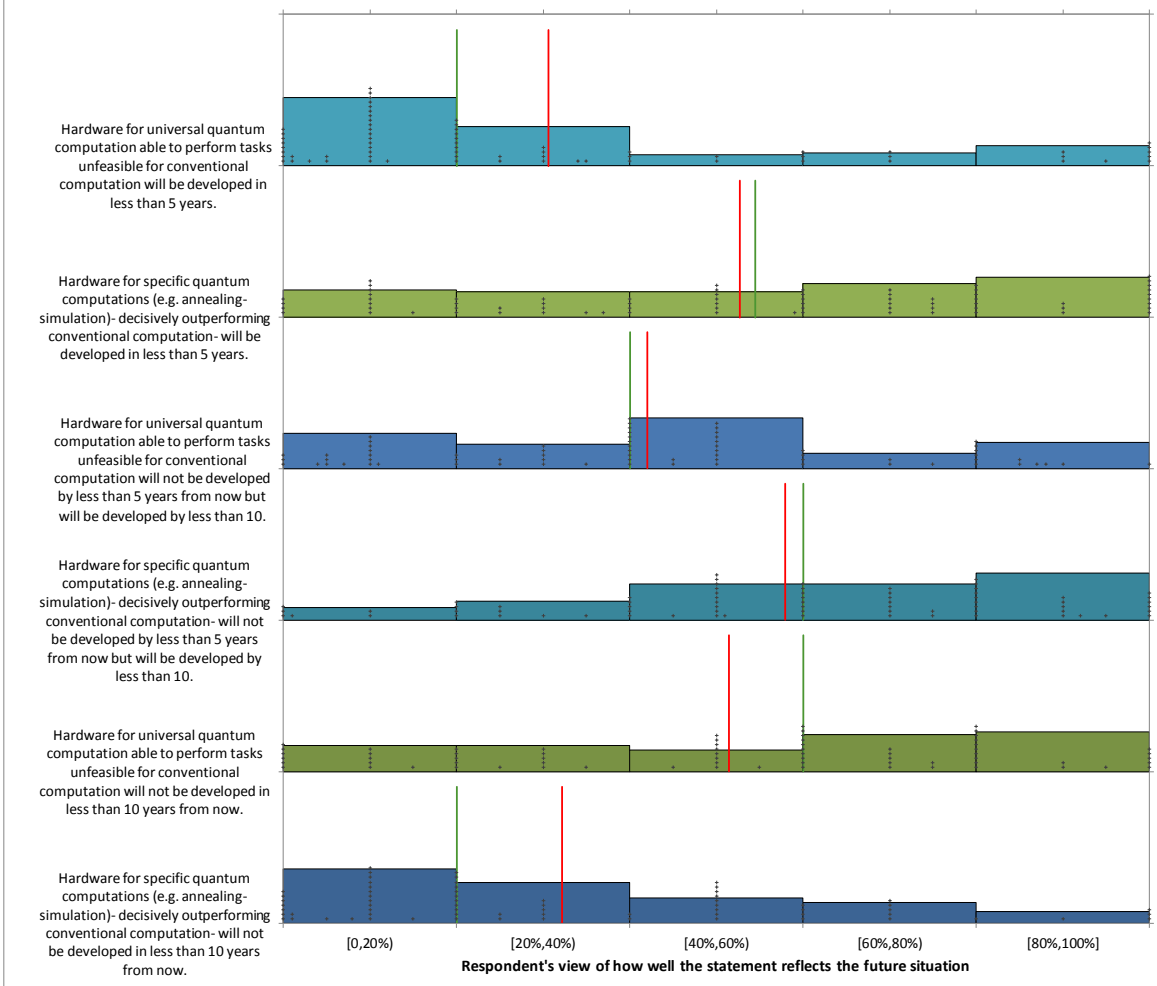


Fig. 15.2 Evolution of quantum hardware

median mean + individual responses, stacked vertically

Table 15.3 Evolution of quantum computing architecture

	No. of respondents	Mean	Median	IQR
Quantum processors will completely displace classical ones- without radically changing the computer architecture we know now.	71	11.3%	2%	10%pts.
Quantum computers will resemble todays supercomputers- running specific algorithms to solve targeted problems.	71	63.9%	70%	30%pts.
Quantum computers will resemble the mainframes of the sixties- with computing time sold in slots for general-purpose computations.	70	54.3%	57%	50%pts.
Quantum computers will resemble mini-computers of the eighties- with a few terminals for general-purpose computations.	70	24.9%	20%	30%pts.
Quantum processors will complement classical ones in hybrid architectures for general purpose applications.	70	47.5%	50%	50%pts.
Quantum processors will complement classical ones in hybrid architectures for specific scientific applications.	70	73.5%	80%	32%pts.

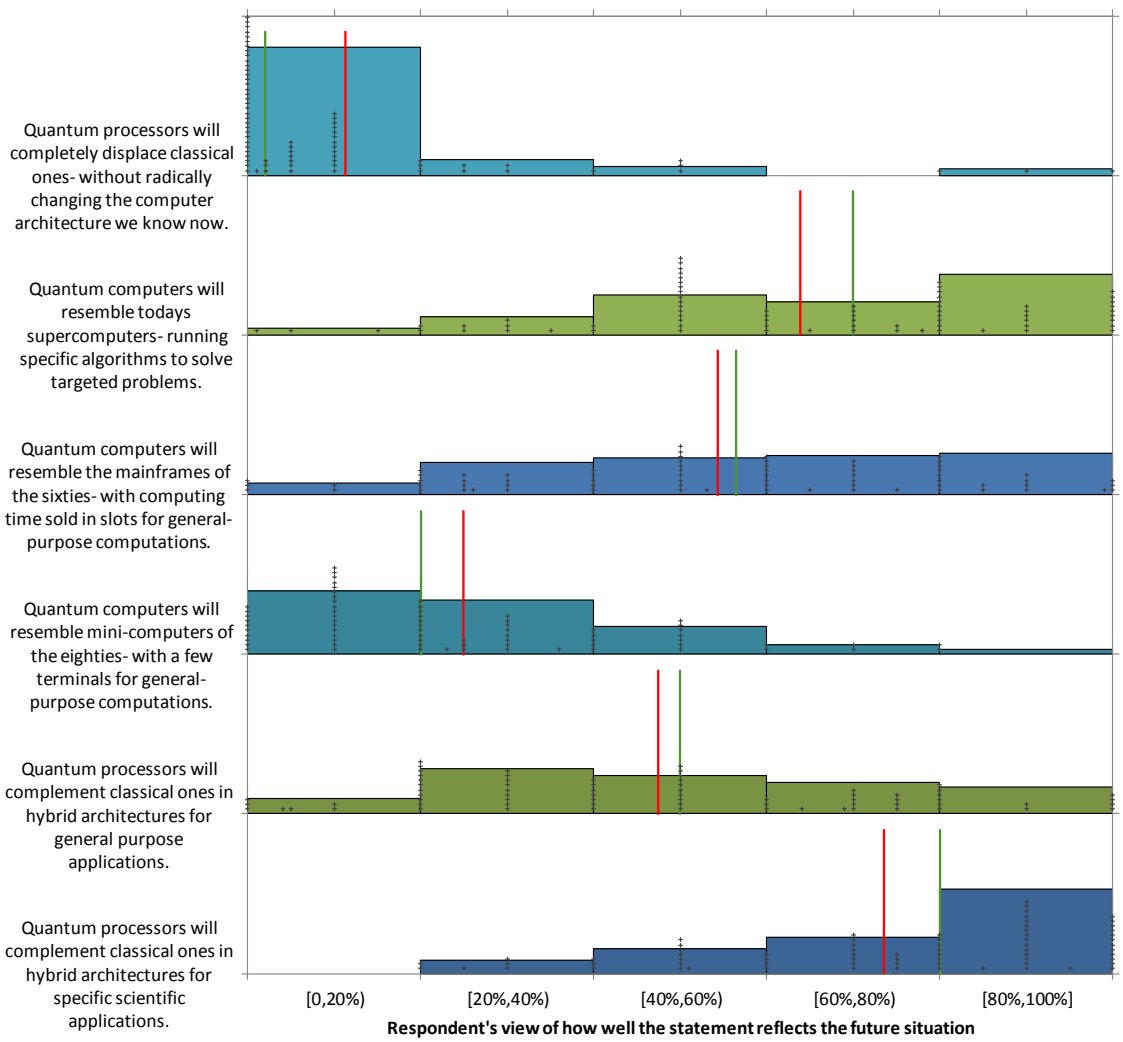


Fig. 15.3 Evolution of quantum computing architecture

median mean + individual responses, stacked vertically

Question #16 Final comments

Please add other comments, suggestions, concerns etc. related to European policy and strategy concerning quantum computing.

Altogether 98 people accessed the question, but only 13 comments were provided. They were grouped by theme as listed below.

Comments and suggestions regarding the FET Flagship and EU funding

1. "The flagship initiative will result in substantial scientific and technological advances in quantum information processing."
2. "First- there is a risk here to mix the Flagship and the quantum computing topic. Quantum computing is just a particular field which could be disrupted by quantum technologies. It would have been interesting to extend this present questionnaire to other fields like sensors- simulation- etc... I'm pretty sure that some of us answered the questions having the larger set of topics of the flagship in mind- while the questions were specifically on computing - and sometimes on simulations which is different. Second- the vast majority of researchers and of funding on quantum topics is already present in Europe- well beyond North-America and Asia. The flagship must bring something else than just funding; it must bring a vision- then a focus- a 'risky' bet on a very few selected proof of concepts. and also a coupling between academics and industries "
3. "It is crucial that EU funds and quantum technology flagship is aware of the need and relevance on proposing- creating- and developing novel disruptive quantum computing paradigms- in theory and experiments- beyond the fashionable paradigms that are condemned to failure in the next decades: i) digital quantum computing with error correction and ii) topological quantum computing- and iii) adiabatic quantum computing. It is also crucial that high-gain high-risk EU funding becomes true to the word- and not fake risky funding for incremental or irrelevant research as is the case of ERC grants at all levels. There is not a single ERC grant that I know that is not just fake follow up of previous development with null advance to the needed quantum computing novel paradigms and quantum technologies."
4. "The Flagship is a unique opportunity to achieve something great that we could not pursue with the other funding instruments. Let us not miss this chance of building the quantum computer."
5. "It is needed to develop a program that binds and exploits existing technologies and developments in materials science rather than sidelining those. The program should offer more clarity on what exactly the expected deliverables are and should strive to connect more strongly to existing flagship programs and bigger EU research and innovation initiatives. It should provide opportunities to researchers with diverse and broader skill set. With giant strides made by international competitors- choosing the right strategy is important- too much focus- at this moment- on just one credible platform will be shortsighted."
6. "EU should fund the development of undergraduate and postgraduate courses on quantum computing and quantum information processing in EU Universities."
7. "Concentrate on the basic research for several more years with some development funding of promising technologies"

Comments regarding the research-industry relationship

8. "Quantum computing has to be align with industry needs- deliverables have to try to solve industry problems. Research & Universities have to work together with industry to build efficient communication channels between them."

9. "Research and industry have to work hand in hand; co-innovation is key here. Long term vision is essential. Quantum computing is about hardware AND software- they have to be conceived together. This area is not so mature as other quantum technologies- however probably an area where Europe can make a difference. Even if the effort is and should be international- Europe has to be careful to keep his excellence (i.e. not producing high-quality and excellent research that is used and exploited by non-European industries)."

Suggestions concerning specific science and technology issues

10. "As I have mentioned along my answers I think that quantum mechanics needs to be explained by demystifying several issues (like collapse- measurement etc.) that provides many difficulties to students to get an intuitive/familiar understanding of quantum phenomena. Such type of explanations of quantum mechanics (beyond the orthodox one) exist and are very recommendable. On the other hand- quantum computers will always suffer from the decoherence (quantum systems become classical at a macroscopic level). Surprisingly- our understanding of such quantum-to-classical transition is very- very poor. The question on this survey also shows this poor understanding of the transition between quantum and classical systems. It is not a well-defined line (an switch that changes the classical world to the quantum one)- but a diffuse interface that we have to better understand/control to make quantum computing applications realistic."
11. "As highlighted in my answers I think Europe must focus on the application of Quantum Computing to Artificial Intelligence and Machine Learning. In this way we could develop a strong and specific approach toward a futuristic vision where powerful quantum technologies are merged with intelligent methods for designing algorithms useful for the next generation of computer applications (self-driving car- humanoid robots and so on)."

Comments regarding broader societal implications

12. "Make sure that European policy focuses on the right values within the global context. I sure will contribute to that."
13. "We need also to think more broadly about the social and economic implications. For example- not only will quantum computing be important for machine learning or searching large databases- etc.- but if quantum computing transforms machine learning- what might this mean for society? Of course- this can only be speculative at this stage- but if we don't at least try to look ahead we will be surprised by unexpected and possibly unintended consequences."

4 Conclusions

The participants in the Real-time Delphi were mostly positive about the technical prospects for quantum computing with only a few dissenting voices seeing it as unfeasible or not useful. This reflects the fact that most people who chose to respond were members of the relevant scientific community, with both a belief in their field and an interest in advocating for it. Response rates were high, with many participants keen to express their point of view.

The participants were strongly optimistic about the scale of the societal and economic impact of quantum computing and about its benefits versus its risks. Most thought that its impact could be as great as, or greater than that which conventional IT has had, which is to say, enormous; and largely or strongly beneficial and safe. Quantum computing is not seen as a job-destroying technology; the main effect on employment will likely be new jobs created in the field. Fears that quantum computing could destroy internet commerce by rendering existing cryptography useless are outweighed by hopes for its application, especially in chemistry, materials science, optimization, database search, machine learning and pattern recognition. The most benefit is seen for basic knowledge and applied science, with benefits also for health, security, education and training.

Different technical approaches each have their advocates, and there are diverse opinions on priorities and organisational aspects. On most of these important questions there is little consensus.

The expected time scale for the first applications is 10-15 years. The results in this respect do support the proposal to give quantum computing a prominent place in the FET flagship. However, there was also a consensus that the field is not yet ripe for a concentrated development effort in a selected direction and funding from all sources should be mainly directed to basic research and early stage development. This view is not in accordance with the aim of the flagship, which is intended to drive technology to high readiness levels and to foster commercialisation.

Appendix A. The Real-time Delphi questionnaire

Following is the RTD questionnaire composed of screenshots of the online form.

Quantum Computing, its Potential and Possible Implications for Policy and Society

Dear Colleagues,

The rapid development of quantum technologies is set to have major impacts on innovation across disciplines and sectors. The purpose of this study, conducted by the European Commission Directorate General Joint Research Centre, is to gather and summarize expert opinion about emerging quantum computing developments to help design European strategies for the field. The questionnaire (using Real Time Delphi - RTD - methodology) is intended to identify forces of change, to foster dialogue among experts and the wider community of stakeholders, to improve understanding of future policy questions and to help in setting priorities. It addresses, through 16 questions:

- Quantum computing **technical aspects** -- applications and drivers that help innovation.
- The **state of research** and the **different approaches,** across countries and institutions.
- Integration of **funding, research, and public policies** to accelerate the development of quantum computing for various applications.
- **Actions, methods and time frames** to identify and support the most effective research and technological developments.
- Potential **social and economic** implications within time frames, including **risks** and the need for **responsible innovation.**

The study seeks to identify existing signals that point to windows of opportunity that may open, and new ideas about how to intervene to exploit them.

All the responses are **anonymous by default;** no attributions will be made unless you indicate otherwise by identifying yourself in the comments section of the respective question. Do not feel obliged to answer every question. It is completely acceptable to leave questions unanswered, but please give your own answers without consulting colleagues or contacts. All respondents will receive a copy of the report with the results of the study.

You do NOT have to fill out the entire questionnaire in one visit; you can return to it -- and are encouraged to -- at any time you wish. When you return, you will find your previous answers and you can complete or edit them.

For most questions, there is the possibility, if you wish, to enter free-text to amplify your answer: a "Discussion" text box will open after you click "Submit". Be sure to click on "Submit Explanation" after you have entered your text. You will also see how the results and responses from your colleagues evolve. The average answer will appear close to the answer box with, in parenthesis, the number of people who have responded so far.

At the and of the questionnaire, under Click her to view the results of this RTD as it is in progress you can see the answers from everyone who has responded so far. [Please note that there might be some waiting time for the system to respond after you click to see the answers and/or after you click the final "Save and Exit" button]

Please return to the questionnaire as often as you like, until **30th April 2017.**

Please make sure to click "Submit" for your entries to be recorded.

Question #1 [-]

About you

Please indicate your level of expertise in the field of Quantum Computing and the area(s) you work in. After you click on "Submit", a textbox will appear that can be used to provide further detail.

Level of expertise	Area of expertise
Select one of the following options:	You work mainly in (check all that apply):
○ Very high - has successfully proposed projects and directed work	☐ Quantum information
○ High - has produced original work and/or contributed substantially to advances	☐ Physics
○ Medium - has extensively studied the area and its scientific literature	☐ Chemistry
○ Low - has studied the area and read popular science articles	☐ Engineering
○ No significant exposure to the area	☐ Computer science
Submit	☐ Applied computer sciences
	☐ Manufacturing
	☐ Management
	☐ Other (please detail in the textbox after "Submit")
	Submit

Question #2 [-]

Technical aspects, drivers

Please assess the following drivers for large-scale manufacturing of quantum computers

Main reasons	Funding priorities	Level of confidence
Which would be the main reasons for quantum computing products to be useful? Please rate the following potential drivers on a scale of 0 to 100. (From 0=not important reason to 100=extremely important reason)	Which do you think would be the priorities for public funding support? Please drag the drivers to order them decreasingly (highest priority at top, lowest at bottom).	Please indicate your level of confidence in your own answers to the questions on "Main reasons" and "Funding priorities". (From 0=not confident at all to 100=extremely confident)
Addressing optimization issues [ ] Increasing energy efficiency of computing [ ] Increasing processing speed in specific applications [ ] Having the ability to control quantum systems [ ] Simulating quantum systems [ ] Simulating classical complex systems [ ] Enhancing machine learning [ ] Attacking and defending data security [ ] Other (please specify in the textbox after "Submit") [ ] Submit	▪ Addressing optimization issues ▪ Increasing energy efficiency of computing ▪ Increasing processing speed in specific applications ▪ Simulating classical complex systems ▪ Having the ability to control quantum systems ▪ Simulating quantum systems ▪ Enhancing machine learning ▪ Attacking and defending data security ▪ Other (as optionally specified in the first column) Submit	Level of confidence in the "Main reasons" answer [ ] Level of confidence in the "Funding priorities" answer [ ] Submit

Question #3 [-]

Technical aspects, IT applications:

Please indicate how important you think quantum computing may be for IT applications, and the timeframe.

Importance for applications	Timeframe	Level of confidence
Please rate on a scale of 0 to 100 the importance you think quantum computing could play for the following applications: (From 0=not important at all to 100=extremely important)	Please indicate the expected time-scale in years for validation in a relevant environment (i.e. to achieve Technology Readiness Level 5), for the following applications: (e.g. enter 3 for "in 3 years"; enter 0 for "already in use", enter 999 for "never")	Please insert a number to indicate your level of confidence in your own answers to the questions on "Importance for applications" and "Timeframe". (From 0=not confident at all to 100=extremely confident)
High speed search of large databases [ ] Optimization [ ] Increase safety of cloud computing systems [ ] Breaking current cryptographic protocols [ ] Machine learning [ ] Pattern recognition [ ] Other (please specify in the textbox after "Submit") [ ] Submit	High speed search of large databases [ ] Optimization [ ] Increase safety of cloud computing systems [ ] Breaking current cryptographic protocols [ ] Machine learning [ ] Pattern recognition [ ] Other (as optionally specified in the first column textbox) [ ] Submit	Level of confidence in the importance for applications [ ] Level of confidence in the timeframe [ ] Submit

Question #4 [-]

Technical aspects, scientific and engineering applications

Please indicate how important you think quantum computing may be for scientific and engineering applications, and the timeframe.

Importance for applications	Timeframe	Level of confidence
Please rate on a scale of 0 to 100 the importance you think quantum computing could play for the following applications: (From 0=not important at all to 100=extremely important)	Please indicate the expected time-scale in years for validation in a relevant environment (i.e. to achieve Technology Readiness Level 5), for the following applications: (e.g. enter 3 for "in 3 years"; enter 0 for "already in use", enter 999 for "never")	Please insert a number to indicate your level of confidence in your own answers to the questions on "Importance for applications" and "Timeframe". (From 0=not confident at all to 100=extremely confident)
Material science	Material science	Level of confidence in the importance for applications
Molecular simulations / quantum chemistry	Molecular simulations / quantum chemistry	Level of confidence in the timeframe
Aerospace	Aerospace	Submit
Other fluid dynamics, e.g. climate modelling	Other fluid dynamics, e.g. climate modelling	
Exoplanetary research	Exoplanetary research	
Economics and finance	Economics and finance	
Simulation of smart cities	Simulation of smart cities	
Software validation	Software validation	
Other (please specify in the textbox that opens after you click "Submit")	Other (please specify in the textbox that opens after you click "Submit")	
Submit	Submit	

Question #5 [-]

Social aspects

Potential implications of quantum computing, when it is operationally available

Impact on society	Areas of benefit	Potential regulatory implications	Certification
Please indicate your opinion about the potential benefits and risks of quantum computing to society at large. Add an optional explanation in the text box that will appear after you click "Submit"	Indicate how the following areas could be affected by quantum computing, inserting negative values for a detrimental effect, positive for a beneficial one. (From -100=very harmful to 100=very beneficial)	Please indicate your judgement about potential regulatory implications	Is any certification specific to quantum computing needed -- e.g. for security, privacy or quality? What kind? In which area(s)? Why?
From -100=very harmful to 100=very beneficial	Basic knowledge	Few drawbacks and no special controls needed	
From -100=very dangerous to 100=very safe	Applied Science	Requiring some regulation to control abuse, based on incremental development of existing IT law	
Submit	Health	Requiring rigorous control and restriction to a limited number of trusted users and organizations	
	Security	Be confined only to research, requiring only research-ethics controls	
	Education and training	Other (please indicate after "Submit")	
	Finance	Submit	Submit
	Quality of life (e.g. job-satisfaction, work/leisure balance)		
	Other (please add in the textbox after "Submit")		
	Submit		

Question #6 [-]

Economic aspects

Implications of quantum computing, when it is operationally available

Potential economic implications	Concentration	Future job market
Please indicate your judgment of the potential economic implications of quantum computing, on all sectors of the economy. Assume a scenario in which conventional computing ceases to evolve in cost and performance as it has done whilst Moore's law has remained valid. The economic effect of quantum computing could be: ○ greater than that which conventional IT has had. ○ similar to that which conventional IT has had. ○ smaller than that which conventional IT has had. ○ a net loss. ○ any of these, it is too uncertain to say. Submit	Please indicate your opinion about the potential effect of quantum computing on the IT sector generally. It will: ○ lead to a near-monopoly in IT. ○ tend to concentrate control of IT in the hands of a fewer major players. ○ have no effect on the concentration of the sector. ○ tend to make the sector somewhat more diverse. ○ lead to a highly diverse market in which no company can dominate even a small part. Submit	What will be the impact of quantum computing on the job market? Insert a number to indicate the likelihood of each expected outcome. (From 0=not likely to 100=very probable) Quantum computing will have a disrupting impact on employment, destroying many existing jobs. [ ] Quantum computing will always be limited to a small niche for very highly skilled, specialized experts. [ ] A new generation of computer programmers will arise for developing quantum software. [ ] Applications and satellite activities enabled by quantum computers will generate significant concomitant employment. [ ] Other (enter explanation in the textbox that will appear after "Submit"). [ ] Submit

Question #7 [-]

Preparations are now under way for a Future and Emerging Technologies (FET) Flagship in quantum technology; see https://ec.europa.eu/digital-single-market/en/quantum-technologies#Article. The following two questions concern both the ramp-up phase of the Flagship, under Horizon 2020, and the Flagship itself, under the next research, technology and innovation programme.

European public funding I

Please give your opinion about the priorities of European public funding for quantum computing hardware.

Public funding priorities	Reasoning for public funding	Level of confidence
Please indicate which quantum computing hardware should European public funding give priority to. (Drag the options with higher priority above those with lower). ▪ Basic research, e.g. because it is premature to move ahead with technology development and the attempts being made to do so are misguided. ▪ Enabling technologies, which would increase the available options for a full-scale quantum computer. ▪ Solutions such as quantum simulation and adiabatic computing, which have a good chance of being useful in the medium term. ▪ Two or three credible candidate platforms, with an aim to produce full-scale computers. ▪ One chosen leading candidate platform, since only by focusing all available resources is there a reasonable chance of success. ▪ Other (please indicate in the textbox after "Submit"). Submit	Please explain your response to the public funding choice Submit	Please insert a number to indicate your level of confidence in your own answers to the questions on "Public funding priorities" and on "Reasoning for public funding". (From 0=not confident at all to 100=extremely confident) Level of confidence in public funding priorities Level of confidence in reasoning for public funding Submit

Question #8 [-]

European public funding II

This question concerns the types of funding instruments which you consider useful for quantum computing, taking the ones currently used in Horizon 2020 as the starting point (see http://ec.europa.eu/research/participants/data/ref/h2020/other/wp/2016-2017/annexes/h2020-wp1617-annex-ga_en.pdf#page=10 for definitions.)

Please do also indicate other possibilities which you think would be appropriate for quantum computing, using the second column.

Horizon 2020 instruments	Other instruments	Level of confidence
Indicate your preferred distribution of funding among the following types of funding action, on a scale of 0 to 100%. (Your answers will be normalized to 100% total) Research & innovation actions (RIA) [ ] Innovation actions (IA) [ ] Coordination & support actions (CSA) [ ] SME instrument actions [ ] ERA-NET Cofund actions [ ] Precommercial procurement (PCP) & Public procurement of Innovative solutions (PPI) actions [ ] European Joint Programme (EJP) Cofund actions [ ] Other (please explain in second column) [ ] Submit	Please indicate any other funding instruments which you think would be suitable, such as those from national programmes or previous European programmes. [ ] Submit	Please insert a number to indicate your level of confidence in your own answers to the questions on "Horizon 2020 instruments" and on "Other instruments". (From 0=not confident at all to 100=extremely confident) Level of confidence in your preferred funding distribution among Horizon 2020 instruments [ ] Level of confidence in your indications of other instruments [ ] Submit

Question #9 [-]

External funding

Please give your opinion about the funding priorities for quantum computing hardware by other sources.

Largest funding sources	Private sector	Non EU-institutional public funding
What do you think should be the partitioning of funding for quantum computing over the next 20 years, excluding European public funding? (Your answers will be normalized to 100% total)	Please indicate which quantum computing hardware you believe the private sector will give priority to. If your rationale differs from that suggested, use the textbox to explain it. (Drag the options with higher priority above those with lower).	Please indicate which quantum computing hardware you believe the public sector, excluding the EU institutions, will give priority to. If your rationale differs from that suggested, use the text box to explain it. (Drag the options with higher priority above those with lower).
Civil private sector	Basic research, e.g. since it is premature to move ahead with technology development and the attempts being made to do so are misguided.	Basic research, e.g. since it is premature to move ahead with technology development and the attempts being made to do so are misguided.
Research institutions (non-publicly funded)	Enabling technologies, e.g. since they would increase the available options for a full-scale quantum computer.	Enabling technologies, e.g. since they would increase the available options for a full-scale quantum computer.
Defence (non-publicly funded)	Interim solutions, such as quantum simulation and adiabatic computing, e.g. since they would have a good chance of being useful in the medium term.	Interim solutions, such as quantum simulation and adiabatic computing, e.g. since they would have a good chance of being useful in the medium term.
Donations	Two or three credible candidate platforms, with an aim to produce full-scale computers.	Two or three credible candidate platforms, with an aim to produce full-scale computers.
Venture capital	One chosen leading candidate platform, e.g. since only by focusing all available resources is there a reasonable chance of success.	One chosen leading candidate platform, e.g. since only by focusing all available resources is there a reasonable chance of success.
National governments	Other (please explain in the textbox after submitting).	Other (please indicate in the textbox after submitting).
Other (please indicate after "Submit")	Submit	Submit
Submit		

Question #10 [-]

Quantum computing software and hardware

Please indicate your opinion on how the quantum computing software and hardware might evolve.

Software and hardware development	Explanation	Level of confidence
Consider the following statements about the relationship of software and hardware for quantum computing and check those that you think are likely to be true. ☐ Quantum computing software and hardware will always need to be developed together. ☐ A quantum software industry will emerge independently from hardware developers. ☐ Quantum computer programming will always require major specific competences distinct from conventional programming. ☐ A general purpose language will emerge, suitable for running any task on a quantum computer. ☐ Quantum computers will always run specific algorithms only. ☐ Software and hardware development will reinforce each other's development. ☐ Other (please explain in the textbox after "Submit"). Submit	What might the future of quantum computer software and hardware development be? Submit	Please indicate your level of confidence in your own answers to the questions on the future of the quantum computing hardware/software relationship (From 0=not confident at all to 100=extremely confident) Level of confidence for "Software and hardware development" Level of confidence for your "Explanation" Submit

Question #11 [-]

Quantum computation's future place

Please give your opinion on the place of quantum computing in the future computational landscape.

Future computing scenarios	Potential synergies	Explanation	Level of confidence
What do you think the place of quantum computing will be if and when it becomes established? (Chose the one scenario that you think is most likely to be true.) ○ Quantum computing will be the only form of computation in the future. ○ Quantum computing will coexist with other computational methods, but will be the most important. ○ Quantum computing will be only one among a number of coexisting computational methods of similar importance. ○ Quantum computing will be important only in a limited number of applications. ○ Quantum computing will be abandoned, replaced by a new paradigm. Submit	Which areas could develop in tandem with quantum computing, to their mutual benefit? Indicate with a numeric value your assessment of potential synergies. (From 0=no synergies at all to 100=extremely important synergies) Nanotechnology Electronics Materials science Chemistry Engineering Other (please add in the textbox after "Submit") Submit	What might the future computing landscape be? Submit	What is your level of confidence in your own answer to the question of the three previous columns? (From 0=not confident at all to 100=extremely confident) Level of confidence for "Future computing scenarios" Level of confidence for "Synergies" Level of confidence in your own "Explanation" Submit

Question #12 [-]

Quantum computing physical platforms

Please give your assessment of the possible physical platforms that can be used to build a quantum computer, and evaluate how Europe is positioned in each of them with respect to international competitors.

Intrinsic strengths	European positioning	Self-assessment
Which are the most promising physical platforms on which to build a large-scale quantum computer? (From 0=not promising at all to 100=extremely promising)	Please assess the European potential for developing these platforms into a fully operational, large-scale machine, given the capabilities of European universities, research centres, and industry. (From 0=extremely low to 100=extremely high)	What would you consider to be your own level of expertise in each of the following areas? (From 0=very low to 100=very high)
Superconducting qubits	Superconducting qubits	Superconducting qubits
Trapped ions	Trapped ions	Trapped ions
Photonics	Photonics	Photonics
Semiconductor qubits	Semiconductor qubits	Semiconductor qubits
Topological qubits	Topological qubits	Topological qubits
Other (please indicate after "submit")	Other (please indicate after "submit")	Other (please indicate after "submit")
Submit	Submit	Submit

Question #13 [-]

European strengths

Is there a specific aspect of quantum computing for which Europe seems to enjoy some competitive advantages in the international landscape?

Hardware and software	Level of confidence	Open text
In which field is Europe better positioned? (From 0=extremely weak with respect to competitors to 100=very strong in the global landscape)	Which is your level of confidence in each of the answers given in the first column? (From 0=not confident at all to 100=extremely confident)	Please indicate other quantum computing areas in which Europe might have a competitive advantage or, conversely, structural weaknesses.
Processors	Processors	
Memories	Memories	
Communications and interconnect	Communications and interconnect	
Fundamental algorithms	Fundamental algorithms	
Software for quantum simulations	Software for quantum simulations	
Firmware for hybrid classical-quantum hardware components	Firmware for hybrid classical-quantum hardware components	
User interfaces	User interfaces	
Other (please indicate after "Submit")	Other (please indicate after "Submit")	
Submit	Submit	Submit

Question #14 [-]

Education

What are the education aspects impacted by quantum computing?

Educational value	Awareness level	Training	Adaptation
What is the educational value of a small scale quantum computer in each of the following contexts? (From 0=no value to 100=extremely high value) Platform on which software developers can learn Means to train quantum engineers Unknown yet Other known educational value (please indicate what, after "Submit") Submit	What is the awareness of quantum technology among different targets? (From 0=no knowledge to 100=high awareness) Physicists Chemists Engineers Computer scientists Others (please specify after "Submit") Submit	How important is it to train new quantum computing specialists in these categories? (From 0=of no importance to 100=extremely important) Physicists Chemists Engineers Computer scientists Others (please specify after "Submit") Submit	Which aspects of education should be adapted and how? (e.g. promote training, finding jobs, etc.) Submit

Question #15 [-]

Status and evolution

Which of the following statements do you think reflect the current situation and the future evolution of quantum computing?

(Enter a number from 0 to 100, with a higher score for the statements you are more confident of.)

Status and evolution of quantum algorithms	Evolution of quantum hardware	Evolution of quantum computing architecture
Quantum algorithms with proven performance enhancement with respect to classical ones will remain limited in number, and useful only in very specific tasks. A growing number of useful quantum algorithms will be designed. Already a significant number of quantum algorithms with proven performance enhancement with respect to classical ones have been found, and they can address computational tasks of practical use. Performance enhancement of currently available quantum algorithms is still an open question but will be resolved in the next years. Performance enhancement of currently available quantum algorithms is still an open question, and the situation will remain unsettled for the foreseeable future. The quantum algorithms that have been found up to now do not provide useful solutions for computational problems of any practical importance. Submit	Hardware for universal quantum computation able to perform tasks unfeasible for conventional computation will be developed in less than 5 years. Hardware for specific quantum computations (e.g. annealing, simulation), decisively outperforming conventional computation, will be developed in less than 5 years. Hardware for universal quantum computation able to perform tasks unfeasible for conventional computation will not be developed by less than 5 years from now but will be developed by less than 10. Hardware for specific quantum computations (e.g. annealing, simulation), decisively outperforming conventional computation, will not be developed by less than 5 years from now but will be developed by less than 10. Hardware for universal quantum computation able to perform tasks unfeasible for conventional computation will not be developed in less than 10 years from now. Hardware for specific quantum computations (e.g. annealing, simulation), decisively outperforming conventional computation, will not be developed in less than 10 years from now. Submit	Quantum processors will completely displace classical ones, without radically changing the computer architecture we know now. Quantum computers will resemble today's supercomputers, running specific algorithms to solve targeted problems. Quantum computers will resemble the mainframes of the sixties, with computing time sold in slots for general-purpose computations. Quantum computers will resemble mini-computers of the eighties, with a few terminals for general-purpose computations. Quantum processors will complement classical ones in hybrid architectures for general purpose applications. Quantum processors will complement classical ones in hybrid architectures for specific scientific applications. Submit

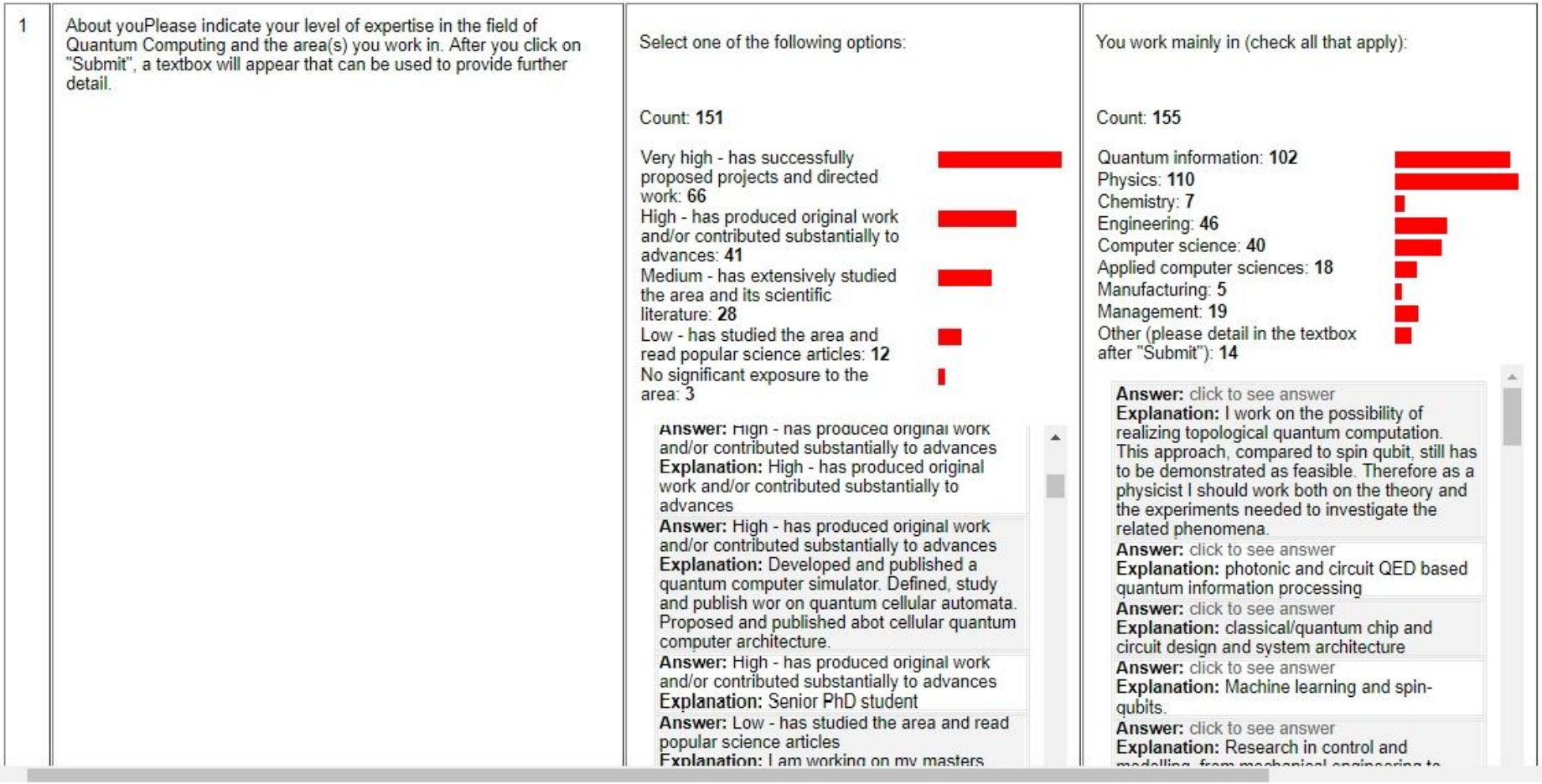
Question #16 [-]

Please add other comments, suggestions, concerns, etc. related to European policy and strategy concerning quantum computing.

Submit

Appendix B. Snapshot review of the responses

During the period that the RTD was open for participation, the respondents could see in real-time how the responses were evolving, as well as access the summarizing page. Following is the summary and raw analysis of the responses (the screenshots of the online form.)



2	Technical aspects, drivers Please assess the following drivers for large-scale manufacturing of quantum computers	Which would be the main reasons for quantum computing products to be useful? Please rate the following potential drivers on a scale of 0 to 100. (From 0=not important reason to 100=extremely important reason) Count: **138**	Which do you think would be the priorities for public funding support? Please drag the drivers to order them decreasingly (highest priority at top, lowest at bottom). Count: **129**	Please indicate your level of confidence in your own answers to the questions on "Main reasons" and "Funding priorities". (From 0=not confident at all to 100=extremely confident) Count: **134**

Answer	Mean	Min	Max	Median	Count	Std
Addressing optimization issues	71.06	0	100	80	133	25.21
Increasing energy efficiency of computing	36.3	0	100	30	127	29.14
Increasing processing speed in specific applications	78.56	0	100	85	130	24.19
Having the ability to control quantum systems	69.18	0	100	80	128	27.57
Simulating quantum systems	86.18	10	100	90	132	19.3
Simulating classical complex systems	59.84	0	100	70	126	29.28
Enhancing machine learning	59.73	0	100	60	128	26.92
Attacking and defending data security	64.26	0	100	70	130	31.32
Other (please specify in the textbox after "Submit")	67.5	0	100	80	24	37.66

Addressing optimization issues: **305**
Increasing energy efficiency of computing: **637**
Increasing processing speed in specific applications: **333**
Simulating classical complex systems: **544**
Having the ability to control quantum systems: **458**
Simulating quantum systems: **319**
Enhancing machine learning: **553**
Attacking and defending data security: **553**
Other (as optionally specified in the first column): **942**

Discussion

Answer: click to see answer
Explanation: It is not clear that quantum computers can defend data security, on the other hand the mere threat that they could break security is already there. It is not clear that there is a commercial interest in cracking security but defending against their attacks is critical and has been for some time.

Answer: click to see answer
Explanation: I would predict strong interest from public funding bodies where there is a UK strategic interest (eg defence and security) and where there is likely to be more nearer-term payoffs, ie the low hanging fruit.

Answer: click to see answer
Explanation: Whilst a theorist, my objective view is that if we wish to fund three things that we can be sure will directly affect the public in the years to come then it is a no brainer. Better ability to control quantum systems, which would lead to our ability to simulate quantum and complex classical systems of larger and larger size.

Answer: click to see answer
Explanation: They need to be able to tackle

search

Answer	Mean	Min	Max	Median	Count	Std
Level of confidence in the "Main reasons" answer	75.63	5	100	80	127	16.64
Level of confidence in the "Funding priorities" answer	71.08	0	100	70	125	19.03

computer

Answer: click to see answer
Explanation: More confident in the "Main reasons" answer because of my own motivation to achieve successes in areas that can offer significant benefit to people's lives through medicine or technology, over any timeframe. Bit less confident in the "Funding priorities" answer because this will be decided by others with more political agendas I suspect.

Answer: click to see answer
Explanation: Being involved in academia within europe for the past 5 years, and being involved in many conferences and discussions with experts in the field I am confident of the reasons and priorities I have indicated. I can be selfish and ask to prioritise more theoretical and fundamental research which is what i do. Whilst i do wish that more fundamental research is funded, as a European taxpayer, I think our wisest investment for the betterment of our society is to prioritise in the areas indicated.

Answer: click to see answer
Explanation: Main reasons: More confident in some categories than others where I am more

3

Technical aspects, IT applications:Please indicate how important you think quantum computing may be for IT applications, and the timeframe.

Please rate on a scale of 0 to 100 the importance you think quantum computing could play for the following applications:

(From 0=not important at all to 100=extremely important)

Count: **119**

Answer	Mean	Min	Max	Median	Count	Std
High speed search of large databases	59.37	0	100	70	109	32.13
Optimization	74.06	10	100	80	110	20.85
Increase safety of cloud computing systems	49.7	0	100	50	106	29.02
Breaking current cryptographic protocols	66.57	0	100	70	108	27.47
Machine learning	65.1	0	100	70	105	24.77
Pattern recognition	63.45	0	100	70	102	24.18
Other (please specify in the textbox after "Submit")	69.44	0	100	80	18	33.07

Answer: click to see answer
Explanation: Modeling complex quantum systems leads to better control of cumbersome quantum effects in basic physics research and to building quantum materials with new properties.
Answer: click to see answer
Explanation: Modelling physical systems is also a significant application.
Database search is not a likely application because the database has to be held in quantum memory and needs to be unsorted, which few databases are.
Answer: click to see answer

Please indicate the expected time-scale in years for validation in a relevant environment (i.e. to achieve Technology Readiness Level 5), for the following applications:
(e.g. enter 3 for "in 3 years"; enter 0 for "already in use", enter 999 for "never")

Count: **114**

Answer	Mean	Min	Max	Median	Count	Std
High speed search of large databases	83.91	0	999	13.5	98	235.53
Optimization	24.61	0	999	8	98	100.89
Increase safety of cloud computing systems	86.73	0	999	11.5	94	239.61
Breaking current cryptographic protocols	43.05	0	999	15	97	141.87
Machine learning	37.85	0	999	10	95	141.99
Pattern recognition	38.08	0	999	10	93	143.53
Other (as optionally specified in the first column textbox)	65.33	0	999	10	18	226.59

your answer
Answer: click to see answer
Explanation: Secure communications (quantum cryptography)
Answer: click to see answer
Explanation: I expect that within 5-15 years an understanding that quantum error-correcting codes are beyond reach will emerge.
Answer: click to see answer
Explanation: Quantum key distribution is

Please insert a number to indicate your level of confidence in your own answers to the questions on "Importance for applications" and "Timeframe".

(From 0=not confident at all to 100=extremely confident)

Count: **112**

Answer	Mean	Min	Max	Median	Count	Std
Level of confidence in the importance for applications	69.99	10	100	72.5	102	18.03
Level of confidence in the timeframe	54.44	0	100	55	101	25.55

Answer: click to see answer
Explanation: As I am not an experimentalist I have indicated the timeframe based on what I read and hear from colleagues. So my timeline is at best an optimistic one.
Answer: click to see answer
Explanation: The Grover Family, (database searched and pattern recognition) have large differences. Alike encryption breaking (RSA very easy, Ellipitic Curve a little harder, and other harder) etc. but RSA is dead by 2020
Answer: click to see answer
Explanation: please enter an explanation for your answer
Answer: click to see answer
Explanation: Have high confidence in areas of achievable impact, except for the data search item. But the timeframe depends, among other things, on what R&D is done, and on how it goes even if done right. Risk is often more a matter of personalities than of objective difficulty! Traditional corporate cultures could easily get bogged down and get nowhere.
Answer: click to see answer
Explanation: It seems like a guessing game at this point, with available information skewed by

4	Technical aspects, scientific and engineering applicationsPlease indicate how important you think quantum computing may be for scientific and engineering applications, and the timeframe.	Please rate on a scale of 0 to 100 the importance you think quantum computing could play for the following applications: (From 0=not important at all to 100=extremely important) Count: **112**	Please indicate the expected time-scale in years for validation in a relevant environment (i.e. to achieve Technology Readiness Level 5), for the following applications: (e.g. enter 3 for "in 3 years"; enter 0 for "already in use", enter 999 for "never") Count: **110**	Please insert a number to indicate your level of confidence in your own answers to the questions on "Importance for applications" and "Timeframe". (From 0=not confident at all to 100=extremely confident) Count: **110**

Answer	Mean	Min	Max	Median	Count	Std
Material science	80.95	10	100	80	99	17.48
Molecular simulations / quantum chemistry	86.23	30	100	90	99	13.87
Aerospace	46.25	0	100	50	97	27.43
Other fluid dynamics, e.g. climate modelling	47.84	0	100	50	94	28.04
Exoplanetary research	30.98	0	100	22.5	92	26.7
Economics and finance	48.78	0	100	50	96	27.19
Simulation of smart cities	37.16	0	90	34.5	92	25.49
Software validation	36.58	0	90	40	93	24.38
Other (please specify in the textbox that opens after you click "Submit")	65.83	0	100	75	12	31.21

relevant. The rest is too remote from what we are likely to be able to actually achieve to be considered. Links to medical and semiconductor technologies applications are missing.
Answer: click to see answer
Explanation: Drug design, materials research
Answer: click to see answer
Explanation: please enter an explanation for

Answer	Mean	Min	Max	Median	Count	Std
Material science	14.96	1	100	10	92	15.59
Molecular simulations / quantum chemistry	12.09	0	100	10	92	14.49
Aerospace	91.91	5	999	20	90	243.69
Other fluid dynamics, e.g. climate modelling	83.34	3	999	20	87	227.45
Exoplanetary research	217.21	0	999	27.5	84	380.21
Economics and finance	58.73	0	999	15	88	178.54
Simulation of smart cities	136.05	0	999	20	84	300.7
Software validation	146.38	0	999	20	85	315.36
Other (please specify in the textbox that opens after you click "Submit")	83.85	0	999	12.5	14	254.05

Answer: click to see answer
Explanation: Quantum metrology, and instrumentation

Answer	Mean	Min	Max	Median	Count	Std
Level of confidence in the importance for applications	69.48	20	100	70	94	17.65
Level of confidence in the timeframe	53.09	0	100	50	94	22.67

Answer: click to see answer
Explanation: Material Science, Molecular simulations, fluid dynamics, economics and finance: High confidence (90)
The rest: low confidence (50)
Answer: click to see answer
Explanation: please enter an explanation for your answer

5	Social aspectsPotential implications of quantum computing, when it is operationally available	Please indicate your opinion about the potential benefits and risks of quantum computing to society at large. Add an optional explanation in the text box that will appear after you click "Submit" Count: **109**	Indicate how the following areas could be affected by quantum computing, inserting negative values for a detrimental effect, positive for a beneficial one. (From -100=very harmful to 100=very beneficial) Count: **108**	Please indicate your judgement about potential regulatory implications Count: **106**	Is any certification specific to quantum computing needed security, privacy or quality? What kind? In which area(s)? Count: **103**

Answer	Mean	Min	Max	Median	Count	Std
From -100=very harmful to 100=very beneficial	74.83	0	100	80	93	27.1
From -100=very dangerous to 100=very safe	54.83	-70	100	80	91	42.22

Answer: click to see answer
Explanation: I'm not sure I can answer this - for example, if quantum simulation turns out to be very useful for discovery of new materials then it could be very beneficial but in the wrong hands it could also be very harmful - it is not that technology is "neutral" but that the way it is developed and appropriated reflects underlying social structures.
Answer: click to see answer
Explanation: Depends on the decision making process and several factors which are very difficult to predict. This only means that an strong and parallel ethical control should be established
Answer: click to see answer
Explanation: Well this is a tricky question. Any technology in the right hands can be very beneficial and fairly safe. In the wrong hands it can be the opposite.
It depends on the state of affairs of the world and on politicians really.
Answer: click to see answer
Explanation: Not more or less harmful or beneficial than any other technology and can be used for good or bad. It depends what we choose to do with it. I don't see any specific safety issues compared to current technologies in use and generally seems safe (if we put nuclear energy at 0).
Answer: click to see answer
Explanation: Definitly beneficial, but it would

Answer	Mean	Min	Max	Median	Count	Std
Basic knowledge	82.62	0	100	90	91	24.63
Applied Science	83.24	5	100	90	90	20.26
Health	58.9	0	100	60	88	29.38
Security	53.56	-50	100	60	91	37.72
Education and training	59.93	0	100	60	87	31.47
Finance	38.48	-20	100	50	88	33.49
Quality of life (e.g. job-satisfaction, work/leisure balance)	27.67	-2	100	10	83	32.27
Other (please add in the textbox after "Submit")	37.25	0	99	25	4	41.08

Answer: click to see answer
Explanation: Again it's hard to say what will be "beneficial". For example in "Security", QC might break existing security but also provide ways to identify security threats (and QKD etc to address them directly).
Answer: click to see answer
Explanation: Again, aside from basic knowledge and applied science the remainder of the questions are subject to how the technology is used.
Answer: click to see answer
Explanation: Basic knowledge would strongly benefit if we either manage to implement large scale QC, or know why we can't. Applied sciences should benefit similarly. Health and understanding of biological systems may also be generally positive. Security will get worse than it already is assuming QC works and will

Few drawbacks and no special controls needed: **32**
Requiring some regulation to control abuse, based on incremental development of existing IT law: **45**
Requiring rigorous control and restriction to a limited number of trusted users and organizations: **6**
Be confined only to research, requiring only research-ethics controls: **0**
Other (please indicate after "Submit"): **3**

advance some responses but now it is too early to pre-suppose an answer
Answer: Requiring some regulation to control abuse, based on incremental development of existing IT law
Explanation: Laws and regulations will have to be reviewed, as usual, but no special approach is required. Unlikely, though, that these will catch up with actual capabilities and what is possible will be done, and build, no matter the law or the funding.
Answer: Few drawbacks and no special controls needed
Explanation: Quite frankly, most of Today's law isn't ready for normal IT, let alone advanced Quantum IT. I am not saying it would not be nice to have some controls, but I am saying that it is very unlikely that these controls effectively exist at all.
Answer: Requiring some regulation to control abuse, based on incremental development of existing IT law
Explanation: Same as with conventional computing
Answer: Few drawbacks and no special controls needed
Explanation: please enter an explanation for your answer
Answer: Few drawbacks and no special controls needed

Answer: Same as conventional computing
Answer: Some standard benchmarking (is being worke on by industry)
government should certify quantum computing as a ser in the blind-computing protocol. To prevent illegal activi
Answer: At first standards need to be developed. Certifications may follow or not
Answer: Quantum cryptography require a sort of quan certificate. The same applies to quantum communicatic channels.
Answer: No more than classical equivalent
Answer: Well, it's already hard to know whether a "quantum" process really has taken place. And in some cases, it's hard to verify the answer. (which is inherent probabilistic anyway). So QC will always be surrounded some uncertainty. But can there be some sort of quality assurance? Hard to see how this would work or who w issue it.
Answer: In principle it would be probably necessary fo security and quality as for other information technologie
Answer: It's too early to say.
Answer: needed for security
Answer: no need for certification
Answer: Certification of quantum devices for security a quantum simulatiion is clearly needed.
Answer: Verification Methode are Not known setzt. Th are a research topic themselves
Answer: no
Answer: too soon to state anything meaningful
Answer: No special control is needed. Quantum computing is just a tool. Needs regular certification as a other tools to be compatible.

Answer: No
Answer: Quantum security
Answer: No
Answer: No special certification due to the quantum na of the applications seems necesary. It will require the s certifications that are used in different fields (medical, security, biology, etc.) when using classical techniques.
Answer: Certification that it is genuine
Answer: No.
Answer: Quantum computing is sensitive to national security. An adversary with quantum computing capabi can indeed break today's encryption protocols with eas

6	Economic aspectsImplications of quantum computing, when it is operationally available	Please indicate your judgment of the potential economic implications of quantum computing, on all sectors of the economy. Assume a scenario in which conventional computing ceases to evolve in cost and performance as it has done whilst Moore's law has remained valid. The economic effect of quantum computing could be: Count: **106** greater than that which conventional IT has had.: **17** similar to that which conventional IT has had.: **36** smaller than that which conventional IT has had.: **29** a net loss. : **1** any of these, it is too uncertain to say.: **7** **Answer:** similar to that which conventional IT has had. **Explanation:** We are still learning which applications a quantum computer might have. Currently the applications are limited to several algorithms (Shor,...) with ideas how to extend this to other areas (machine learning, simulation of chemical reactions, biological systems). At the moment it is still difficult to extrapolate the future impact. **Answer:** smaller than that which conventional IT has had. **Explanation:** It's not really a relevant question, because QC will always work alongside conventional IT. But QC might increase the already large economic implications of IT as a whole - perhaps by orders of magnitude. Do you mean, will QC overcome the limits to Moore's Law? No. **Answer:** smaller than that which conventional IT has had	Please indicate your opinion about the potential effect of quantum computing on the IT sector generally. It will: Count: **108** lead to a near-monopoly in IT.: **2** tend to concentrate control of IT in the hands of a fewer major players. : **41** have no effect on the concentration of the sector.: **30** tend to make the sector somewhat more diverse.: **15** lead to a highly diverse market in which no company can dominate even a small part.: **3** **Answer:** have no effect on the concentration of the sector. **Explanation:** The development of a quantum computer requires significant technology development, similar like for classical computers. **Answer:** tend to concentrate control of IT in the hands of a fewer major players. **Explanation:** Requiring large and resources and specialised skills, QC is likely to concentrate ownership. However, not necessarily in the current big corporations - new ones might emerge. At the same time, new and specialised markets for QC-related products and services can be expected. **Answer:** tend to concentrate control of IT in the hands of a fewer major players. **Explanation:** Unless an immense breakthrough happens and we get silicon based QC, I am afraid this technology would be concentrate in the hands of a few major players **Answer:** have no effect on the concentration of the sector	What will be the impact of quantum computing on the job market? Insert a number to indicate the likelihood of each expected outcome. (From 0=not likely to 100=very probable) Count: **106**

Answer	Mean	Min	Max	Median	Count	Std
Quantum computing will have a disrupting impact on employment, destroying many existing jobs.	14.41	0	100	10	90	20.67
Quantum computing will always be limited to a small niche for very highly skilled, specialized experts.	47.87	0	100	50	89	28.13
A new generation of computer programmers will arise for developing quantum software.	71.25	0	100	77.5	90	25.25
Applications and satellite activities enabled by quantum computers will generate significant concomitant employment	60.06	0	100	60	88	27.38

7	Preparations are now under way for a Future and Emerging Technologies (FET) Flagship in quantum technology; see https://ec.europa.eu/digital-single-market/en/quantum-technologies#Article. The following two questions concern both the ramp-up phase of the Flagship, under Horizon 2020, and the Flagship itself, under the next research, technology and innovation programme.European public funding IPlease give your opinion about the priorities of European public funding for quantum computing hardware.	Please indicate which quantum computing hardware should European public funding give priority to. (Drag the options with higher priority above those with lower). Count: **106** Basic research, e.g. because it is premature to move ahead with technology development and the attempts being made to do so are misguided.: **129** Enabling technologies, which would increase the available options for a full-scale quantum computer.: **133** Solutions such as quantum simulation and adiabatic computing, which have a good chance of being useful in the medium term.: **204** Two or three credible candidate platforms, with an aim to produce full-scale computers.: **217** One chosen leading candidate platform, since only by focusing all available resources is there a reasonable chance of success.: **397** Other (please indicate in the textbox after "Submit").: **510** Discussion **Answer:** click to see answer **Explanation:** I do not think that we know already which technology will be able to function as a scalable quantum computer. Thus, public funding will need to support the most promising ideas, but should not be focused only on one technology, yet. The craziest idea at the moment might make it in the end. **Answer:** click to see answer **Explanation:** "Two or three" seems to be opposed to "one" - but I think the EC will need to take an expert overview, because soonish it might become apparent which of the QC approaches is likely to be the "winner". Unless this is clear, I think you should not put all of your eggs in one basket. **Answer:** click to see answer **Explanation:** Quantum internet requires only	Please explain your response to the public funding choice Count: **99** **Answer:** Two platforms are reasonable at this point as both have a reasonable chance of success. **Answer:** EU must hold itself on a global market. Let's face it, we are lagging behind tremendously on China and the American Corporations. The FET is booting up sluggishly, and other continents are taking over many of our resources. We cannot hope to be leaders in quantum computing hardware. We must look a step further and deal with the step after that. We should focus on what we are still leading in, (Quantum Software, Quantum Sensing and Quantum Internet), large scale quantum computers will be a side-effect of these investments. **Answer:** Quantum technologies still need mainly research. Enabling technologies and demonstrations are important to verify or European progress. **Answer:** Quantum computing is still at an early stage and funding still needs to be given to basic research as well as studies on scalability. **Answer:** Basic research is always important, but for achieving QC, a balance will be needed - there is still quite a lot of "basic" Physics and engineering required to make this work. So this is not "basic" in the sense of "curiosity-driven" (good though that is) but also driven by the need to make something work. **Answer:** Building a large scale quantum computer is the greatest challenge with the greatest benefits. Hence we should aim for it seriously in Europe. The funding reserved for quantum computing is not so large that it would	Please insert a number to indicate your level of confidence in your own answers to the questions on "Public funding priorities" and on "Reasoning for public funding". (From 0=not confident at all to 100=extremely confident) Count: **102** Answer | Mean | Min | Max | Median | Count | Std Level of confidence in public funding priorities | **76.08** | **10** | **100** | **80** | **82** | **18.78** Level of confidence in reasoning for public funding | **75.11** | **0** | **100** | **80** | **69** | **24.11** **Answer:** click to see answer **Explanation:** If we could be completely confident, it wouldn't be research. **Answer:** click to see answer **Explanation:** please enter an explanation for your answer **Answer:** click to see answer **Explanation:** It is often hard to predict the success of program.

8

European public funding IIThis question concerns the types of funding instruments which you consider useful for quantum computing, taking the ones currently used in Horizon 2020 as the starting point (see http://ec.europa.eu/research/participants/data/ref/h2020/other/wp/2016-2017/annexes/h2020-wp1617-annex-ga_en.pdf#page=10 for definitions.)Please do also indicate other possibilities which you think would be appropriate for quantum computing, using the second column.

Indicate your preferred distribution of funding among the following types of funding action, on a scale of 0 to 100%.

(Your answers will be normalized to 100% total)

Count: **101**

Answer	Mean	Min	Max	Median	Count	Std
Research & innovation actions (RIA)	64.76	0	100	70	63	23.67
Innovation actions (IA)	36.67	0	100	30	58	26.4
Coordination & support actions (CSA)	21.43	0	100	10	57	23.72
SME instrument actions	23.32	0	100	10	53	24.3
ERA-NET Cofund actions	26.24	0	100	15	53	26.31
Precommercial procurement (PCP) & Public procurement of Innovative solutions (PPI) actions	17.6	0	80	10	48	20.84
European Joint Programme (EJP) Cofund actions	24.95	0	100	10	44	26.94
Other (please explain in second column)	50.83	0	100	52.5	6	49.19

Answer: click to see answer
Explanation: I have given a high score to CSA because a few overview projects, each quite small, could greatly improve the focus and impact of the Flagship. I don't really have an

Please indicate any other funding instruments which you think would be suitable, such as those from national programmes or previous European programmes.

Count: **95**

Answer: Invest in Quantum Campusses. With something this distant from the business-as-usual mindset, a physical location is dire to let the achievements bloom.
Answer: Quantum Flagship which supports large demonstration projects
Answer: Research training networks for education of the next generation scientists in quantum information.
Answer: I am not well familiar with funding instruments.
Answer: Research training;
Answer: national programs, national networks, IP and STREPS
Answer: I don't understand these instruments.
Answer: Sorry, but I don't have time to read 10 pages of definitions of these categories. What I'll say is that quantum computing is still a research question at heart, and funding should be concentrated on developing the science and not trying to push unready technologies into commercialisation.
Answer: I think that basic reaserach is mandatory in fields of many-body physics, decoherence and quantum-to-classical transition.
Answer: Encourage basic research into quantum physics to look for new technologies. Regular grant schemes but with added funding. What I'll say is that quantum computing is still a research question at heart, and funding should be concentrated on developing the science and not trying to push unready technologies into commercialisation.
Answer: Venture and angel investment
Answer: To Foster shared initiatives between

Please insert a number to indicate your level of confidence in your own answers to the questions on "Horizon 2020 instruments" and on "Other instruments".

(From 0=not confident at all to 100=extremely confident)

Count: **100**

Answer	Mean	Min	Max	Median	Count	Std
Level of confidence in your preferred funding distribution among Horizon 2020 instruments	57.9	0	100	70	65	26.51
Level of confidence in your indications of other instruments	48.01	0	100	50	51	32.48

Answer: click to see answer
Explanation: I didn't suggest any other instruments so that's not relevant. I have no idea how confident I am about the H2020 instruments - I think this is for the Commission to decide.
Answer: click to see answer
Explanation: I don't really understand all these different actions so my judgements may be a little off. Main point is: prioritise basic public research with private sector involvement around the margins.
Answer: click to see answer
Explanation: Perhaps more hopeful than confident.
Answer: click to see answer
Explanation: Perhaps more hopeful than confident.
Answer: click to see answer
Explanation: Did not understand the categories so did not apply feedback.

9	External fundingPlease give your opinion about the funding priorities for quantum computing hardware by other sources.	What do you think should be the partitioning of funding for quantum computing over the next 20 years, excluding European public funding? (Your answers will be normalized to 100% total) Count: **102**	Please indicate which quantum computing hardware you believe the private sector will give priority to. If your rationale differs from that suggested, use the textbox to explain it. (Drag the options with higher priority above those with lower). Count: **100**	Please indicate which quantum computing hardware you believe the public sector, excluding the EU institutions, will give priority to. If your rationale differs from that suggested, use the text box to explain it. (Drag the options with higher priority above those with lower). Count: **100**

Answer	Mean	Min	Max	Median	Count	Std
Civil private sector	27.3	0	100	20	65	18.81
Research institutions (non-publicly funded)	26.98	5	100	20	67	20.96
Defence (non-publicly funded)	19.82	0	80	15	58	16.42
Donations	10.86	0	80	7.5	52	13.49
Venture capital	22.62	0	89	20	59	17.91
National governments	45.44	0	100	40	67	26.07
Other (please indicate after "Submit")	68.33	5	100	100	3	44.78

Answer: click to see answer
Explanation: I am sure that Defence will be very interested in QC. I can't say I am very happy about that but in terms of what "should" be the partitioning of funding resources, I can see many applications for defence and national security. I do not think we should rely too much on VC funding, which will always come with strings attached and focus on the short term.
Answer: click to see answer
Explanation: I cannot really answer this question. What I can say with certainty is that I would like 0 contributions from any private defence company. I am not opposed to private investment, but this would normally only arise once technology has been pushed through to a sufficient degree to warrant investment. Ergo, the majority of the funding would have to be

Basic research, e.g. since it is premature to move ahead with technology development and the attempts being made to do so are misguided.: **181**
Enabling technologies, e.g. since they would increase the available options for a full-scale quantum computer.: **140**
Interim solutions, such as quantum simulation and adiabatic computing, e.g. since they would have a good chance of being useful in the medium term.: **175**
Two or three credible candidate platforms, with an aim to produce full-scale computers.: **217**
One chosen leading candidate platform, e.g. since only by focusing all available resources is there a reasonable chance of success.: **299**
Other (please explain in the textbox after submitting).: **488**

Discussion

Answer: click to see answer
Explanation: I have given the same answers as for European funding as this is what the private sector "should" fund. It also makes the most long-term sense for the sector as a whole. However I suspect that in reality they will pick and choose short-term winners.
Answer: click to see answer
Explanation: Unfortunately this is what i believe they will fund.. I stress that this is NOT what I want them to fund.
Answer: click to see answer
Explanation: I'd hope focus is on interim solutions. Likely and sadly some will focus on specific platforms, but hopefully keep options open instead of choosing too quickly. Unlikely they see basic research as relevant and

search

Basic research, e.g. since it is premature to move ahead with technology development and the attempts being made to do so are misguided.: **65**
Enabling technologies, e.g. since they would increase the available options for a full-scale quantum computer.: **138**
Interim solutions, such as quantum simulation and adiabatic computing, e.g. since they would have a good chance of being useful in the medium term.: **200**
Two or three credible candidate platforms, with an aim to produce full-scale computers.: **224**
One chosen leading candidate platform, e.g. since only by focusing all available resources is there a reasonable chance of success.: **373**
Other (please indicate in the textbox after submitting).: **500**

Discussion

Answer: click to see answer
Explanation: It is usual to suggest public funding for things that the private sector can't or won't fund. However, in the case of Quantum, this is relatively close-to-market, and clearly application-oriented, so in terms of what to fund, the interests are the same, but with a clear willingness from the public to fund more cutting-edge and risky approaches.
Answer: click to see answer
Explanation: Public sector funding should be more focused towards basic research as this is less likely to be funded by the private sector
Answer: click to see answer
Explanation: Again, unfortunately, I see the public sector of governments moving along the same lines as the private sector (short to

10	Quantum computing software and hardwarePlease indicate your opinion on how the quantum computing software and hardware might evolve.	Consider the following statements about the relationship of software and hardware for quantum computing and check those that you think are likely to be true. Count: **100** Quantum computing software and hardware will always need to be developed together.: **37** A quantum software industry will emerge independently from hardware developers.: **33** Quantum computer programming will always require major specific competences distinct from conventional programming.: **49** A general purpose language will emerge, suitable for running any task on a quantum computer.: **29** Quantum computers will always run specific algorithms only.: **25** Software and hardware development will reinforce each other's development.: **61** Other (please explain in the textbox after "Submit").: **3** **Answer:** click to see answer **Explanation:** All of these are probably true, because they are not inconsistent. The development of quantum software as hardware develops does not preclude the emergence of a new QC software industry. The question as to how commodified it will become is still hard to answer - looking back at the development of classical computers, this seems likely, but quantum algorithms are inherently harder (sometimes, much harder). Conceivably, a general interface could hide the complexity from average programmers. As to whether a general	What might the future of quantum computer software and hardware development be? Count: **98** **Answer:** Due to the disruptive character of the field, this will grow exponentially and needs to grow together especially during the early stages. **Answer:** Moore's law for quantum computing (Leo's law) Software will start from 100% human developed to about 65% AI developed and 35% human developed by 2035. **Answer:** Soft and Hardware development will get integrated into traditional environments. Eventually, an application programmer does not have to care what will run on quantum or classical hardware. **Answer:** It is possible that in the far future (>70 y), the technology that we develop for the quantum computer will become so energy efficient that power-consumption-wise also classical logic is economical to be run on a quantum computer. Thus it may be that classical and quantum computing will merge and hence quantum computers will not be limited only to a small set of algorithms. This obviously needs also a new computing paradigm which may be found. A general purpose language would be likely to emerge here. **Answer:** The main current problem is development of quantum hardware. When quantum hardware is developed it will be not so difficult to write appropriate quantum software. Quantum software already exists. It is not clear to me whether this software will well fit future quantum hardware. **Answer:** Interfaces between classical	Please indicate your level of confidence in your own answers to the questions on the future of the quantum computing hardware/software relationship (From 0=not confident at all to 100=extremely confident) Count: **100**

Answer	Mean	Min	Max	Median	Count	Std
Level of confidence for "Software and hardware development"	68.8	30	100	70	71	17.36
Level of confidence for your "Explanation"	52.06	0	100	50	47	33.7

11

Quantum computation's future placePlease give your opinion on the place of quantum computing in the future computational landscape.

What do you think the place of quantum computing will be if and when it becomes established?

(Chose the one scenario that you think is most likely to be true.)

Count: **100**

Quantum computing will be the only form of computation in the future.: **0**

Quantum computing will coexist with other computational methods, but will be the most important.: **19**

Quantum computing will be only one among a number of coexisting computational methods of similar importance.: **46**

Quantum computing will be important only in a limited number of applications.: **18**

Quantum computing will be abandoned, replaced by a new paradigm.: **0**

Answer: Quantum computing will be only one among a number of coexisting computational methods of similar importance.
Explanation: I considered ticking "only in a limited number of applications", but these applications might turn out to be very powerful, so even though QC is not a "general speed-up" but, as far as we know, will only be able to do specific things, these things could transform what we are able to do in unexpected ways. For example, QC can already help with some optimisation problems - but many problems can be "turned into" optimisation.

Answer: Quantum computing will coexist with other computational methods, but will be the most important.
Explanation: For controlling a screen for example, no quantum comuter is needed.

Which areas could develop in tandem with quantum computing, to their mutual benefit? Indicate with a numeric value your assessment of potential synergies.

(From 0=no synergies at all to 100=extremely important synergies)

Count: **99**

Answer	Mean	Min	Max	Median	Count	Std
Nanotechnology	76.53	0	100	80	76	24.94
Electronics	70.41	10	100	72.5	78	22.37
Materials science	74.52	10	100	80	78	21.31
Chemistry	60.7	0	100	60	78	27.85
Engineering	69.67	15	100	70	77	23.16
Other (please add in the textbox after "Submit")	50	0	100	50	5	44.72

Answer: click to see answer
Explanation: Instrumentation! communication!

Answer: click to see answer
Explanation: Some arbitrary numbers... of course they could all benefit. Who knows...

Answer: click to see answer
Explanation: This question is too vague

Answer: click to see answer
Explanation: Physics, Biology, Material Science, Information Theory

Answer: click to see answer
Explanation: Basic physics is still the first core issue here. But of course, maximum throughput will eventually require small feature size, and nanotechnology, even if it should be more like plasmonics than electronics. (Too early to tell.) Materials and electronics are both areas where quantum simulation is important.

Answer: click to see answer
Explanation: Not quite sure what this question is asking. Quantum computer cannot be developed in isolation.

Answer: click to see answer
Explanation: Material science will be

What might the future computing landscape be?

Count: **97**

Answer: We will see quantum computing emerging as a cloud resource sitting along side other diverse computing platforms that are used for different work loads.

Answer: Conventional computers will keep going strong, but quantum machines will shine in certain specific areas.

Answer: I think that the problem of decoherence (quantum-to-clasical transition) will be always present, making a lot of difficulties in the practical implementation of many qunatum computing ideas.

Answer: Classical will be dominant and quantum for specialised applications

Answer: New paradigm in Data processing and management

Answer: hybrid world with classical and quantum computing, together with other technologies.
At the same time, quantum computing has to think differently, and not just reproducing the same 'old' logic and (only) running it quickly

Answer: Quantum computing cloud services with emerging standards for programming interfaces.

Answer: going through artificial intelligent using quantum technology.

Answer: Merging Quantum Technologies with Artificial Intelligence.

Answer: An interplay between classical and quantum computing, each playing its strengths.

Answer: quantum computers will be larger centralized machines (due to isolation from environment and complexity of control); we will still carry around classical computers for standart applications (smartphone, ...)

Answer: I would see quantum computing power as an available on-demand ressource in the cloud, not available locally "at home"

Answer: I do not have a view

Answer: Conventional computing will keep its position as the main method of information processing. Quantum computing will be used in specific applications, which could be vast and important.

Answer: A mixture between a number of coexisting paradigms, within this quantum computing will be used to solve special tasks.

What is your level of confidence in your own answer to the of the three previous columns?

(From 0=not confident at all to 100=extremely confident)

Count: **100**

Answer	Mean	Min	Max	Median	Count	St
Level of confidence for "Future computing scenarios"	72.67	12	100	75	77	18.
Level of confidence for "Synergies"	67.31	20	100	70	74	20.
Level of confidence in your own "Explanation"	55.23	0	100	70	51	36.

12	Quantum computing physical platformsPlease give your assessment of the possible physical platforms that can be used to build a quantum computer, and evaluate how Europe is positioned in each of them with respect to international competitors.

Which are the most promising physical platforms on which to build a large-scale quantum computer?

(From 0=not promising at all to 100=extremely promising)

Count: **104**

Answer	Mean	Min	Max	Median	Count	Std
Superconducting qubits	72.76	3	100	80	77	25.04
Trapped ions	53.98	0	100	52.5	72	28.34
Photonics	42.39	0	100	50	71	27.58
Semiconductor qubits	56.36	1	100	52.5	72	25.58
Topological qubits	41.38	0	100	40	70	26.1
Other (please indicate after "submit")	54.5	0	100	55	10	34.67

Answer: click to see answer
Explanation: quantum simulations with cold atoms / Rydberg atoms

Answer: click to see answer
Explanation: Superconducting, trapped ions, photonics all seem promising, but all have drawbacks. One important point is that economic or political considerations might play a bigger role that technological advantage in determining the "winner" (or their might not be a single "winner")

Answer: click to see answer
Explanation: Topological qubits are quite premature and may not even work at all.

Answer: click to see answer
Explanation: NV in diamond. Especially for a quantum internet it is highly desirable to have both decent storage times, the ability to connect optically, and full control.

Answer: click to see answer
Explanation: Other: NVs

Please assess the European potential for developing these platforms into a fully operational, large-scale machine, given the capabilities of European universities, research centres, and industry.

(From 0=extremely low to 100=extremely high)

Count: **101**

Answer	Mean	Min	Max	Median	Count	Std
Superconducting qubits	66.47	10	100	70	68	23.4
Trapped ions	62.47	0	100	60	63	27.94
Photonics	51.11	0	100	50	63	29.66
Semiconductor qubits	52.87	5	100	50	63	24.86
Topological qubits	46.3	0	100	50	60	26.9
Other (please indicate after "submit")	55.83	0	100	57.5	6	38.55

Answer: click to see answer
Explanation: I guess, topological qubits are supposed to be e.g. majorana states in solid state. I think in any of these systems (trapped ion or superconducting qubits) we will need to use topological quantum error correction.

Answer: click to see answer
Explanation: I don't have the expertise to say, but the USA appears to be ahead in superconducting

Answer: click to see answer
Explanation:

Answer: click to see answer
Explanation: Superconducting qubits are promising, but maybe not for europe alone. Semiconductor qubits, trapped ions and photonics may be better for europe.

Answer: click to see answer
Explanation: I am not fully updated upon this.

What would you consider to be your own level of expertise in each of the following areas?

(From 0=very low to 100=very high)

Count: **100**

Answer	Mean	Min	Max	Median	Count	Std
Superconducting qubits	52.01	0	100	50	67	30.79
Trapped ions	38.63	0	100	30	65	30.95
Photonics	45.98	0	100	47.5	66	29.77
Semiconductor qubits	43.87	0	100	45	66	27.74
Topological qubits	33.33	0	100	30	65	27.01
Other (please indicate after "submit")	46.42	0	100	50	7	38.05

Answer: click to see answer
Explanation: cold atoms / Rydberg atoms

Answer: click to see answer
Explanation: I have some understanding of all of these, but I'm not a Physicist so it's quite superficial.

Answer: click to see answer
Explanation: I am a theorist. I do know a lot about photonic implementations, and a bit about Ion traps in theory as i have worked on translating some theoretical proposals to implementations. My evaluations is based on what little i know, but mostly from what i read and hear from colleagues.

Answer: click to see answer
Explanation: Know something about all of them, but focused on providing methods to make use of either of the approaches with modelling, control and learning techniques.

Answer: click to see answer
Explanation: Know & understand them all, never worked with any of them directly

13	European strengthsIs there a specific aspect of quantum computing for which Europe seems to enjoy some competitive advantages in the international landscape?	In which field is Europe better positioned? (From 0=extremely weak with respect to competitors to 100=very strong in the global landscape) Count: 99	Which is your level of confidence in each of the answers given in the first column? (From 0=not confident at all to 100=extremely confident) Count: 98	Please indicate other quantum computing areas in which Europe might have a competitive advantage or, conversely, structural weaknesses. Count: 97

Answer	Mean	Min	Max	Median	Count	Std
Processors	56.11	0	100	51	60	25.29
Memories	53.45	0	100	50	59	24.43
Communications and interconnect	68	0	100	70	60	23.43
Fundamental algorithms	60.68	10	100	60	58	24.57
Software for quantum simulations	59.01	0	100	55	56	23.46
Firmware for hybrid classical-quantum hardware components	50.18	0	90	50	54	22.66
User interfaces	40.91	0	100	40	49	23.81
Other (please indicate after "Submit")	86.66	80	100	80	3	9.42

Answer: click to see answer
Explanation: Fundamental research
Answer: click to see answer
Explanation: Note: quantum computers may not have processors separated from memory.
Answer: click to see answer
Explanation: Sorry i am not fully aware about most of the question here. I know groups making huge progress in quantum memories and communications. Unfortunately i know very little about any of the rest to give an informed opinion.

Answer	Mean	Min	Max	Median	Count	Std
Processors	59.11	0	100	60	54	27.02
Memories	58.3	0	100	60	53	24.58
Communications and interconnect	63.43	0	100	70	53	25.91
Fundamental algorithms	53.47	0	100	60	53	27.43
Software for quantum simulations	54.54	0	100	60	53	28.25
Firmware for hybrid classical-quantum hardware components	47.39	0	100	50	51	26.3
User interfaces	42.89	0	100	50	47	27.9
Other (please indicate after "Submit")	48.57	0	90	50	7	33.56

Answer: click to see answer
Explanation: I think basic reaserach is mandatory in fields like many-body physics, decoherence and quantum-to-classical transition.
Answer: click to see answer
Explanation: Basic research strong
Answer: click to see answer
Explanation: Atomtronic devices
Answer: click to see answer
Explanation:

Answer: Quantum simulators
Answer: Strengths:
Quantum Internet
General Quantum Software
Cryogenics
Weaknesses:
Quantum computer development
Answer: The greatest weakness is the missing silicon industry which is required to build a quantum computer.
The advantage in Europe is the high level of knowledge on quantum people have - even in industry.
Answer: Advantages in
*Utilization of controllable dissipation
*Heat management at the quantum and chip level
*Cryogenics
Answer: Interfacing stationary and flying qubits is rather weak.
Answer: I do not have answers to this and two previous questions.
Answer: Europe leads quantum simualtions with ultracold atoms and ions.
Answer: Europe leads the area of cold-ions platform for general gate-based quantum computing. The superconducting computing research has been at the forefront in the past but needs rejuvenation to catch up with resent significant private industry efforts in North America. The quantum simulation using multiple quantum physical platforms is under active development in many parts of Europe but the pressure from quantum annealing simulators is

14	EducationWhat are the education aspects impacted by quantum computing?	What is the educational value of a small scale quantum computer in each of the following contexts? (From 0=no value to 100=extremely high value) Count: **100**	What is the awareness of quantum technology among different targets? (From 0=no knowledge to 100=high awareness) Count: **100**	How important is it to train new quantum computing specialists in these categories? (From 0=of no importance to 100=extremely important) Count: **99**	Which aspects of education should be adapted and how? (promote training, finding jobs, etc.) Count: **97**

Answer	Mean	Min	Max	Median	Count	Std
Platform on which software developers can learn	71.01	10	100	80	72	21.84
Means to train quantum engineers	81.28	40	100	80	71	16.01
Unknown yet	55.38	0	100	60	39	30.64
Other known educational value (please indicate what, after "Submit")	35	0	100	25	6	38.18

Answer: click to see answer
Explanation: I suspect that until/if there is a reasonable scale QC, small scale will only give a very basic training platform. But it might be useful for people to learn about Qubits etc.

Answer: click to see answer
Explanation: General training in STEM subjects.

Answer: click to see answer
Explanation: more than just training software developers to use quantum computers, they should also think differently, probably a new range of mathematic, on top of software engineering

Answer: click to see answer
Explanation: Develop a "quantum way-of-thinking" in the brain of the future scientists and engineers

Answer	Mean	Min	Max	Median	Count	Std
Physicists	79.75	30	100	80	74	18.24
Chemists	50.05	5	100	50	71	21.34
Engineers	42.31	0	100	40	72	21.51
Computer scientists	49.5	5	90	50	73	24.92
Others (please specify after "Submit")	22.5	0	50	20	4	18.2

Answer: click to see answer
Explanation: I'm guessing here - if you want to find out, a better way would be to do a survey of these different groups. I suspect that most of these are aware of QC, but probably not of the potential or anything much about it.

Answer: click to see answer
Explanation: well known among physicists, not considered by computer scientists

Answer: click to see answer
Explanation: People learn the basics at university, but they are not well aware of quantum computing and its opportunities.

Answer: click to see answer
Explanation: Material Sciences

Answer: click to see answer
Explanation: Biologist

Answer	Mean	Min	Max	Median	Count	Std
Physicists	80.39	10	100	81	68	22
Chemists	63.55	0	100	70	69	23.68
Engineers	76.54	5	100	80	70	21.61
Computer scientists	80.57	20	100	80	70	17.85
Others (please specify after "Submit")	52.5	0	90	60	4	38.97

Answer: click to see answer
Explanation: Software engineers.

Answer: click to see answer
Explanation: By others, I am referring to people in life sciences;

Answer: Applicability

Answer: Basic physics education, starting in secondary schools. We'll never use the full potential of quantum technologies if every person starting in the field still coin as 'weird'...

Answer: Basic quantum technology knowledge - people needs to understand the concept behind.

Answer: training networks, doctoral centres...are one ni way to train new scientists. Public awareness is also ve important

Answer: For the moment, perhaps it is enough to offer more undergraduate and graduate courses on quantum computing. Not so many universities offer such courses.

Answer: Creating jobs

Answer: promote training and r&d positions between industry and academia

Answer: Cross-disciplinary education and training

Answer: promote training

Answer: Progress in quantum computing will depend o highly specialized laboratory equipment, materials and supply chains.

Answer: Incorporating Quantum Programming into curr physics, engineering and compsci programs via quantu simulators on classical machines.

Answer: Explain quantum mechanics demystifying seve issues (like collapse, measurement,etc) that provides m difficulties to students to get an intuitive understanding c quantum phenomena. Such type of explanations of quantum mechanics (beyond the orthodox one) exist an are very recomendable for students.

Answer: -Teach basic quantum mechanics in secondar schools

Answer: Post-graduate

Answer: 2 areas here: quantum hardware specialists n more physics
quantum software specialists need define new areas in software engineering and mathematics. they need to understand the different approach, however they don't need to understand quantum physics

Answer: Open Source tool-kits, principally the interface

15 Status and evolutionWhich of the following statements do you think reflect the current situation and the future evolution of quantum computing?(Enter a number from 0 to 100, with a higher score for the statements you are more confident of.)

Count: **101**

Answer	Mean	Min	Max	Median	Count	Std
Quantum algorithms with proven performance enhancement with respect to classical ones will remain limited in number, and useful only in very specific tasks.	46.91	0	100	50	71	29.36
A growing number of useful quantum algorithms will be designed.	72.16	0	100	80	73	22.64
Already a significant number of quantum algorithms with proven performance enhancement with respect to classical ones have been found, and they can address computational tasks of practical use.	46.94	0	100	40	69	28.84
Performance enhancement of currently available quantum algorithms is still an open question but will be resolved in the next years.	51.84	0	100	50	69	26.3
Performance enhancement of currently available quantum algorithms is still an open question, and the situation will remain unsettled for the foreseeable future.	29.42	0	100	25	66	24.31
The quantum algorithms that have been found up to now do not provide useful solutions for computational problems of any practical importance.	17.41	0	100	10	68	24.15

Answer: click to see answer
Explanation: It depends on what is considered "useful". It is true that QC won't provide general speed-up of many computer processes, but there are many algorithms, although some are actually quite similar. I have been told that at a similar stage in the development of classical computers, there were many more algorithms already devised, but I don't know whether that is correct, or how significant that is. If even a small number of Q algorithms turn out to be useful, it could be very significant.
Answer: click to see answer

Count: **101**

Answer	Mean	Min	Max	Median	Count	Std
Hardware for universal quantum computation able to perform tasks unfeasible for conventional computation will be developed in less than 5 years.	30.88	0	100	20	69	31
Hardware for specific quantum computations (e.g. annealing, simulation), decisively outperforming conventional computation, will be developed in less than 5 years.	53.69	0	100	59.5	72	30.58
Hardware for universal quantum computation able to perform tasks unfeasible for conventional computation will not be developed by less than 5 years from now but will be developed by less than 10.	41.62	0	100	40	69	26.81
Hardware for specific quantum computations (e.g. annealing, simulation), decisively outperforming conventional computation, will not be developed by less than 5 years from now but will be developed by less than 10.	58.22	0	100	60	71	27.94
Hardware for universal quantum computation able to perform tasks unfeasible for conventional computation will not be developed in less than 10 years from now.	50.72	0	100	55	69	29.5
Hardware for specific quantum computations (e.g. annealing, simulation), decisively outperforming conventional computation, will not be developed in less than 10 years from now.	31.04	0	100	20	67	26.37

Answer: click to see answer
Explanation: Keeping in mind that yes they will be universal and present, but not applicable for all

Count: **101**

Answer	Mean	Min	Max	Median	Count	Std
Quantum processors will completely displace classical ones, without radically changing the computer architecture we know now.	11.57	0	100	2	71	20.63
Quantum computers will resemble today's supercomputers, running specific algorithms to solve targeted problems.	64.28	1	100	70	71	25.37
Quantum computers will resemble the mainframes of the sixties, with computing time sold in slots for general-purpose computations.	54.54	0	100	56.5	70	26.76
Quantum computers will resemble mini-computers of the eighties, with a few terminals for general-purpose computations.	24.91	0	80	20	70	20.33
Quantum processors will complement classical ones in hybrid architectures for general purpose applications.	46.6	0	100	45	70	26.66
Quantum processors will complement classical ones in hybrid architectures for specific scientific applications.	72.94	20	100	80	70	22.43

Answer: click to see answer
Explanation: It is very unlikely that Q computers will replace existing ones. As to what the architecture is, that depends on how small/cheap QC can be made. Will we have one on our smartphones? I doubt it, but more impressive technological advances have happened before. QC is not only not better, but in some ways worse for most applications, so it won't replace classical, but it will run alongside it, either on a remote server or HPC, or a co-processor.
Answer: click to see answer
Explanation: depending of applications, there could be different way of using it. The hybrid solution will be at least an intermediate stage, but could also be the goal. i.e. we may not need to have Q computers to replace everything, just to use them where and when they are useful
Answer: click to see answer
Explanation:

16	Please add other comments, suggestions, concerns, etc. related to European policy and strategy concerning quantum computing.	Count: 98 **Answer:** Make sure that European policy focusses on the right values within the global context. I sure will contribute to that. **Answer:** We need also to think more broadly about the social and economic implications. For example, not only "will QC be important for ML or searching large databases", etc., but "if QC transforms ML, what might this mean for society"? Of course, this can only be speculative at this stage, but if we don't at least try to look ahead we will be surprised by unexpected and possibly unintended consequences. **Answer:** The Flagship is a unique opportunity to achieve something great that we could not pursue with the other funding instruments. Let us not miss this chance of building the quantum computer.

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List of abbreviations and definitions

AI	Artificial intelligence
DG CNECT	Directorate–General for Communications Networks, Content and Technology, of the European Commission
Delphi	a questionnaire –based foresight method in which participants can adapt their replies in response to those of other participants.
FET	Future and Emerging Technologies
GFIS	Global Futures Intelligence System
Grover's algorithm	a quantum algorithm for searching an unsorted database
FP7	Seventh Framework programme for research and technological development of the EU (2007-13)
H2020	Horizon 2020, EU programme for research and technological development (2013-20)
JRC	Joint Research Centre of the European Commission
ML	machine learning
NIST	National Institute of Science and Technology (USA)
QC	Quantum computing
QKD	Quantum key distribution
QUROPE	an internet community for quantum technology in Europe, currently funded by the H2020 Coordination Action QUTE-EUROPE
RTD	Real Time Delphi, a form of Delphi where participants can see other participants' replies online and modify their own, throughout a defined time period
Shor's algorithm	a quantum algorithm for discrete logarithms and factoring
TRL	Technology readiness level

List of Figures

List of tables

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