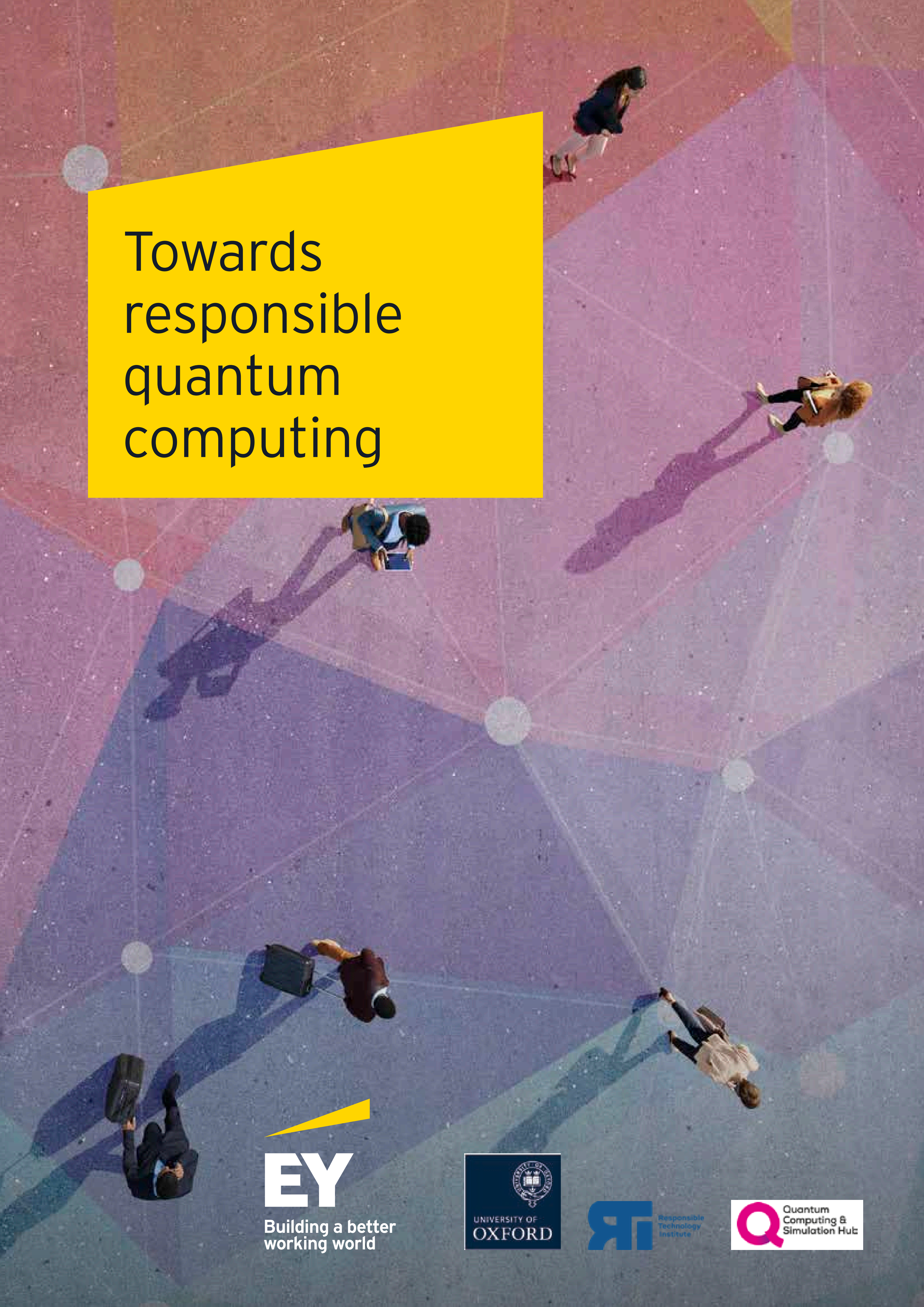
Towards responsible quantum computing



EY
Building a better working world

UNIVERSITY OF OXFORD

Responsible Technology Institute

Quantum Computing & Simulation Hub

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Foreword

Humanity has a collective opportunity to embed responsibility into the fabric of scientific and technological innovation for the benefit of businesses, society, and the planet. Recognising this opportunity, the collaborative efforts between EY and the University of Oxford's Responsible Technology Institute (RTI) underscore the importance of proactive risk mitigation, interdisciplinary dialogue, and responsible innovation in ethically navigating the transformative potential of quantum computing.

The road to responsibility

Across the technologies that EY interfaces with globally, we have come to recognise the criticality of responsible innovation (RI) in shaping a more equitable and sustainable technology future. RI is not merely a philosophical concept; it embodies a proactive approach and entails adopting "a long-term perspective on the type of world in which we want to live"[1] to assist us in addressing pressing global challenges and the various implications of technological advancements. It guides us in steering innovation towards morally and socially desirable outcomes for a diverse set of stakeholders, both present and future.

Quantum technologies, which includes quantum computing, communication, and sensing, are a frontier to which RI is becoming rapidly relevant. In fact, in a recent report published by the Regulatory Horizons Council (RHC) in the UK regarding the future of quantum regulation, RHC has expressly highlighted RI as a pre-requisite to ensuring "innovation progresses in harmony with the principles of transparency, equity, and integrity".[2] Expanding our understanding of RI's significance in the quantum domain reveals its multifaceted role. From facilitating beneficent use case selection and research directions, to proactively spotting and planning for potential risks, RI provides the quantum ecosystem – comprising industry, government, and academia – with the foresight and tools to thoughtfully reflect, plan, and de-risk our quantum future.

In assessing the optimal direction of travel for quantum technologies, we can learn significantly from history. Concerns raised in the past several years about artificial intelligence (AI) and generative AI (genAI) with respect to algorithmic bias, hallucinations, sustainable value chains, and misinformation are tremendously instructive as to the importance of RI in building the right technology and building technology right. In fact, drawing from EY's CEO Outlook Pulse from late 2023, 65% of surveyed CEOs indicated that more work is needed to address the ethical risks associated with AI and that not enough is being done to mitigate said risks at present.[3] In recognition of these imperatives, EY has worked with the University of Oxford's Responsible Technology Institute (RTI) to delve into the realm of responsible quantum computing, culminating in the following White Paper.

This White Paper considers what responsible quantum computing might look like practically and offers insights into the technology's possible futures – both positive and negative – drawn from an expert survey conducted in 2023. Notably, this research has uncovered key findings relevant to quantum practitioners, policymakers, and researchers, including:

- The importance of **responsible science communication** when discussing and exploring the opportunities and risks of quantum technologies to set realistic expectations of use cases and time scales amidst market hype.
- **The role of cross-sector and cross-disciplinary collaboration** as a recurrent theme and driver for increased trust in quantum technologies, with broad resistance towards the idea of quantum innovation being driven by the public or private sector alone.
- Despite the widespread media attention on the cryptographic risks associated with quantum computers, this narrow focus can detract from the broader risk landscape, with surveyed experts recognising **exacerbated digital divides between nations** as being the most likely quantum future.
- Finally, above all else, this research points to the fact that quantum computing has the **potential to accelerate and transform very different futures for business and society**. Which future is realised is dependent on the steps that we take as a quantum ecosystem, today.

In line with these insights, EY advocates for a collaborative, integrated approach to RI within the quantum ecosystem. By fostering alignment, communication, and dialogue, we can proactively shape the trajectory of quantum technologies and validate that they conform to our collective values and aspirations. Increased alignment, communication, and dialogue across the quantum ecosystem will be critical to balancing experimentation with proportionate governance as quantum technologies mature and become more commercially scalable.

This report underscores the urgency for collective action by stakeholders from across sectors and disciplinary backgrounds to set the groundwork for a responsible quantum future that is anchored by human-centred values. The time to act is now.

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This White Paper is part of the EY Quantum Intersection, a series of articles, surveys, and opinions on the business impacts of quantum computing, communication, and sensing.

About EY's Global Quantum Computing Lab

In 2022, EY established a Global Quantum Lab with a mission to accelerate EY's drive in Advanced Technology – leveraging Artificial Intelligence (AI), High Performance Computing (HPC), and quantum technologies while enabling a focus on responsibility, sustainability, and transformation.

About the Responsible Technology Institute (RTI)

The Institute is based at the University of Oxford, but draws its membership from national and international institutions, seeking to evolve the broad interdisciplinary community focused on the responsible development and deployment of technology. It engages with all stages of the innovation chain; from doctoral students, through to industry partners trying to develop their business in responsible ways, and policymakers tackling questions of governance. Its team has been working on responsible quantum computing since 2015.

Acknowledgements

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Executive summary

Executive summary

Recent years have seen rapid developments in quantum computing, and a global surge of interest and investment as nations seek to develop their own quantum programmes. Research shows that public attitudes towards quantum computing and quantum technologies are generally positive[4] – but to maintain (and be worthy of) societal trust and acceptance, it is essential to pay ongoing attention to the responsible development of these technologies. This may include paying attention to emerging digital divides impacting the quantum domains, as well as making efforts to resolve such challenges to advance innovation in this space overall.

Expert survey

The work overviewed in this White Paper was carried out as part of a collaboration between EY and the ResQCCom – Responsible Quantum Computing Communication – project (funded by the Quantum Computing and Simulation Hub[5]). The research programme built on one-to-one interviews with key informants to develop a survey that was distributed to expert technologists, researchers, and policymakers. Half of the experts who responded were in academia, with the remaining half hailing from industry or elsewhere (e.g., professional services). A mix of qualitative and quantitative methods were employed in the survey to offer the richest source of data in support of subsequent analysis.

The topics covered in the expert survey included general attitudes towards and knowledge of emerging technologies, the role of government and governance in technological development and innovation, as well as a range of suggested scenarios regarding the future of quantum computing that the experts were invited to rank and comment upon in terms of likelihood, impact, and time-scale to realisation.

Analysis demonstrated that most expert respondents agreed with many of the foundational principles of Responsible Innovation (RI):

- That **thinking ahead** about the effects of new technologies may help us to better prepare for them.
- That the rush to develop new technologies may **outpace our understanding** of the potential risks and societal implications.
- That it is important to involve **many different groups** in the development of new technologies.

Further, the findings of the survey lead us to make several recommendations with respect to responsible quantum computing, including:

1. Managing expectations around timeframes for quantum computing at scale and proceeding with caution when discussing the potential capabilities (and limitations) of quantum computers. This is partly due to the size of ongoing engineering challenges within the field, but also the still-uncertain nature of potential applications of the technology (and the associated ethical risks).
2. Continuing to foreground equitable access to quantum computing resources, infrastructure, and talent to advance global responses and collaboration.
3. Developing more nuanced approaches to the competitive nature of the quantum computing field to better address capacity issues and mitigate digital divides within and between nations.
4. Taking advantage of governmental capacity for absorbing risk, building markets, shaping governance, and levelling the playing field within and between nations.
5. Recognising that the development of this potentially powerful new technology is a marathon, not a sprint, and that treating it in a manner akin to the 'space race' may hinder overall progress.

In the meantime, it is incumbent upon the quantum ecosystem and its members to continue engaging in constructive dialogue regarding the enablement of responsible and ethical quantum computing for the benefit of present and future generations.

Contents

1 Introduction

The state of the nation – and indeed the world – is changing at pace when it comes to quantum computing and its possible applications and impacts. The rate of progress in this domain has been driven by heightened investment and capacity-building across countries that have developed quantum technology strategies at the national level, such as India, Poland, China, the United States, and the United Kingdom to name a few. The industrial sector too is becoming more developed, with 2022 emerging as a record year for quantum technology start-up investment[7], and quantum use-cases coming into clearer focus in different sectors. Accordingly, preparation for the impacts of quantum computing has become increasingly important to delineate across multiple stakeholder groups (e.g., academia, government, and industry) to effectively gauge progress, develop responses, and assess possible pathways forward.

> “Quantum computing could impact on society [in ways that] are so profound it is hard to ignore.[6]

Speed of development

At the time of writing, quantum commercialisation – and thus return on investment – is seen to be within touching distance, evidenced by such events as the first deliberate ‘shorting’ of quantum computing stock in March 2022[8]; the large ‘Commercialising Quantum Global’ conference hosted annually by The Economist; and the development of research competitions seeking to encourage practical applications of existing technology in areas such as finance, and materials development.

Whether acknowledged or not, there are many who consider that the quantum computing hardware pathway has become a race – and it becomes imperative to question whether this is a productive and responsible avenue to pursue. The sector may learn from the example of the nationalistic space ‘race’ in the mid-20th century, which – whilst technologically productive – also amplified existing geopolitical tensions and was widely regarded as a surrogate for combat during the Cold War.[9] By contrast, the series of international agreements that led to the foundation of the International Space Station have changed the terms on which many countries interact, while continuing to develop technologies collaboratively for the benefit of all.

Geopolitical importance

The level of political significance that has been attached to the development of quantum computing is perhaps the strongest driver of progress. Within the UK, the high profile of the National Quantum Technologies Programme is illustrated by the ongoing investment in the four national quantum technology Hubs – multi-institution research consortia focused on quantum sensing, communications, imaging, and computing – and particularly the development of the National Quantum Computing Centre (NQCC). The government has also established the Office for Quantum within the Department for Science, Innovation and Technology (DSIT), giving the Office a policy-making remit across all quantum technologies (i.e., not only quantum computing).

Activity in the UK reflects similar levels of government investment elsewhere, which signals the growing global profile of quantum technologies. National interests have started to be prioritised at regulatory levels (e.g., the UK’s National Security & Investment Act[10]). However, many researchers perceive risks around efforts to control collaboration along nation-state lines, arguing that trying to shield research in this way will impoverish and impede the development of the field, as well as amplify current capacity and resource challenges. The level of national interest in quantum technologies is not least due to the much-discussed possibility that a large, error-corrected quantum computer, also known as a *cryptographically relevant quantum computer*, could compromise a significant portion of current cryptographic systems. Such a feat could hypothetically be performed using Shor's algorithm, which enables a computing system to find the prime factors of an integer. Consequently, no nation that has built significant public infrastructure on the internet can afford to ignore the threat that this would represent. It was to respond to this challenge that the USA's National Institute for Science and Technology (NIST) launched a global competition to find quantum-resistant public-key algorithms in 2016.[11]

Applications and use-cases

Aside from the possibility of breaking public-key encryption, there are other, more positive prospective use-cases offered by quantum computation – many of which may be within closer reach than the threat of a cryptographically relevant quantum computer[12] (e.g., quantum chemistry[13], quantum machine learning[14], and various applications in drug discovery.[15]) Unsurprisingly, these use-cases are also subjects of keen interest to governments around the world, given probable impact of quantum computers in industries ranging from chemistry to biology and finance.

It should be noted that there is currently no single universally accepted way to build a quantum computer. Indeed, the term 'quantum computer' itself may refer to several different types of devices. Besides fully error-corrected quantum computers, which are not yet available and may not be for some time, there is increasing interest in what could be achieved with the quantum computers of today, namely, *noisy, intermediate-scale quantum computers* (NISQ), a name that also characterises the present era of quantum computing (i.e., the NISQ era). There are also 'analogue' architectures such as D-Wave, and other physical realisations of quantum computers being explored by innovators. Different modalities have different advantages and limitations and vary with respect to maturity and commercial readiness. Thus, it is possible that there may not just be one single optimal architecture for a 'quantum computer', but many (see figure 1 below).[16]

There remain many engineering challenges for the commercialisation of quantum computing and its integration into relevant industry sectors, as well as uncertainties around the shaping of a commercial quantum computing sector itself. Recent research suggests that quantum computing is only likely to achieve advantage in real-world scenarios if it can produce more than quadratic[18], ideally exponential, speed-ups over classical methods and with relatively small amounts of data.[19] Nevertheless, smaller speed-ups could still be valuable for specific use-cases, including some challenging problems in quantum chemistry and materials science.

Quantum divides

A 2021 report by the Canadian Institute for Advanced Research (CIFAR)[20] surveyed the global implementation of quantum programmes, with investments ranging from several millions to billions of dollars. In doing so, the report further highlighted the prevailing inequity in the existing levels of investment and access to quantum computing across different countries. An updated analysis of global national strategies from the World Economic Forum (WEF) shows that the situation has not substantially changed since the CIFAR report, with a vast amount of the world's population located in countries that do not have such programmes or access (see figure 2).

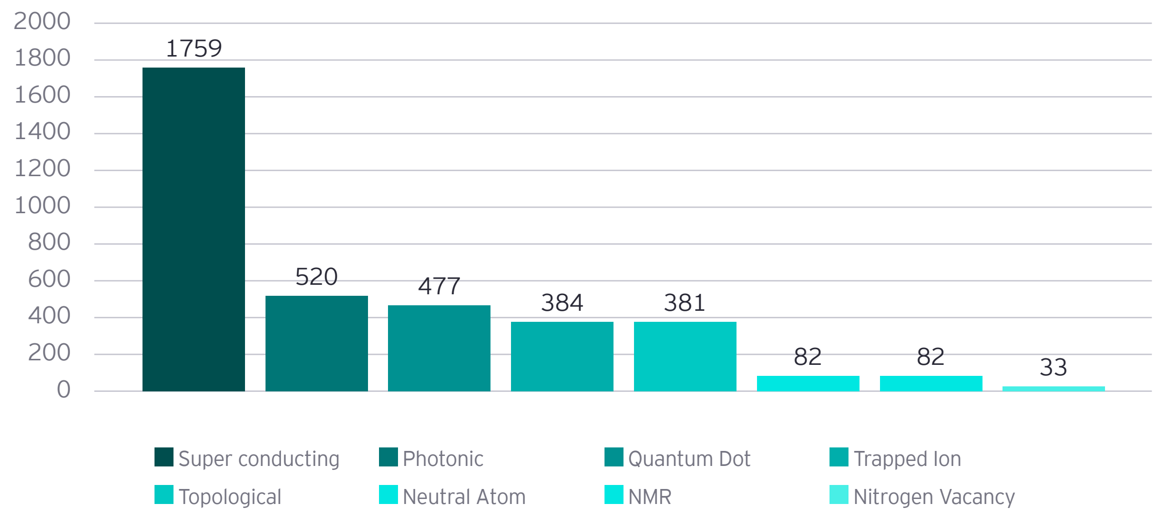
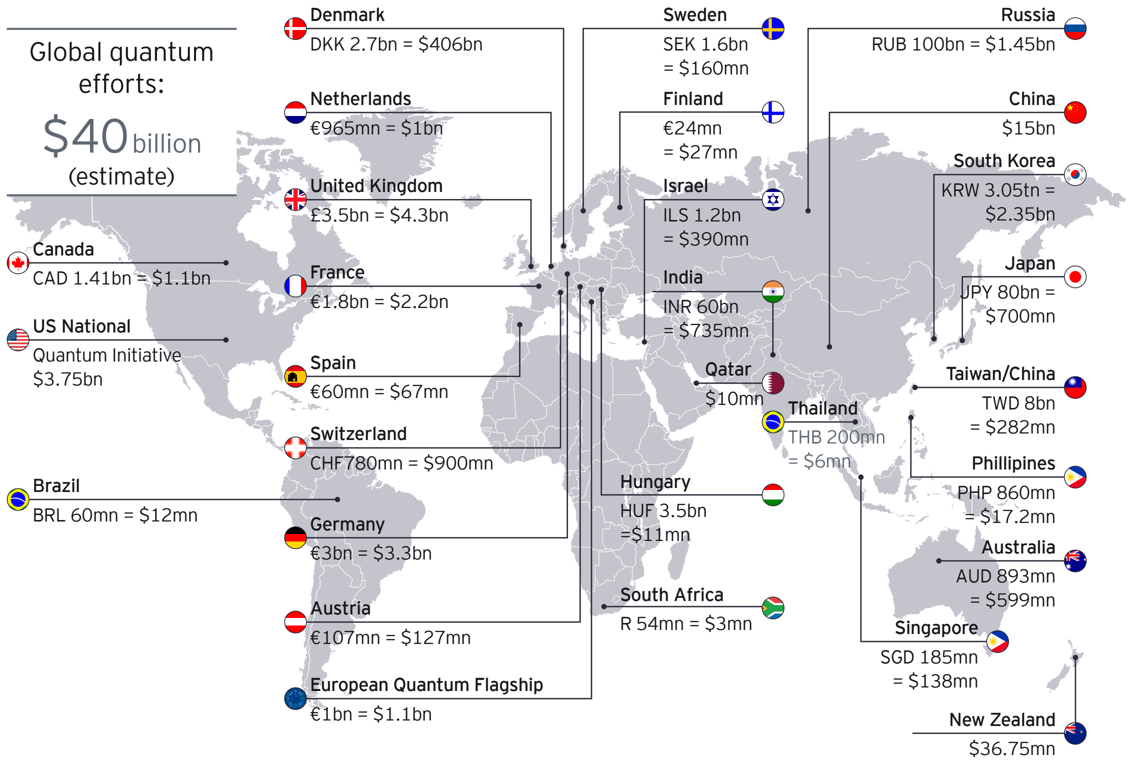


Figure 1: Published Patent Applications by Modality (2004-2023) from IP Watchdog[17]



Note: Not exhaustive, timelines for funding vary by country.

Sources: "Overview of Quantum Initiatives Worldwide 2023". **QURECA**, 19 July 2023; Department of Industry, Science and Resources, Australia, ETH Domain (ETH Zurich, EPFL, PSI).

Figure 2: Taken from Quantum Economy Blueprint, published by the World Economic Forum 2024

The challenge of unequal access, which has been discussed in the scholarly and public discourse for several years (e.g., De Wolf 2017[21], Ten Holter et al 2022[22]), is now appearing in increasingly high-level groups, including the WEF[23]. Given the predicted capabilities of quantum computing-enabled industries, the consequences of lack of access to quantum talent and the technology itself may amplify existing digital divides. These divides may, for example, be both between and within countries, or between those organisations and institutions that have access to quantum knowledge and resources, and those that do not. As a global society, the world faces many collective grand challenges on climate change, dwindling resources, and the need for new materials, amongst others. As such, it may be in the best interests of humanity and the environment to enable more equity of access to quantum talent and technology, given that quantum technologies stand to be a substantial differentiator in tackling some of these challenges.

Responsible quantum computing

As the global conversation around quantum computing has developed and more countries launch their own national quantum computing strategies and associated programmes, it has become clear that alongside the research and development of the quantum computing 'stack', there is another conversation taking place about the use, and use-cases of quantum computers. The development of a 'responsible' quantum computing mindset originated in the UK with its 2014 National Quantum Technologies Programme. This programme incorporated the tenets of RI (also referred to as Responsible Research and Innovation or RRI) into calls for proposals and required all the UK's Quantum Technology Hubs (2014-2019) to include RI approaches within their work plan. RI was also incorporated in the second generation of Hubs (2019-2024) and has been taken forward into the third round of funding (2024-2029), as well as by the NQCC, which has a designated Quantum Computing Policy and Ethics Lead.

However, such approaches are not exclusive to the UK. Many countries with a quantum computing development programme also have researchers working on responsible and ethical approaches to the technology. TU Delft (Netherlands), Karlsruhe Institute of Technology (Germany), and the Sydney Quantum Academy (Australia), as well as others have all produced significant research on responsible quantum computing, while the Netherlands, UK, and Australia have utilised the WEF's Quantum Computing Governance Principles to help inform associated policy.

RI as a concept has become widely accepted within the Engineering and Physical Sciences Research Council (EPSRC) in the UK and across Europe; its application to the development and deployment of quantum computing has become the subject of increased study in recent years (e.g., Inglesant et al., 2016[24], 2021[25]). For the purposes of comparison, within the field of synthetic biology, commentators discuss how RI's impacts have both benefited the discipline and developed the researchers' own understanding of how inclusivity and dialogue can support responsible development and outcomes.[26] Nanotechnology also has a current of RI, with a corpus of literature examining how it has developed in the field. Although it is never possible *"to know what would have happened"*[27] if RI approaches had not been utilised in these domains, it is possible to draw lessons from the relative absence of 'science scandals' in these fields when compared to the field of AI, where there has been greater relative resistance towards responsible and ethical innovation until recently.

The 2021 study "Creating a Responsible Quantum Future" by Ten Holter et al advocates for a dedicated national hub centred on RI in quantum computing.[28] The authors view this as increasingly essential, aiming to foster deeper engagement between the quantum computing community and broader society, as well as supporting businesses venturing into commercial sectors for the first time. Only by addressing specific challenges in the industry, policy, and social dialogue can the forward-thinking aspects of responsibility, such as 'taking care' (Pellizzoni, 2004[29]), be turned into concrete action. This is necessary to ensure that society experiences not only the benefits of advanced quantum computing research, but that principles of good governance, transparency, and other aspects of responsible development are translated from the research environment into the commercial sector.

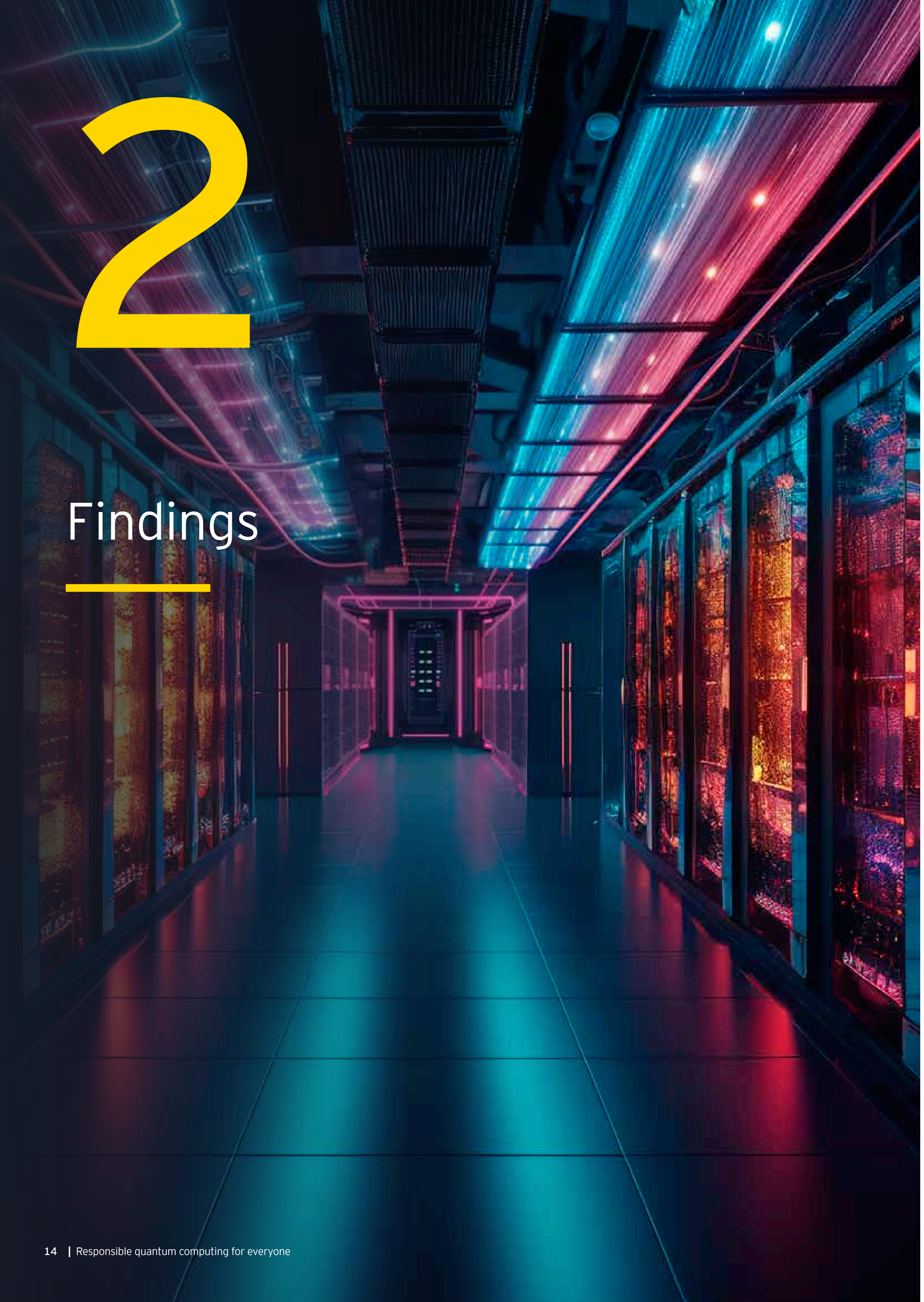
RI tenets are particularly relevant to these challenges outlined above because these anticipatory governance techniques can not only assist with translational governance from research into industry but can address concerns around sovereign capability technologies, such as quantum computing. With the growth of investment across the globe into quantum computing, the conversations around its responsible and ethical development and rollout become more urgent.

Quantum computing contextualised against other technologies

It was within this rapidly changing context, and with the recommendations of the responsible quantum computing community in mind, that the research described below was carried out. The overall purpose of our survey was to 'take the temperature' of current expert thinking about quantum computing, as well as to place these considerations within the context of discussions surrounding novel technologies in general.

Accordingly, respondents were initially asked about their knowledge of, and attitudes to, a group of novel technologies. The technologies selected are those that have been identified by the UK government as being key for its own strategic capacity, as published in the Integrated Review Refresh of March 2023.[30] Additionally, respondents were asked about their own views on 'responsible' technological development, and their thoughts on government involvement and governance in general. Finally, they were asked to consider various scenarios around the future development of quantum computing, both nationally and internationally, and comment on their likelihood and impact. The survey was confined to an expert group of researchers, professional advisers, policymakers, and those with an industrial or commercial role in the quantum ecosystem.

Further information about the methodology adopted in running this survey can be found in **About the research**.



2 Findings

As expected, our group of respondents were confident in their expertise around quantum computing and regarded themselves as having a good level of knowledge around what might be considered as 'sister' technologies, such as semiconductors and AI. In contrast, most respondents did not regard themselves as well-informed on engineering biology and future telecoms, which are the remaining two technologies seen by the UK government as being of strategic and commercial importance, with significant numbers being unaware of either set of technologies. This grouping of understanding around quantum, semiconductors, and AI perhaps indicates that there is significant crossover and commonality between these technologies in terms of hardware requirement pathways and supply-chain challenges, as well as potential affordances and ethical risks. It was in this context that participants were asked about their own approaches and positions on questions of novel technologies.

Percentage of respondents who "know something about" or are "very knowledgeable about" the five strategic technologies

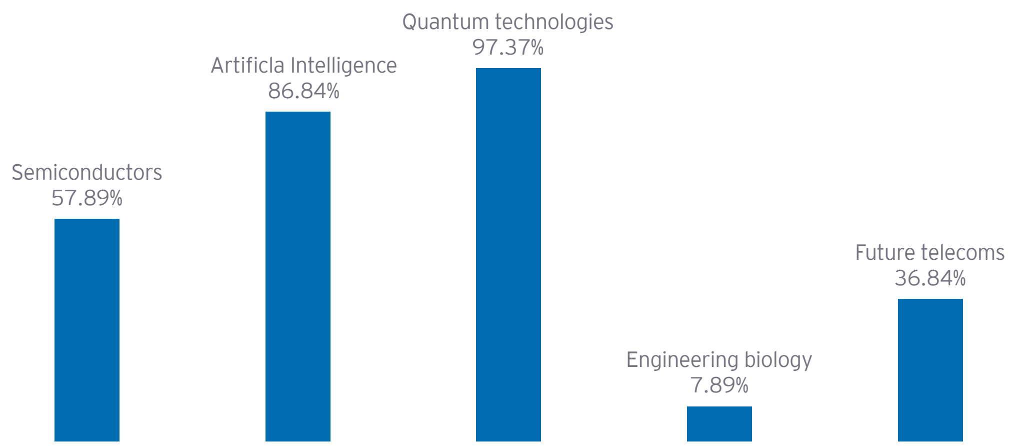


Figure 3: Declared levels of expertise by respondents across five strategic technologies

Development of novel technologies

Although largely (22 of 38, 57.9%) agreeing or strongly agreeing that it may be useful to generate some excitement in society and communities about novel technologies, most respondents (84%) believed that claims made around such technologies were very often overblown or exaggerated in popular discourse. This suggests that counteracting 'hype' around such promises and engaging in responsible science communication may be a key element to consider amongst the expert community, with 'right-sizing' expectations being more critical than generating enthusiasm. There are obvious implications for the need to raise venture capital, but a right-sized approach to the promises of the technology may be an important component of 'responsible' quantum computing.

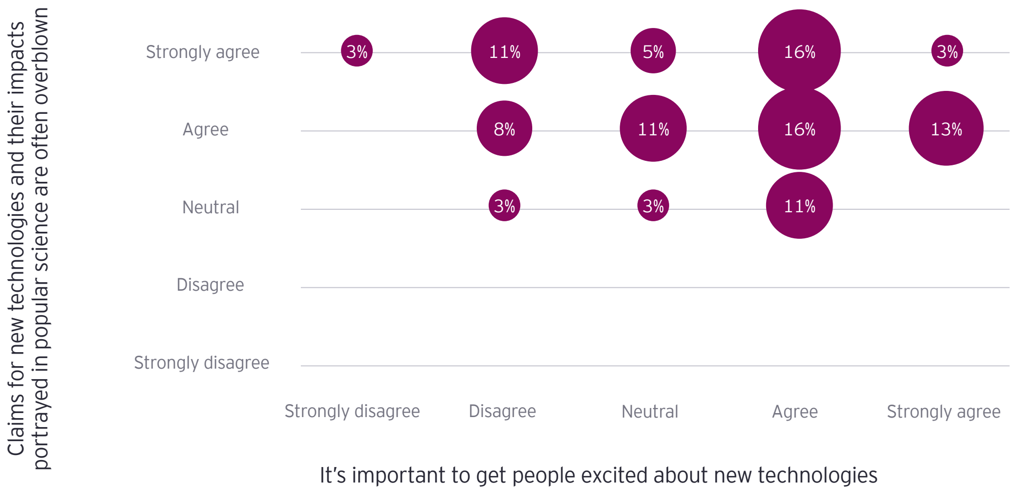


Figure 4: "Excitement" vs. "Overblown", counteracting hype in new technologies. Note the clustering around the "agree"/ "strongly agree" axes and absence of "disagree"/ "strongly disagree" responses, especially for the "Overblown" question.

It's important to get people excited about new technologies

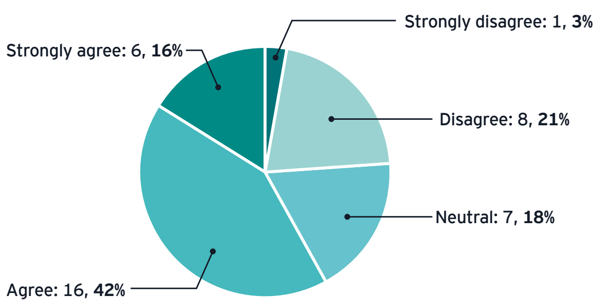


Figure 5: Responses to the question: It's important to get people excited about new technologies (numbers and percentages of respondents)

Claims for new technologies are often overblown

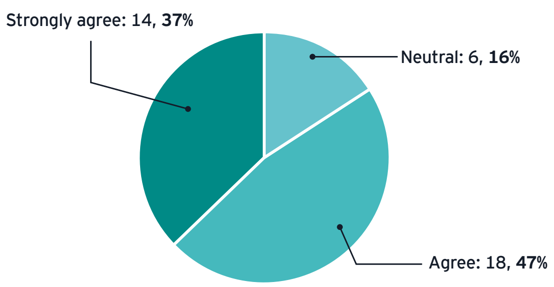


Figure 6: Responses to the question: Claims for new technologies and their impacts portrayed in popular science are often overblown (numbers and percentages of respondents). Note that none responded "Disagree" or "Strongly disagree".

Findings

The critical driving factors for development of novel technologies proved to be slightly more divisive. Although there was almost unanimous agreement (36 of 38, 94.8%) that it is important to consider how novel technologies would affect society, there was not a consensus among participants as to whether technological developments should be driven by societal needs (such as high-level Grand Challenges, typified by the UN Sustainable Development Goals (SDGs)[31]) or whether science and technology should be advanced regardless of its purpose. 27 of 38 (71%) respondents believed that societal need should be key in shaping development pathways, but a significant proportion (24%) were not committed to this as a driver and two respondents overtly disagreeing with this view. When we asked about the importance of scientific advancement regardless of whether there was an objective in view, participants were split, with just over half (52%) agreeing that scientific knowledge should be pushed forward even without clear societal benefit, 29% disagreeing or strongly disagreeing on this, and a relatively high level of undecidedness (19%).

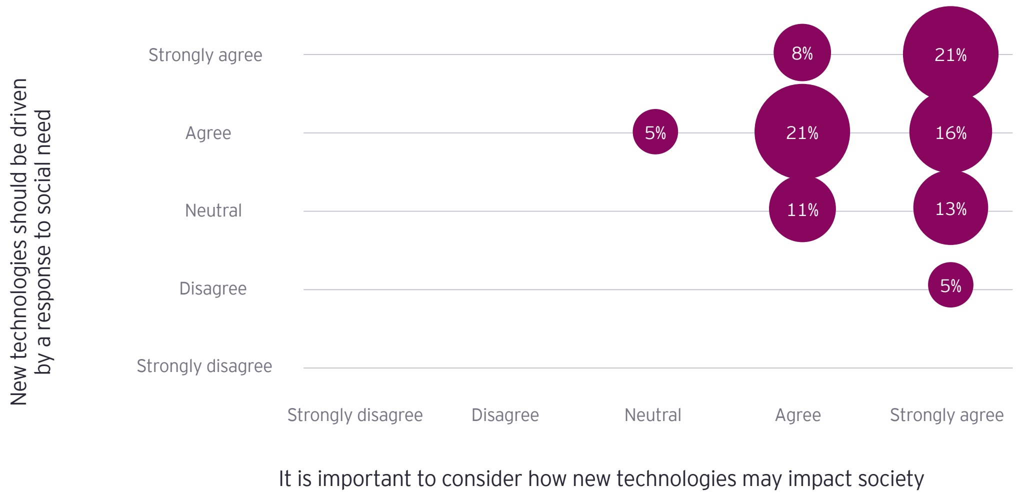


Figure 7: "Societal impact" vs. "Societal need". Note near-unanimity in agreement that it is important to consider the societal impact, but more neutrality and disagreement around new technologies being driven by societal need.

It's important to consider how new technologies may impact society

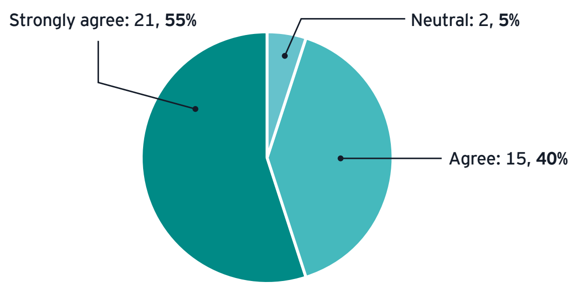


Figure 8: Responses to the question: It is important to consider how new technologies may impact society (numbers and percentages of respondents)

New technologies should be driven by a response to societal need

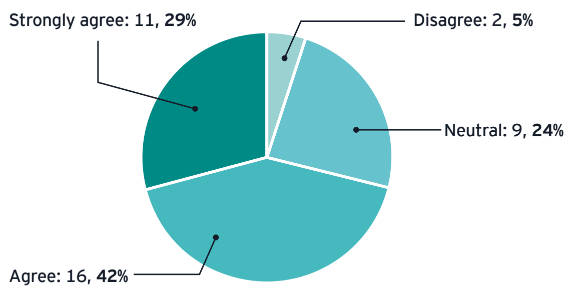


Figure 9: Responses to the question: New technologies should be driven by a response to societal need (numbers and percentages of respondents)

The question of societal impact in terms of the need to anticipate the effects of novel technologies was very clear, however, with 92% of respondents believing that thinking ahead about the effects of new technologies can help us to better prepare for them. This is not a question of prediction, but rather of considering possible outcomes and what might be done to cope with positive effects or mitigate negative ones.

There were also high levels of agreement when it came to questions of societal involvement, with a large majority (87%) of respondents believing that it was important to involve many different stakeholder groups in the development of novel technologies. Perhaps unsurprisingly, all participants expressed that they themselves were deeply interested in novel technologies, with many also being interested in seeing (and participating in) wider societal discussions therein.

Thinking ahead about the effects of new technologies may help us to prepare for them

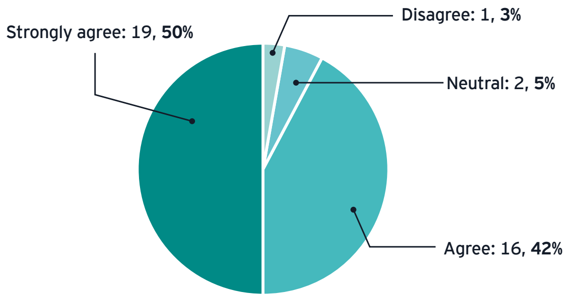


Figure 10: Responses to the question: Thinking ahead about the effects of new technologies may help us to prepare for them (numbers and percentages of respondents)

It is important to involve many different groups in the develpment of new technologies

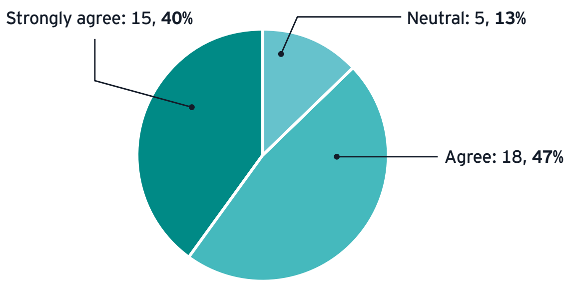


Figure 11: Responses to the question: It is important to involve many different groups in the development of new technologies (numbers and percentages of respondents)

Views regarding the need to consider societal impacts and to draw in broader sets of views when it comes to development pathways may also be seen in the reluctance of participants to leave novel technological development in the hands of private companies alone. Of the respondents, 60% disagreed or strongly disagreed that private companies were most suited to developing novel technologies and a further 24% were undecided on the point. However, there was also unwillingness to leave innovation in the hands of researchers and developers, with 63% disagreeing that this was a desirable route. The combination of these last sets of questions may suggest an unspoken desire for more transparency in the development of novel technologies, perhaps stemming from the concern expressed above of technological development being turned into a 'race'.

Private companies are the most suited to developing new technologies

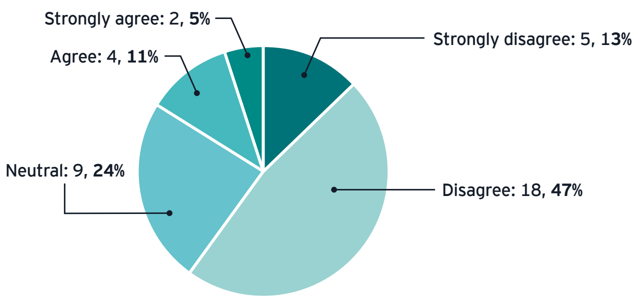


Figure 12: Responses to the question: Private companies are the most suited to developing new technologies (numbers and percentages of respondents)

Science and innovation should be left to developers and researchers

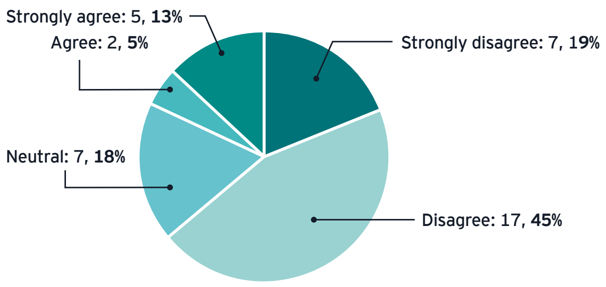


Figure 13: Responses to the question: Science and innovation should be left to developers and researchers (numbers and percentages of respondents)

Finally, we asked participants whether they considered that the rush to develop new technologies may outpace our understanding of the potential risks and societal implications. 76% of respondents agreed, which aligns with the earlier responses about the need to open the discourse to wider communities and create spaces for cross-sector and cross-disciplinary dialogue to permit concerns and questions to be meaningfully aired:

The rush to develop new technologies may outpace our understanding of the potential risks and societal implications

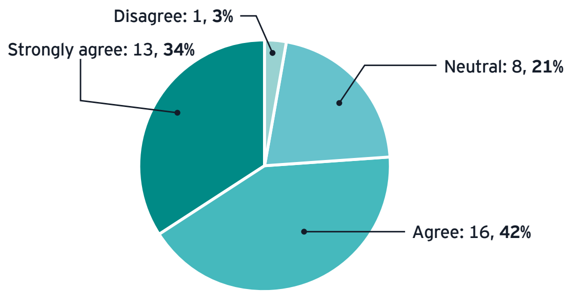


Figure 14: Responses to the question: The rush to develop new technologies may outpace our understanding of the potential risks and societal implications (numbers and percentages of respondents)

Role of government

Quantum computing is frequently characterised by reference to the 'triple-helix' model[32] – the three elements being research/academia, industry, and government. In quantum computing the three elements are very tightly bound. For example, the long-term research profile requires the type of funding that needs to be prioritised at a strategic level by government; many of the start-ups in industry are staffed by university-trained researchers due to the levels of technical expertise required; and government may regard the developing commercial marketplace as a future source of national prosperity. There is therefore considerable overlap between the relevant domains in a way that is not necessarily a feature of all novel technologies.

There are thus numerous roles that government can play in the development of novel technologies in general, and in quantum computing in particular – these roles may be thought of, for example, in terms of:

- Providing governance frameworks
- Offering funding (direct and indirect)
- Creating commercial opportunities
- Shaping the political ecosystem
- Acting as an early customer
- Prioritising national or regional initiatives
- Setting up tax incentives
- Creating infrastructural support
- Supporting long-term risks
- Influencing educational programmes
- Building cross-departmental understandings

There are many other potential roles for government – however, this relatively brief survey was not the place to explore all of these. Accordingly, the survey chose to focus on broad questions around governance and government involvement in novel technologies in general.

There was a very high level of agreement – over 90% – that governments should be involved in the funding of novel technologies. Although, it should be noted that participants had a range of reasons for agreeing with this statement. Several pointed out that 'blue-sky' research is often reliant on government funding before any commercial application is seen, because "Companies will invest in things where there is a clear need already", and government is in a good position to take greater risks (although it may well not), while others suggested that government should be involved to ensure protection and support for the national interest, as it has an overview of the bigger picture. Other comments related to a need for governments to rein in the perceived excesses of big tech companies, or that if it was left to the commercial sector "development would be less 'responsible' and the potential of 'mis-usage' larger".

The government should be involved in funding the development of new technologies

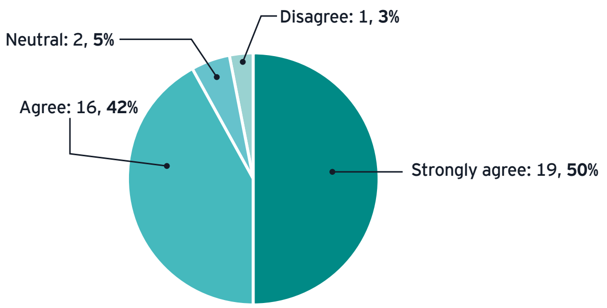


Figure 15: Responses to the question: The government should be involved in funding the development of new technologies (numbers and percentages of respondents)

There was also strong agreement (87%) amongst respondents that policymakers and advisers need to be well-informed about the details of new technologies, with the comment "It is critical for policymakers to understand the technologies that they are crafting policies for, else they miss the nuance required to effectively protect people, the economy, and the environment" representing the overall trend. Other comments discussed the need to be able to ask the right questions when evaluating technologies, and to be able to assess impacts. However, participants were extremely sceptical as to whether policymakers working in technical fields are in fact well-informed; "many policy makers are simply not well enough educated in science and technology", or whether such an ambition was even achievable, with one commentator describing it as "close to impossible".

Policymakers should be well-informed about the details of new technologies

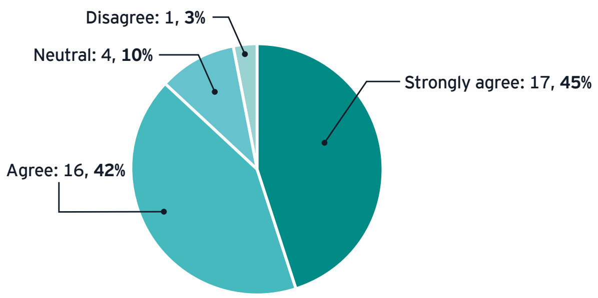


Figure 16: Responses to the question: Policymakers should be well-informed about the details of new technologies (numbers and percentages of respondents)

When asked to comment on whether some technologies are too important to be left in the hands of private firms, although there was high agreement (Agree or Strongly agree, 28 of 38, 74%), again, participants had different views on why they thought that this was the case. Some commented on governments' poor record at development, especially at pace, as a driver for government needing to collaborate with private companies, while others pointed out that some novel technologies are dual-use and that these should not be developed 'out of sight' in the private sector. Participants also commented that "the unchecked approach … is concerning," and that diverse groups are increasingly needed. Corporate 'steamrolling' was a concern, with specific reference to the development of self-driving cars and their deployment on the roads without public consultation, which reflect the earlier point concerning the role that governments can play in providing a check on the activities of private companies.

Science and innovation should be left to developers and researchers

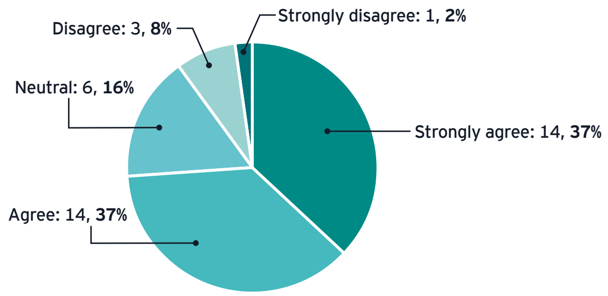
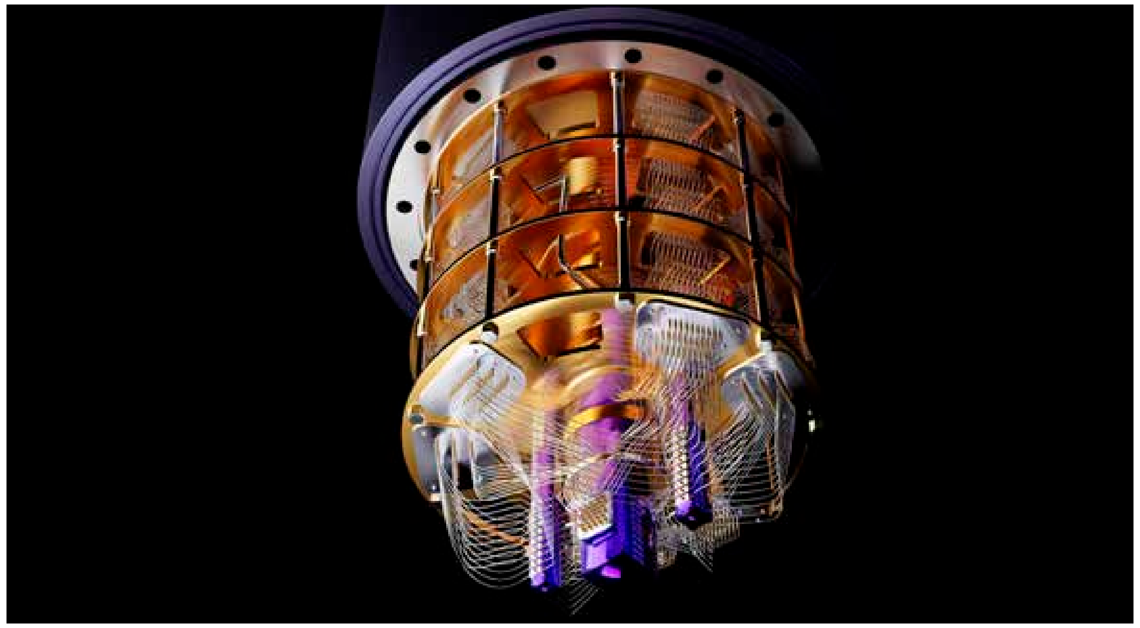


Figure 17: Responses to the question: Some technologies are too important to be left in the hands of private firms (numbers and percentages of respondents)



There was less agreement about the timing of the governance of novel technologies, with 63% of respondents agreeing or strongly agreeing with the statement that governance should be built in from the "earliest possible" point. However, this is still considerably higher than might have been expected, given that the survey involved many industry participants, who are often represented as adopting an anti-governance position. In fact, the same number of industry participants – 12 – as of academic participants agreed or strongly agreed with this statement. Participants pointed out that governance should be developed on a case-by-case basis and should be 'appropriate' – not stifling – but also that standards and regulation are frequently helpful for both companies (by providing them with frameworks for compliance) and consumers, as standards can help build public trust. Others suggested that process-based governance techniques such as RI could be helpful in anticipating risks and mitigating them. One participant strongly disagreed with the suggestion, however, arguing that governance blocks creativity and development – a point of view that has been similarly raised regarding AI and data governance in the past.

It is important to build in governance mechanisms around new technologies from the earliest possible point

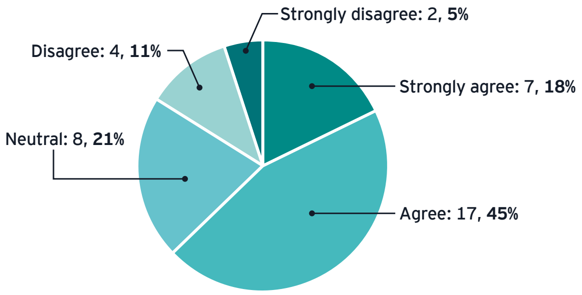


Figure 18: Responses to the question: It is important to build in governance mechanisms around new technologies from the earliest possible point (numbers and percentages of respondents)

The question about whether novel technologies should be regulated received higher levels of agreement than the previous question, with over 81% of respondents agreeing or strongly agreeing that regulation was necessary to ensure both public benefit and public protection. Participants elaborated on their answers, arguing for nuance in the way in which technology regulation is considered, and demonstrating a desire for a broad range of granular approaches at macro, meso, and micro levels to reflect different potential outcomes and challenges.

Private companies are the most suited to developing new technologies

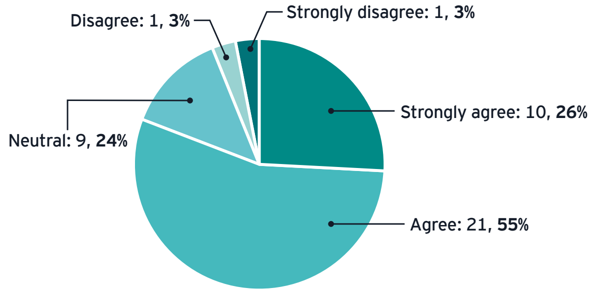


Figure 19: Responses to the question: Regulation of new technologies is necessary to ensure public benefit and protection (numbers and percentages of respondents)

Future scenarios

In the last section of our survey, respondents were asked about eight plausible future scenarios for quantum technologies, and for each, whether they consider the probability to be low, medium, or high; the impact to be low, medium, or high; and their estimate of the timescale to be near-term, medium-term, or long-term. These terms were purposely loosely defined, so that respondents could interpret them as they considered appropriate. This section details specific findings for each scenario, while summary findings are detailed in **Discussion of Scenarios**.

Scenario findings

Scenario 1: Quantum Monopoly. **One company or a small group of companies achieve quantum advantage (demonstrable superiority of a quantum computational device over a classical one) and subsequently monopolise the market for quantum computing. This results in an unequal distribution of benefits and risks associated with quantum computing, and leads to technology lock-in, where users are forced to use a single technology provider. Broader innovation and competition in the ecosystem are stifled as a result.**

For this scenario, a relatively large proportion, 21 respondents, predict a high impact from such as scenario, but only 10 expect this to happen with high probability:

	Impact	Probability	Timescale	All respondents
High	21	10	14	Long-term
Medium	9	16	19	Medium-term
Low	8	12	2	Near-term

Table 1: Summary of Impact and Probability, "Quantum Monopoly" scenario, all respondents

Scenario 2: Quantum Security. **Quantum-based security provides 100% security in transmission. This underpins social and cultural change as data can now be completely secured.**

For this scenario, our respondents' opinions are mixed in terms of its possible impact, with 14 reporting a high impact, 15 a medium impact, and 9 a low impact. Interestingly, industry respondents reported a somewhat higher impact, with 9 of 19 reporting a high and 7 a medium impact, compared with 5 of 19 academic respondents giving this scenario a high impact and 8 a medium impact:

	Impact	Probability	Timescale	All respondents
High	14	10	15	Long-term
Medium	15	15	15	Medium-term
Low	9	13	5	Near-term

Table 2: Summary of Impact and Probability, "Quantum Security" scenario, all respondents

	Impact	Probability	Timescale	Industry respondents
High	9	5	6	Long-term
Medium	7	9	10	Medium-term
Low	3	5	2	Near-term

Table 3: Summary of Impact and Probability, "Quantum Security" scenario, industry and other respondents

	Impact	Probability	Timescale	Academic respondents
High	5	5	9	Long-term
Medium	8	6	5	Medium-term
Low	6	8	3	Near-term

Table 4: Summary of Impact and Probability, "Quantum Security" scenario, academic respondents

Opinions are also mixed in terms of their expectations of the probability of this scenario, with only 10 respondents expecting this with high probability but 15 with medium and 13 with a low probability.

The levels of impact and expected probability for this scenario are perhaps surprising, given that the technical capacity for this scenario is already available commercially and widely publicised. However, this may reflect their opinions of the second part of the scenario – social and cultural change – rather than the simple availability of the technology.

Most respondents expect this scenario to arise in the long- or medium-term, if at all. Again, this is surprising because this technology is already commercially available, however, it is possible that timescales are being driven by the fact that the respondents do not expect this scenario to lead to social or cultural changes if realised. In this and in other timescales, a small number of respondents did not give a response (3 in this case).

Scenario 3: Quantum Divide. Global division emerges as only a few countries or regions have access to quantum computing. Areas without access are left behind as businesses and research institutions that do have access take advantage of faster and more efficient computing power in applicable areas. This has geopolitical implications, as well as raising concerns regarding uneven development and innovation capacity.

The relatively high percentage in the high-impact segment (18 of 38, slightly over 47%) is interesting but not outstanding compared with scenarios 1, 4, and 8. What is notable here, though, is the large number of respondents also reporting a high probability, 21, over 55%, which is far higher than any of the other scenarios. This was true both for academic and industry respondents, although a slightly higher number of industry respondents expect a medium probability of this happening.

All respondents

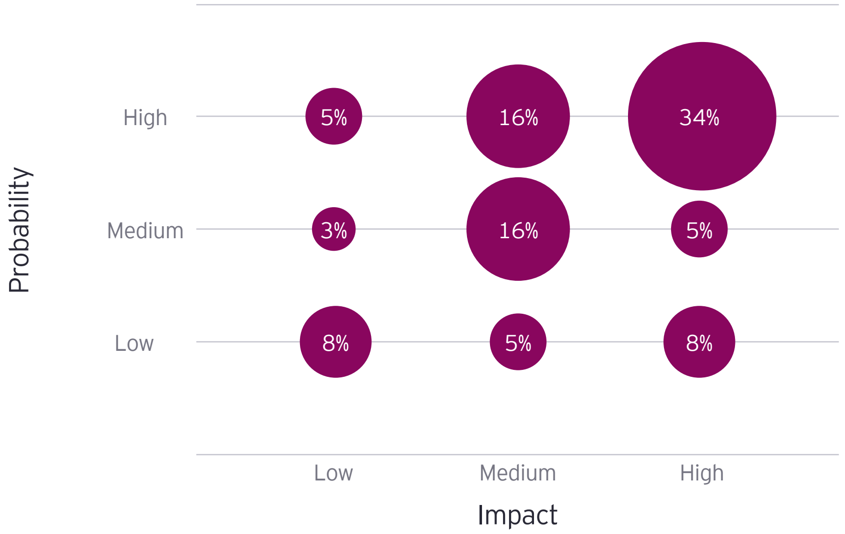


Figure 20: Impact and probability for "Quantum Divide" scenario, all respondents

Academic respondents

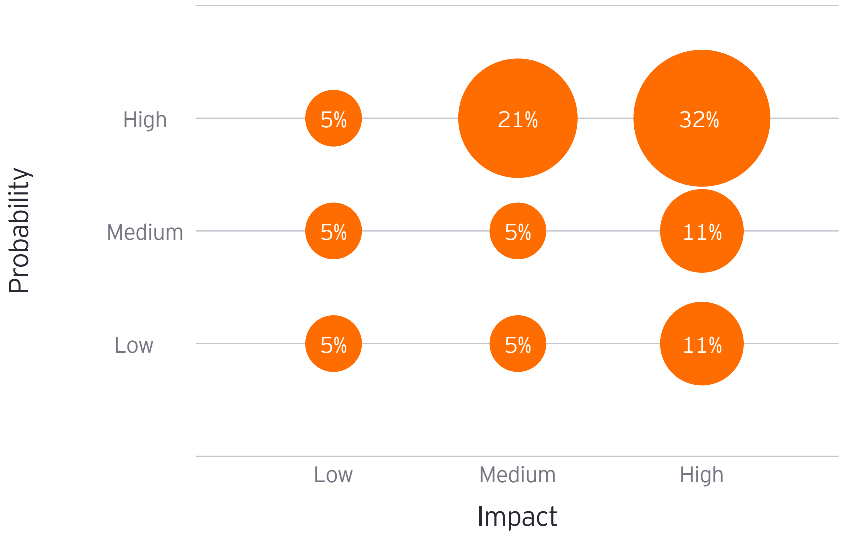


Figure 21: Impact and probability for "Quantum Divide" scenario, academic respondents

Industry respondents

Figure 22: Impact and probability for "Quantum Divide" scenario, industry, and other respondents

Scenario 4: Quantum Decryption. The development of quantum computing outpaces the development of tools and regulations that can manage associated cybersecurity risks. This could result in the potential to break encryption currently used to secure financial transactions and/or sensitive government information.

This scenario is outstanding for having the highest number of respondents reporting a high impact (27 of 38, over 71%). However, only 10 respondents (26.3%) expect this scenario with a high probability; the largest category is those respondents (10, 26.3%) who report that this scenario would have a high impact but who give it a low probability. Also of note is that, overall, the probability is rather evenly spread between high, medium, and low expectations (similar sized bubbles in all three rows), although somewhat more (15 respondents, 39.5%) expecting this scenario with low probability compared with 10 respondent (26.3%) expecting it with a high probability.

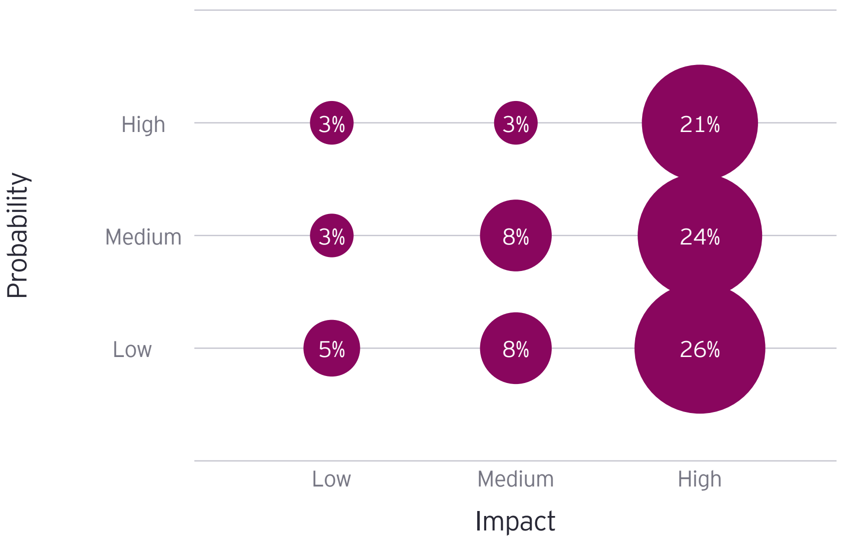


Figure 23: Impact and Probability for "Quantum Decryption" scenario, all respondents – percentages

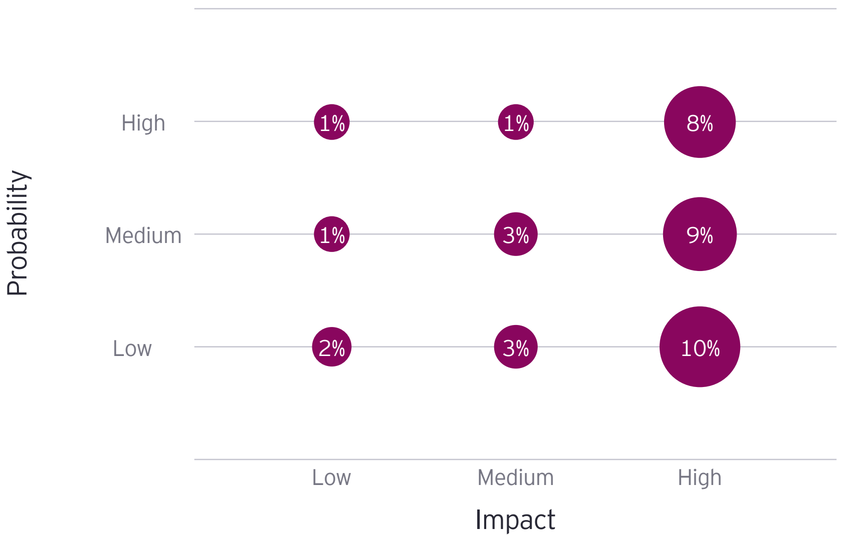


Figure 24: Impact and Probability for "Quantum Decryption" scenario, all respondents – numbers

Scenario 5: Quantum Collaboration. Companies and research institutions collaborate to advance quantum computing technology in a way that is open, transparent, and inclusive. This results in significant progress made in quantum computing that is shared equitably across different domains and leads to greater societal and environmental benefits.

As with some of the other scenarios, the respondents overall report a rather high impact from this scenario, 21 respondents reporting high impact, 14 a medium impact, and only 3 giving it a low impact. However, only 8 overall expect this scenario with a high probability, 13 with a medium probability, and 17 with a low probability.

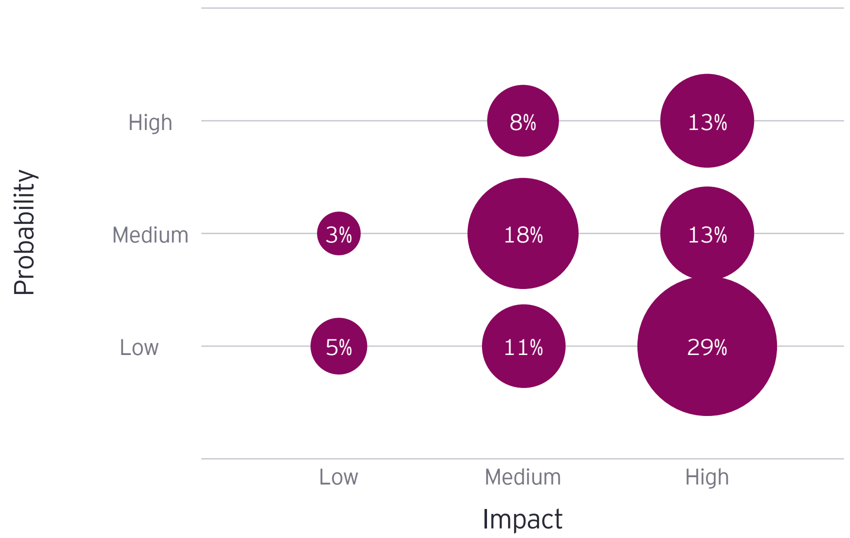


Figure 25: Impact and Probability for "Quantum Collaboration" scenario, all respondents – percentages

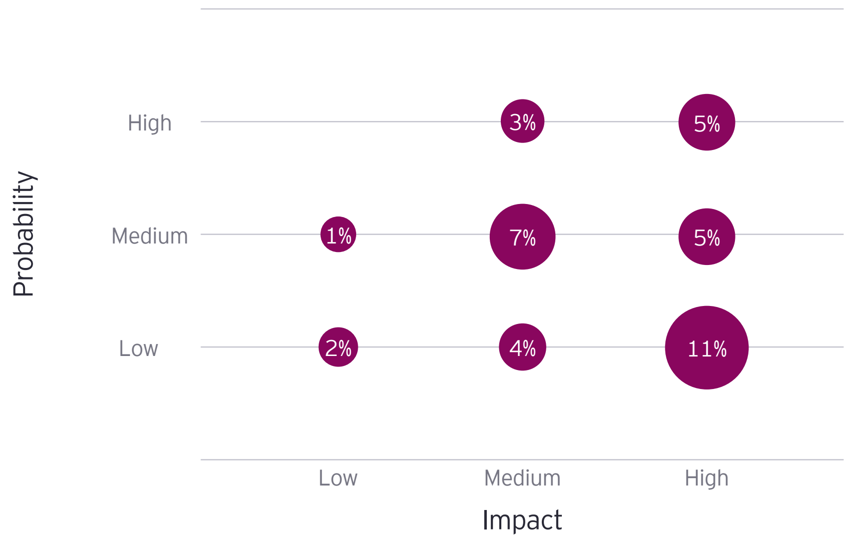


Figure 26: Impact and Probability for "Quantum Collaboration" scenario, all respondents – numbers

	Impact	Probability	Timescale	All respondents
High	21	8	10	Long-term
Medium	14	13	14	Medium-term
Low	3	17	9	Near-term

Table 5: Summary of Impact and Probability, "Quantum Collaboration" scenario, all respondents

Scenario 6: Quantum Resource Requirements. Quantum computing results in a significant increase in energy consumption and resource extraction. This increased energy consumption and carbon footprint exacerbates climate change impacts, leading to significant environmental, geopolitical, and social implications.

It is interesting to compare this scenario with the more optimistic Scenario 8 that envisages quantum computing using far less energy than existing high-powered computing, while also helping to mitigate climate change.

Our respondents gave mixed opinions about the likely impact of this scenario, as shown in table 6 below, but this scenario stands out for the large number of respondents, 24, believing that it had a low probability of occurring:

	Impact	Probability	Timescale	All respondents
High	16	5	13	Long-term
Medium	8	9	15	Medium-term
Low	14	24	5	Near-term

Table 6: Summary of Impact and Probability, "Quantum Resource Requirements" scenario, all respondents

Scenario 7: International Quantum Co-operation. Governments develop multi-lateral agreements that establish frameworks for co-operating across borders. This progresses the field of quantum computing, reduces geopolitical frictions, and leads to the creation of international norms and standards to govern the development and use of quantum computing technology.

This optimistic scenario was largely considered to have potentially high impact (20 of 38 respondents, 52.6%) but only with a low probability. Only five respondents indicated that it would be highly probable, all of them from industry/other, and not a single academic respondent indicated that this would be a highly probable future for quantum computing.

	Impact	Probability	Timescale	All respondents
High	20	5	15	Long-term
Medium	7	12	12	Medium-term
Low	11	21	7	Near-term

Table 7: Summary of Impact and Probability, "International Quantum Co-operation" scenario, all respondents

Scenario 8: Environmental Quantum Benefit: Hardware platforms for quantum computing are optimised to use energy far more efficiently than comparable high-performance computers. Quantum computation is used to accelerate discovery of possible mitigations to climate change through materials discovery and network optimisation.

This scenario yielded a high expected impact, with 26 (68.4%) of respondents giving this a high impact rating. With respect to probability, it is interesting to compare this with the more negative scenario 6. While scenario 6 saw a large majority of respondents giving a low probability, this more positive scenario generated a more even spread of expectations, with only 9 expecting this with a high probability and 10 with a low probability but the largest group, 19 respondents, giving this a medium probability (table 8 and the middle row of the bubble chart in figure 27).

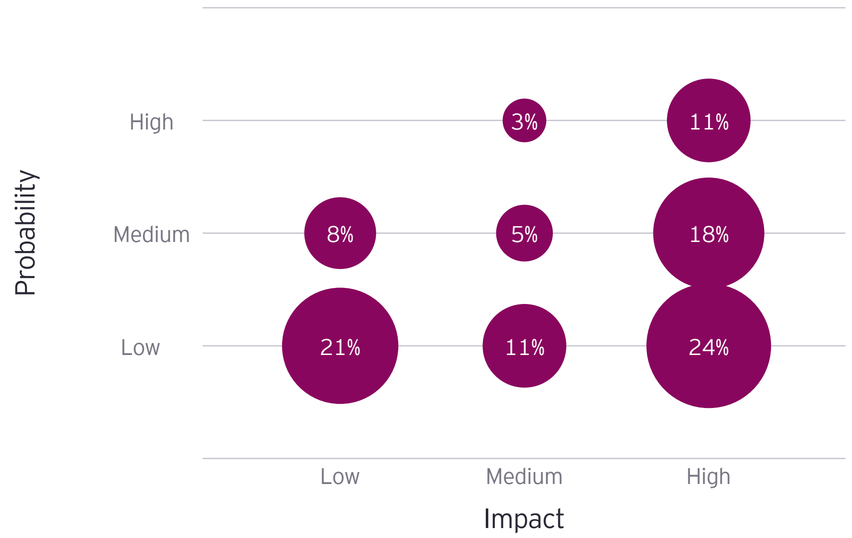


Figure 27: Impact and Probability for "International Quantum Co-operation" scenario, all respondents

	Impact	Probability	Timescale	All respondents
High	26	9	21	Long-term
Medium	7	19	10	Medium-term
Low	5	10	4	Near-term

Table 8: impact and Probability for "Environmental Quantum Benefit" scenario, all respondents

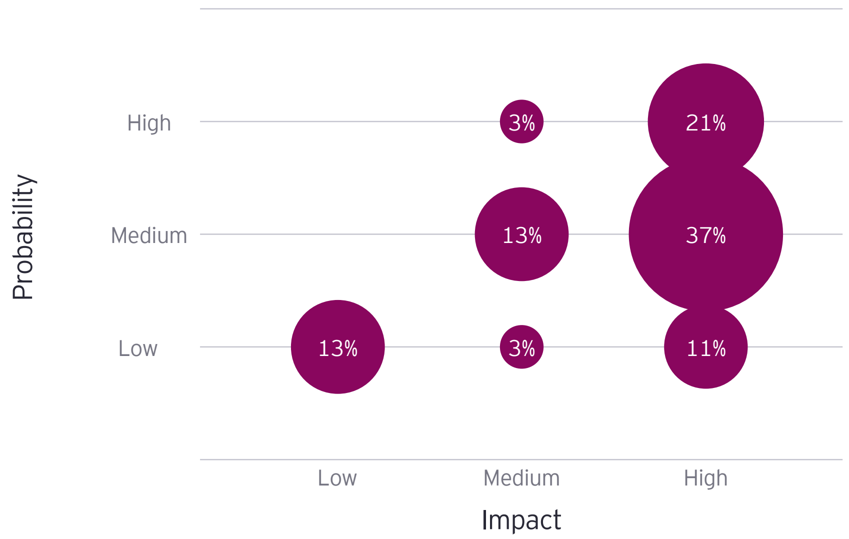


Figure 28: Impact and Probability for "Environmental Quantum Benefit" scenario, all respondents

This response pattern is especially strong among the industry/other respondents, with almost 79% agreeing that quantum computation has the potential for powerful computing using less energy and/or a high impact in mitigating climate change:

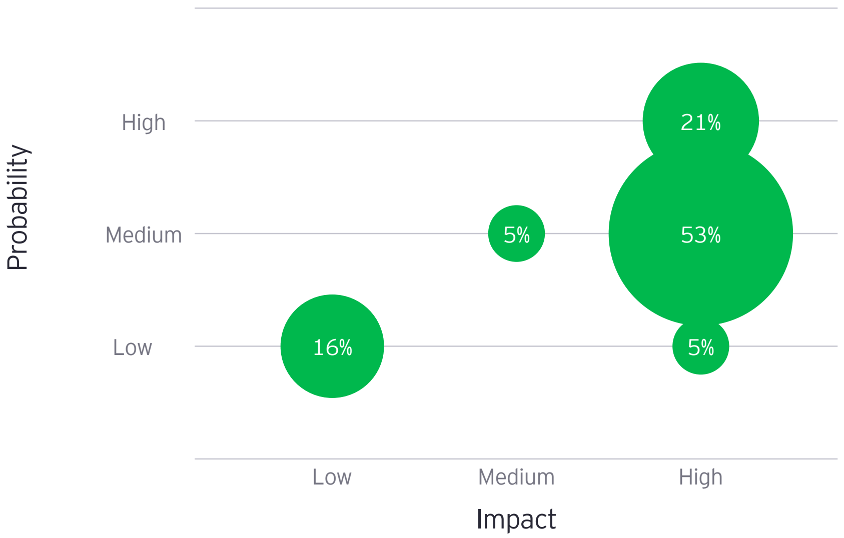


Figure 29: Impact and Probability for "Environmental Quantum Benefit" scenario, industry/other respondents

Discussion of scenarios

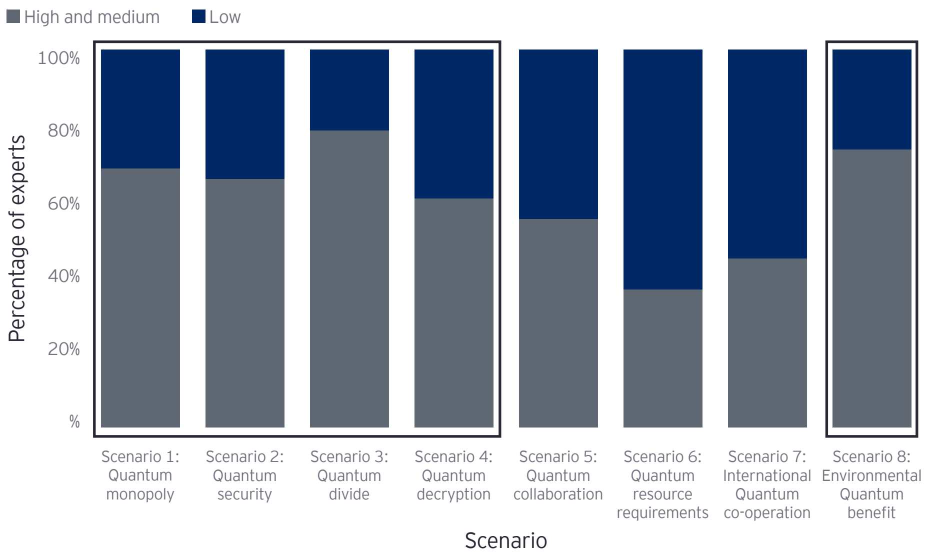


Figure 30: Summary Results – Percentage of experts predicting a high or medium probability of occurrence compared with a low probability, with most likely scenarios highlighted.

In the view of the experts who participated in the survey, the most likely scenarios were (in order):

- Scenario 3: Quantum Divide
- Scenario 8: Environmental Quantum Benefit
- Scenario 1: Quantum Monopoly
- Scenario 2: Quantum Security
- Scenario 4: Quantum Decryption

The scenarios were divided between positive and negative outcomes (Environmental Quantum Benefit, Quantum Security, International Quantum Co-Operation, and Quantum Collaboration suggested positive outcomes, Quantum Divide, Quantum Decryption, Quantum Resource Requirements, and Quantum Monopoly were negative), and those considered most likely to occur were evenly balanced between positive and negative.

Proportion of likely scenarios that are positive and negative

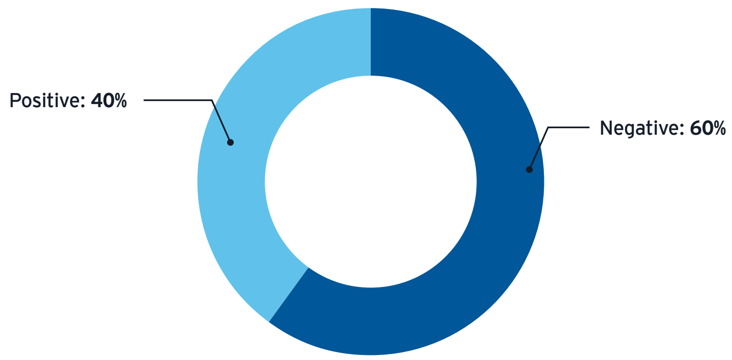


Figure 31: Summary Results – Proportion of likely scenarios, positive and negative

Interestingly, the most-often-quoted possible threat from quantum computing – that of breaching existing cybersecurity protocols (i.e., Scenario 4) – lagged in likelihood when compared to scenarios 3, 8, 1, and 2, suggesting that there may be sufficient awareness of the potential risks, and sufficient action being taken, in a timeframe regarded as realistic when set against the progress being made towards large-scale error-corrected machines.

Notably, our experts saw clear indications that the globe is already on a pathway towards a divided quantum future, with some nations and societies losing out on the benefits of quantum computing. This was regarded as highly impactful – "Most likely quantum advantage will only reach countries in the 'global north' due to the level of infrastructural development needed and the existing research environments". In a reflection of the concerns seen elsewhere in the WEF and in the scholarly literature, the prospect of widening existing gaps between majority-world countries and global-north countries is not a welcome one. A further entrenchment of broader digital divides between Western hegemons and subaltern nations when it comes to quantum computing is further complicated by ongoing discussions and concern in the scholarly discourse regarding digital colonialism – "a structural form of domination exercised through centralised ownership and control of the three core pillars of the digital ecosystem: software, hardware, and network connectivity".[33]

More positively, quantum computing is viewed as potentially having a highly beneficial effect on the search for solutions to climate change challenges, though it should be noted that the urgency of the climate crisis does not encourage waiting for a quantum computer to be built. It was also regarded as likely that quantum computing could reduce the energy demands currently required for high-performance-computing; current predictions from the International Energy Agency are for global power demand to reach over 1,000 terawatt-hours by 2026 (equivalent to the energy use of Japan)[34]. Projects such as the Quantum Energy Initiative[35] are drawing attention to the need to consider the energy requirements of quantum computing, and actively investigating research pathways that can lead to greater efficiencies from a sustainability perspective.

The likelihood of a quantum computing monopoly being established by a company, nation, or small group, was also considered to be relatively high, and again to have a high impact. "Advanced technologies should not be monopolized that would result in severe socio-politico-economic effects". Other concerns centred around competition; "it is very difficult for start-ups and scale-ups to compete financially with corporate behemoths ... basic knowledge discoveries could be privatized, and competition eliminated". This is linked to Scenario 3, quantum divide. Taken together, these scenarios may indicate a need for governance to shape marketplaces and commercial environments in such a way as to level the playing field for competition and allow smaller players to thrive alongside larger organisations.

The last of the 'likely' scenarios was Scenario 2: Quantum Security – this was tied to the cybersecurity risk scenario, but our participants considered it more possible that security could be achieved, and that post-quantum cryptography would (together with classical techniques) offer secure communications and data.

Percentage of experts predicting a high, medium or low impact of the most likely scenarios

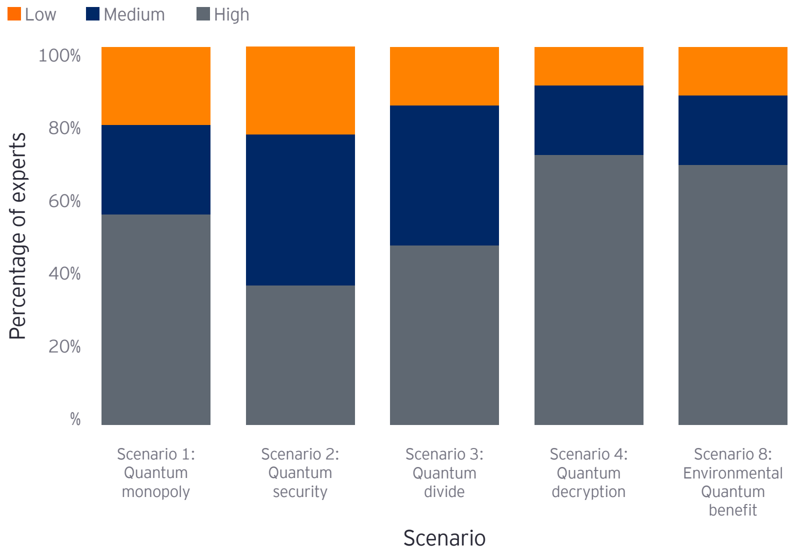
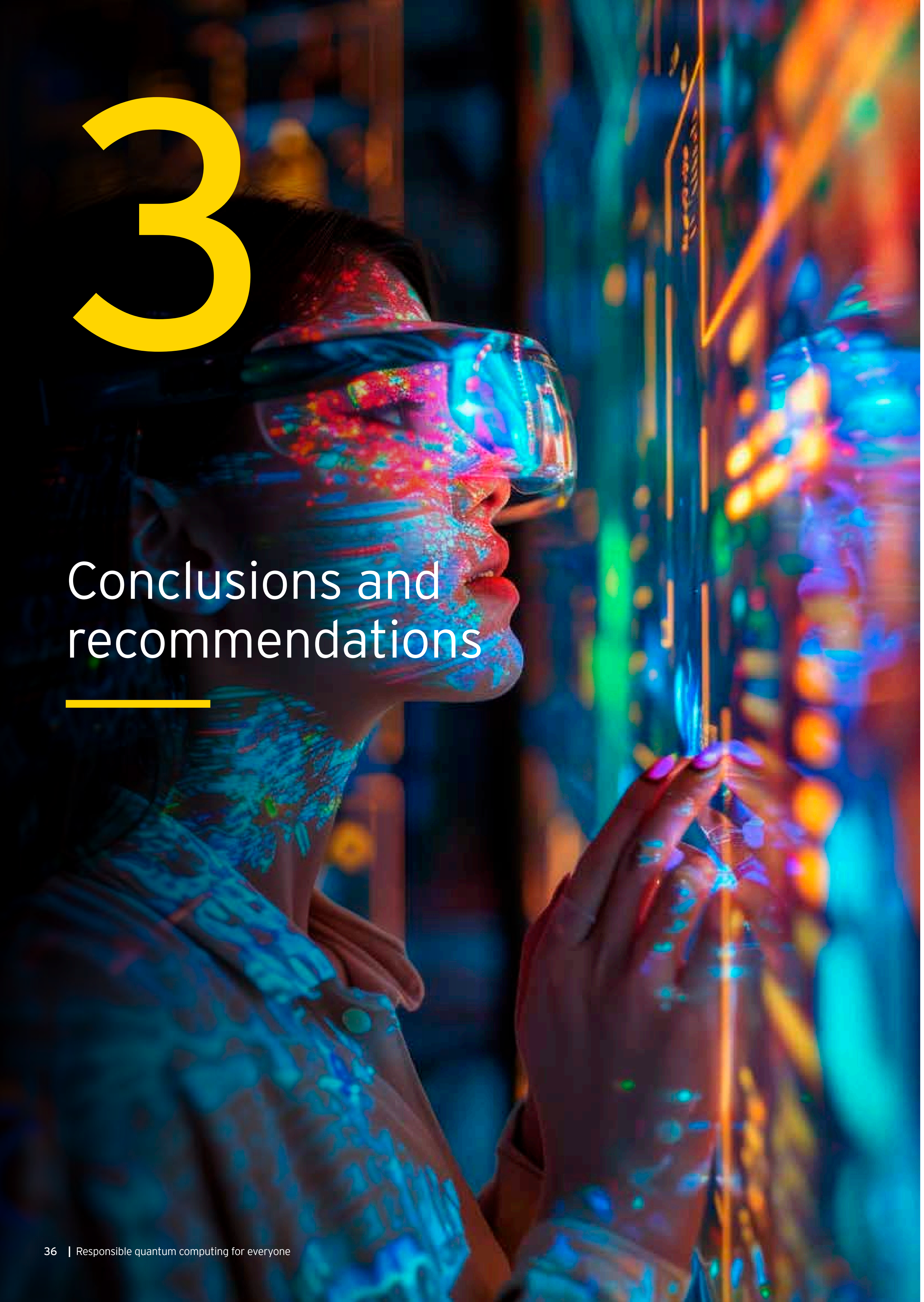


Figure 32: Summary Results - Impact breakdown per scenario

Timescales

Regarding timescales, is notable that experts indicated that most scenarios would be realised in the medium-term, if at all. The exception to this rule were Scenarios 3 and 8 – Quantum Divide and Environmental Benefit – which received a relatively higher proportion of respondents indicating a longer realisation timeline.

Figure 33: Expected timescales for the scenarios, all respondents – percentages



3

Conclusions and recommendations

This expert survey demonstrates that despite the excitement around the development of an entirely novel computational technique and its associated affordances, there is a desire to 'right-size' expectations within expert communities.

This accords with a RI approach, which recognises that although there are some who seek to generate hype around the possibilities of quantum computation, the likely long-term nature of the engineering challenges being faced means that the development of commercial quantum computing is a marathon, not a sprint. It is critical, therefore, to manage any inflated promises and expectations, and adopt a realistic viewpoint regarding the development of the field, particularly regarding capabilities and timelines.

Despite this long-term outlook, however, our participants foresaw both threats and opportunities in the decisions that will be taken in the coming months and years to shape the development of quantum computing and the quantum ecosystem. There are perceptible patterns of development that do not prioritise equity and accessibility to these powerful tools, and the impacts of these patterns are seen to be high. While in wider discourses there are some who suggest that a quantum computing 'race' is a positive method for driving rapid progress, and that competition can be highly productive in terms of technological development, it is one contention of this report that either deliberately adopting or sleepwalking into such a method can have unpredictable side-effects and potentially damaging outcomes for business, people, and the planet. There are many possible positive benefits for quantum computing, but **those involved in the development of the sector at every level should make efforts to form multi-lateral collaborations that can both advance the technology and include the widest possible range of stakeholders**. This is not only for ethical reasons, such as broad-based democratic accountability and inclusion, but also for pragmatic 'capacity' reasons – creating a competitive marketplace for limited resources, highly skilled engineers, and expert developers produces challenges of its own, as those nations and companies with the deepest pockets can sweep the board.

There is also seen to be an opportunity here for governments to take an active role, not by appearing to pick technological 'winners' in a wide-ranging and still-speculative field, but by working collaboratively and recognising that a rising tide can float all boats. The analogy with the space 'race' compared to the development of the International Space Station may provide **new ways to envision the future of this nascent technology**, and to shape its pathways while they are still yet malleable.

Although the last few years have seen accelerated development in the field, speed is not necessarily the only desirable metric – a lesson that is actively being learned with other emerging technologies, including AI. The world has an opportunity to build a powerful, enabling technology in a manner that can benefit the many, not just the few. However, to do so, there is a need to change narratives around a quantum 'race', bring new voices to the table, and shape the future of quantum computing responsibly.

4

About the research

This research was part of the work of the Responsible Quantum Computing Communications (ResQCCom) project, a collaboration between the UKRI-funded Quantum Computing and Simulation Hub, the Responsible Technology Institute, and EY. The project had three strands:

- Collaborating with industry to gain insights into any governance gaps that might exist as companies grow into commercialisation spaces where there is no current scheme of governance, standards, or regulation.
- Engaging with policy and policymakers to bring together different views and teams working around quantum computing.
- Developing public communications tools to open conversations around quantum technologies and the possibilities they hold, as well as being open to concerns that might be raised by citizens.

The project's closing piece of work, an expert survey, sought to gather background and informed opinion on questions around governance, attitudes to technology in general, understanding of quantum computing in particular, as well as sentiment regarding possible future scenarios for the technology. The full set of questions used in the expert survey can be found in Appendix A.

Methodology

The survey adopted a mixed-methods approach, with a blend of quantitative and qualitative questions to benefit from the expert knowledge of the participants. As an example, a Likert scale (Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree) was used to provide responses to a statement such as "The government should be involved in funding the development of new technologies". Subsequently, however, respondents were also invited to comment further on the statement if they should wish to. These responses have been used to add richness and depth to the quantitative data in the earlier section on Findings.

Demographics

These questions were indicative rather than required, and not all respondents answered all of them – however, over 84% answered every question.

- The survey received 38 expert responses. These broke down as:
  - Industry: 14
  - Academia: 19
  - Other (Consulting; other professional services; software development): 5
- Respondents were overwhelmingly (77% of those who answered this question) male, which may be indicative of the demographics of academic physics and the quantum computing sector in general – however the survey was not sent to a 'representative' population sample so no firm conclusions can be drawn from this.
- Most respondents who provided information about their location were UK-based, but other respondents came from India, USA, Canada, Australia, and other European countries.
- 61% of those who answered the question about their educational level had a doctoral degree.

5

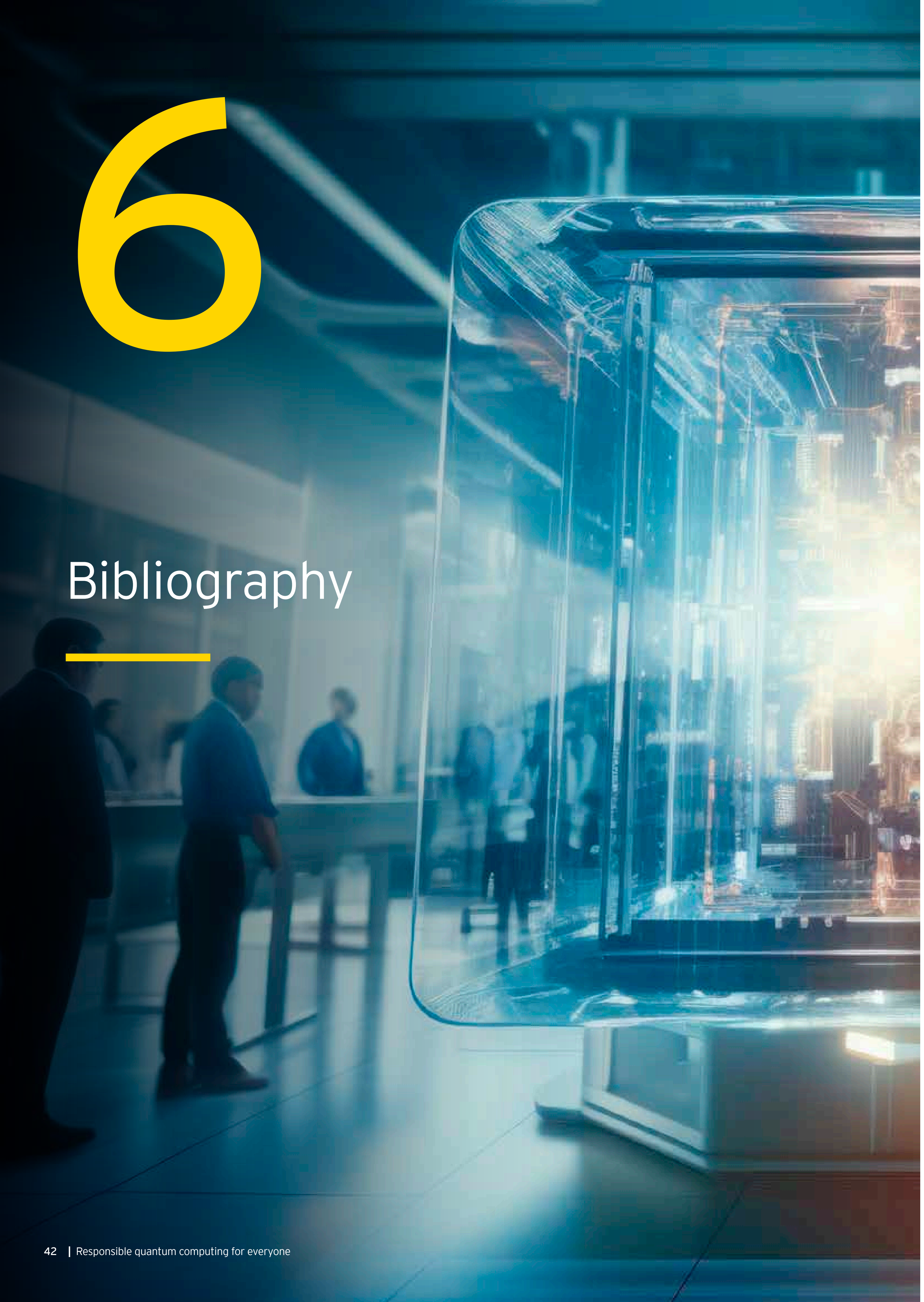
Glossary

Responsible innovation (RI) has been defined in various ways, but one of the most widely-used definitions is from the RRI (Responsible Research and Innovation) Tools project[36] "RRI is a way to do research that takes a long-term perspective on the type of world in which we want to live … [It means] involving society in science and innovation 'very upstream' in the processes of R&I to align its outcomes with the values of society." Another framing comes from Stilgoe et al (2013)[37], "Responsible innovation means taking care of the future through collective stewardship of science and innovation in the present." Accordingly, RI stresses both the relationship of present developments to future consequences, and the need to recognise the duty of care owed by innovators to society.

Quantum computers are devices that utilise the properties of quantum mechanics to perform computational tasks. This is projected to make them potentially much faster for certain tasks, but also to have different capabilities than classical computers: "While a conventional computer uses bits, with values of zero or one, a quantum computer uses qubits. Each qubit can be zero, one, or a combination of both. In other words, it can be put into a quantum superposition: a simultaneous combination that could be, say, 75% zero and 25% one."[38] (The quantum age: technological opportunities. Government Office for Science 2016). This makes possible new kinds of algorithms, offering the possibility to solve specific problems that are, as far as is known, intractable for non-quantum computers.

Artificial intelligence (AI) is a field of research and practice which combines computer science techniques and robust datasets, to enable problem-solving. It also encompasses sub-fields of machine learning and deep learning, which are frequently mentioned in conjunction with AI .

Semiconductors are materials with electrical conductivity properties that fall between highly conductive and non-conductive materials. Their conductivity may be altered through various means, and they can thus be used for a wide variety of applications, including products as varied as smartphones, digital cameras, televisions, washing machines, refrigerators, and LED bulbs.



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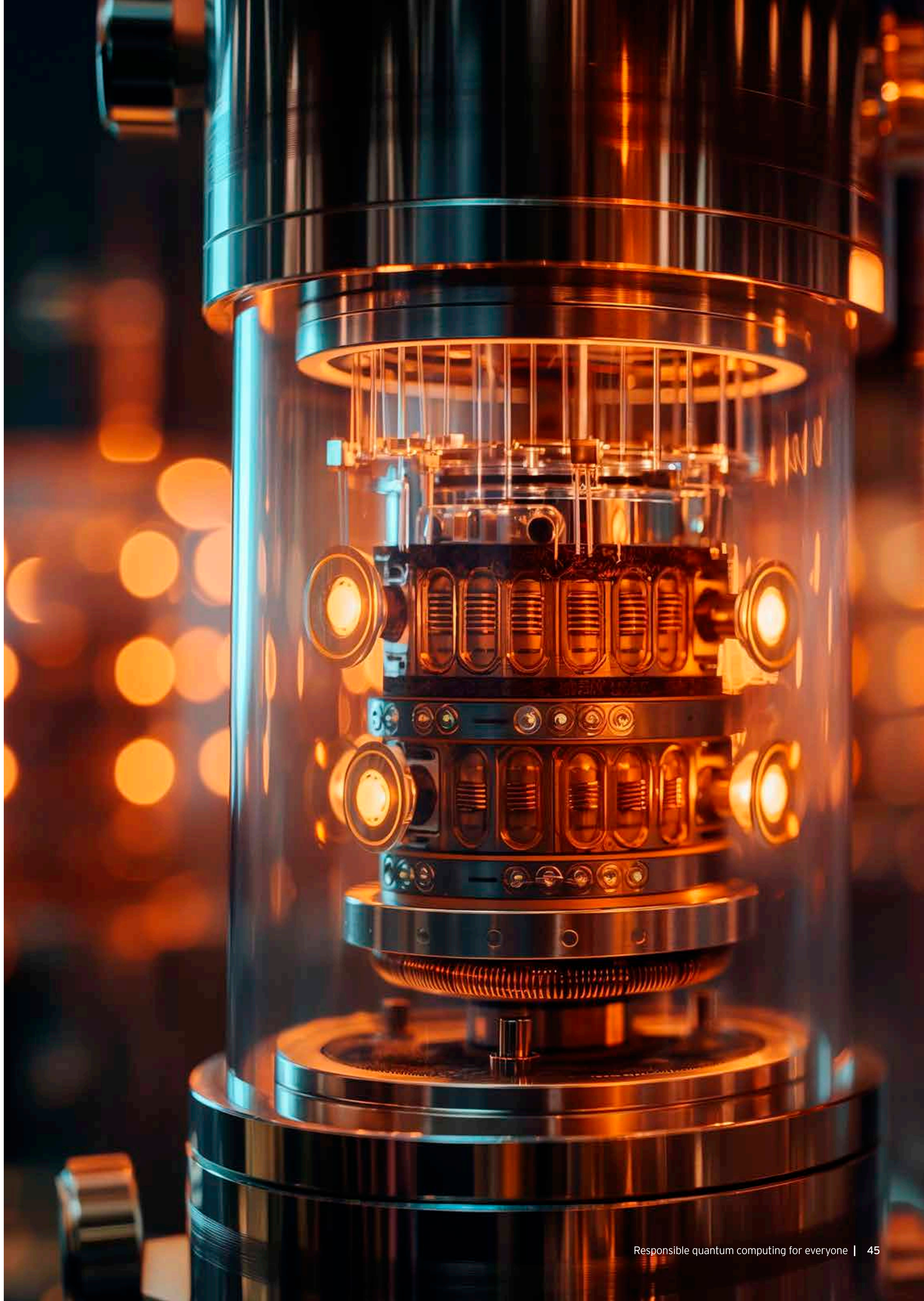

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Appendix A: survey questions

1. Knowledge about new technologies in general

These technologies have been highlighted as priorities by the UK government. Please select your level of knowledge about the technologies and technology groups listed below.

Technology	I am very knowledgeable about this	I know something about this	I know a little about this	I have not heard of this
Semiconductors				
Artificial intelligence				
Quantum technologies				
Engineering biology				
Future telecoms				

2. How much do you agree/disagree with the following statements about new technologies?

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
I am very interested in the development of new technologies					
New technologies should be driven by a response to societal need					
It is important to involve many different groups in the development of novel technologies					
I would be interested in participating in wider discourse around the development of novel technologies					
Science should be advanced without regard to potential application areas					
Claims for new technologies and their impacts portrayed in popular science are often overblown					
It is important to consider how new technologies may impact society					
It's important to get people excited about new technologies					
Private companies are the most suited to developing new technologies					
Science and innovation should be left to developers and researchers					
The rush to develop new technologies may outpace our understanding of the potential risks and societal implications					
Thinking ahead about the effects of novel technologies may help us to prepare for them					

3. Role of government

Please comment further on any of these statements if you would like to

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
The government should be involved in funding the development of new technologies					
Policymakers should be well-informed about the details of new technologies					
Some technologies are too important to be left in the hands of private firms					
It is important to build in governance mechanisms around new technologies from the earliest possible point					
Regulation of new technologies is necessary to ensure public benefit and protection					

4. Knowledge about quantum

	I am very knowledgeable about this	I know something about this	I know a little about this	I have not heard of this
Quantum mechanics is a branch of physics that describes the properties of atoms and subatomic particles. The physical behaviour of these particles is very different from our ordinary experience and can seem quite strange.				
Quantum computing exploits these quantum mechanical properties to build a form of computer that can perform some activities much faster than is possible on conventional computers.				
A large enough quantum computer could break some existing encryption which keeps users safe in areas such as in e-banking, e-shopping, or secure private messaging.				
Building a large quantum computer is very challenging, partly because quantum computers are error-prone. There is a lot of progress but this may take some years or decades.				
Industries including pharmaceuticals, chemicals, and finance are already exploring potential uses for quantum computing.				
Some large companies and universities are developing quantum computers that can be accessed over the cloud.				

5. Scenarios

Please select a probability of each scenario coming to pass (low, medium, high), an impact-level on society (low, medium, high), and a possible timescale (near-term, medium-term, long-term).

Please comment further on any of these scenarios if you would like to.

Scenario 1: Quantum Monopoly
One company or a small group of companies achieve quantum advantage (demonstrable superiority of a quantum computational device over a classical one) and subsequently monopolise the market for quantum computing. This results in an unequal distribution of benefits and risks associated with quantum computing, and leads to technology lock-in, where users are forced to use a single technology provider. Broader innovation and competition in the ecosystem are stifled as a result.

Scenario 2: Quantum Security
Quantum-based security provides 100% security in transmission. This underpins social and cultural change as data can now be completely secured

Scenario 3: Quantum Divide
Global division emerges as only a few countries or regions have access to quantum computing. Areas without access are left behind as businesses and research institutions that do have access take advantage of faster and more efficient computing power in applicable areas. This has geopolitical implications, as well as raising concerns regarding uneven development and innovation capacity.

Scenario 4: Quantum Decryption
The development of quantum computing outpaces the development of tools and regulations that can manage associated cybersecurity risks. This could result in the potential to break encryption currently used to secure financial transactions and/or sensitive government information.

Scenario 5: Quantum Collaboration
Companies and research institutions collaborate to advance quantum computing technology in a way that is open, transparent, and inclusive. This results in significant progress made in quantum computing that is shared equitably across different domains and leads to greater societal and environmental benefits.

Scenario 6: Quantum Resource Requirements
Quantum computing results in a significant increase in energy consumption and resource extraction. This increased energy consumption and carbon footprint exacerbates climate change impacts, leading to significant environmental, geopolitical, and social implications.

Scenario 7: International Quantum Co-operation
Governments develop multi-lateral agreements that establish frameworks for co-operating across borders. This progresses the field of quantum computing, reduces geopolitical frictions, and leads to the creation of international norms and standards to govern the development and use of quantum computing technology.

Scenario 8: Environmental Quantum Benefit
Hardware platforms for quantum computing are optimised to use energy far more efficiently than comparable high-performance computers. Quantum computation is used to accelerate discovery of possible mitigations to climate change through materials discovery and network optimisation.

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