ECONOMIST IMPACT

Overhyped or underestimated?

Preparing for a quantum future

Supported by

Technology Innovation Institute

Contents

About this report

Quantum Horizons is a research programme conducted by Economist Impact, with support from the Technology Innovation Institute (TII). The report explores the actions that policymakers and corporate ledaers could take to tap the opportunities afforded by quantum computing and manage associated risks. This report is the first part of the programme and focuses on the state of quantum computing, drawing on primary data collected from interviews with quantum specialists (drawn from a mix of industry, science and academia) as well as secondary research. The second part is a scenarios forecasting exercise, which models the impact of quantum computing capabilities on the global economy according to three potential scenarios.

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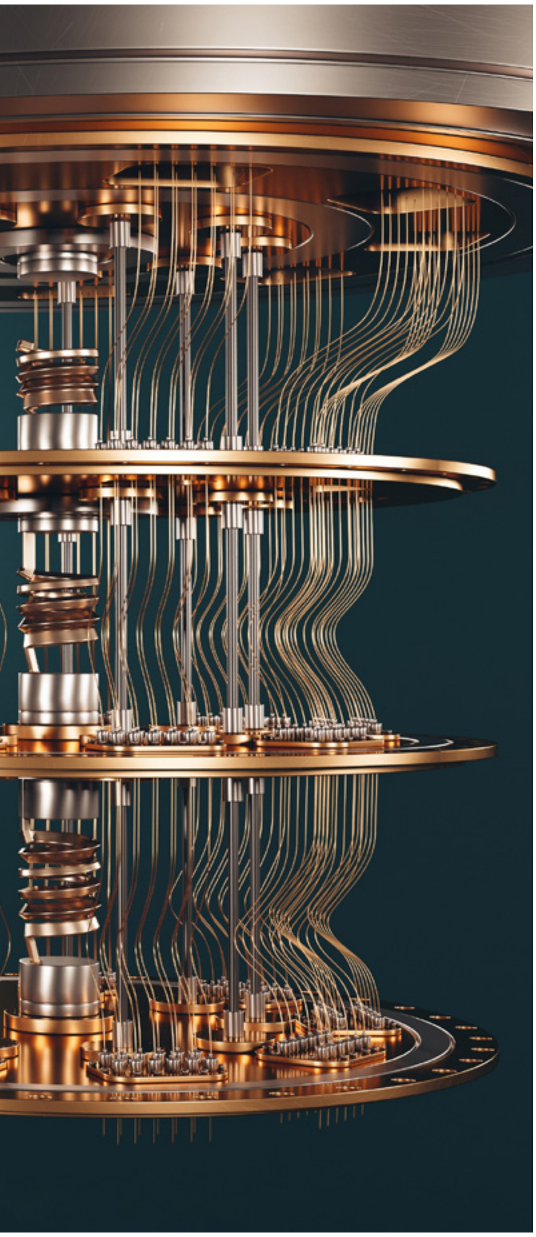
Executive summary



Quantum computing is a nascent technology but shows disruptive potential. Amid both hype and scepticism surrounding the technology's promise, it is hard to discern the true opportunities and risks of quantum computing's advancement. What are quantum computers capable of, and when will practical applications emerge? Which industries are set to benefit? How can business leaders ensure their organisations are quantum-ready? How can policymakers ensure that economies and society can reap the benefits of quantum computing, and navigate accompanying risks? This report draws on a literature review and expert interviews to answer these questions, and suggests some early actions that leaders could take to prepare for the quantum revolution.

Many optimists proclaim that quantum computing will reach maturity by the end of the decade. But other experts urge caution and suggest that it is too early to say when, if ever, quantum computing will bear fruit. However, given the promise that it holds, quantum computing is a field rife with experimentation, innovation and investment among startups, established technology firms, investors and pioneering businesses.

The United States, China and the EU have led the rapid development of quantum computing. While some other countries (Canada and the UK, for example) have also created policy frameworks and allocated funding to promote research and development in quantum computing, China, the EU and the US lead in published research and patents issued, owing to established advanced technology ecosystems and public funding.

As of 2022, most quantum computing applications draw on four key computational capabilities: factorisation, simulation, linear algebra and optimisation. Academic and industry researchers believe that simulation algorithms could be the first "killer app" where quantum computers provide substantial improvements compared to classical computers. The ability to model quantum systems is an important goal for governments and businesses, given their vast potential in almost every industry, including chemistry, material science and clean energy.

Corporate leaders should determine their risk appetite and allocate resources to quantum computing accordingly. Even if businesses don't take decisions to start full-fledged quantum computing operations, they could take some steps to ensure that they are not left behind. They could track developments in quantum computing relevant to their industry, proactively look out for opportunities to collaborate and experiment alongside researchers and startups, and work with specialists to parse hype from reality.

Policymakers must develop a clear vision of how they plan to develop a competitive ecosystem in quantum computing and underpin the vision with a roadmap and key indicators along the way. Even if the technology does not fulfil its potential, it would have some "no-regret" outcomes: a culture of innovation and ideas, a more technology–savvy government, and a highly skilled and versatile science, technology, engineering and mathematics (STEM) workforce.

Although quantum computing promises a wealth of possibilities, it comes with pitfalls, including exacerbated technology inequity, cybersecurity risk and potential geopolitical misuse. Some countries have taken the lead, yet others could still catch up by entering the value chain at points with lower barriers to entry and burnishing the quality of domestic STEM education. Another potential pitfall on the horizon is the use of powerful quantum computers to break current encryption protocols and steal sensitive geopolitical and business information. The technology to secure networks from quantum attacks currently exists. Corporate and IT security leaders must track the development of these cryptographic standards. They should react with agility and decisiveness once these standards are established to revamp their security infrastructure.

[1] Science, technology, engineering and mathematics

Introduction

Hype around the promise and perils of quantum computing technology is reaching fever pitch. Researchers and developers, including academic research labs, startups and big tech, proclaim ever more significant breakthroughs in fast, advanced computing, and increasingly stable technology. Quantum's boosters evangelise the potential for this new era of computing to cure disease and address climate change, while pessimists warn of the next tech bubble. The truth—not unlike quantum superposition—sits somewhere between the two extremes.

A classical computer manipulates a bit (the smallest unit of data in computing) between the binary 0 and 1 states to perform calculations. A quantum computer represents information as a series of bits called quantum bits or qubits. Unlike a classical bit, which is able to represent only one of two possible values (0 or 1), a quantum computer is able to manipulate all possible states of a qubit between 0 and 1—thus delivering exponentially more power than a classical computer with the same number of bits. Ultimately, this property allows quantum computers to perform calculations much faster than a classical computer with the same amount of resources.[1]

Because of such immense power, quantum computing has high potential to solve previously intractable computational problems with hypothesised implications across sectors including finance, energy, climate change and cybersecurity. However, designing and scaling quantum computers with enough computational power is a difficult physics and engineering challenge.[2] Researchers have been able to design the first quantum computers only in the past few years and the field is very much in its infancy. Although quantum advantage[3] is yet to be achieved , players in the field are optimistic about the technology.[4]

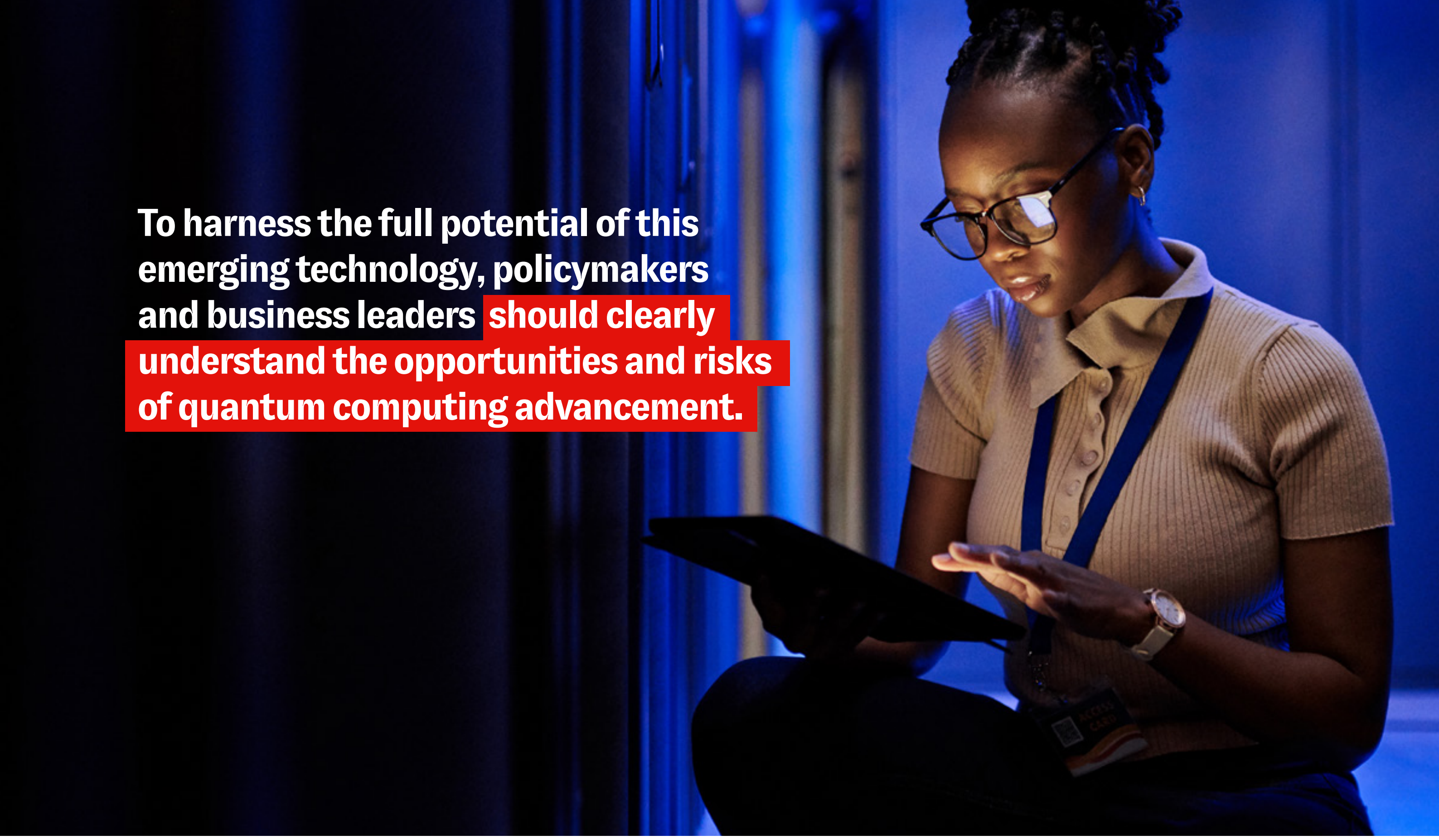
Whether the potential is fulfilled, remains to be seen. Meanwhile, policymakers and corporate leaders could still play a role in nurturing the budding ecosystem and preparing for a

1 The number of qubits is not the only criterion that measures the ability of a quantum computer. Along with the number of qubits (scale), the quality and the speed of the computer are also defining characteristics. For more details, refer to: Gambetta, Jay, et al. "Driving Quantum Performance: More Qubits, Higher Quantum Volume, and Now a Proper Measure of Speed." *IBM Research Blog*, 1 Nov. 2021, www.research.ibm.com/blog/circuit-layer-operations-per-second#fn-2.

2 Examples of engineering challenges include preparing adequate refrigeration, wiring and packaging that is able to perform in extreme environments. Examples of physics-based challenges are error-correcting for signals other than 0 and 1, inputting large datasets, and the ability to replicate quantum calculations. For a fuller discussion, see: *Quantum Computing: Progress and Prospects.* National Academies of Sciences, Engineering, and Medicine 2019.

3 Quantum advantage is defined as the ability of a quantum computer to perform a specific computational task that a classical computer would take an unreasonably long time to compute. For a more technical definition refer to: Krupansky, Jack. "Quantum Computing Glossary — Part 4 — Q." *Medium*, 20 July 2018, www.jackkrupansky.medium.com/quantum-computing-glossary-part-4-q-d06f1dc55a9d.

4 Google and a Chinese research group have each independently claimed to have achieved quantum supremacy in solving some theoretical problems. These claims have been disputed by their peers and there is no consensus on whether even theoretical quantum supremacy has been achieved yet. Quantum advantage for any practical applications has not yet been achieved. For more information, refer to Simonite, Tom. "China Stakes Its Claim to Quantum Supremacy." *Wired*, 3 Dec. 2020, www.wired.com/story/china-stakes-claim-quantum-supremacy.



To harness the full potential of this emerging technology, policymakers and business leaders should clearly understand the opportunities and risks of quantum computing advancement.

potential widespread disruption across the economy. To harness the full potential of this emerging technology, policymakers and business leaders should clearly understand the opportunities and risks of quantum computing advancement. Which use cases are better suited for quantum computing than classical computers? When will quantum computers become practically useful? Which industries will benefit the most from quantum computing? How can business leaders make their organisation quantum ready? How can policymakers ensure that their societies reap the benefits of quantum computing and not get left behind? This report explores some of these questions and looks beyond them.

The state of quantum computing

Advances in quantum computing

Most optimistic projections estimate that quantum computers could become fault-tolerant[5] by the end of the decade and start demonstrating quantum advantage in various industries.

Although these projections are certainly optimistic, the advent of quantum computers is not inevitable. There are significant physics and engineering challenges involved in building large-scale quantum computers and there is no guarantee that these challenges could be overcome at all, let alone in the next few years.

Given the scale of the task ahead, many industry players have focused on developing so-called noisy intermediate-scale quantum (NISQ) computers, essentially a stepping stone in quantum computing technology, in the near future. These computers are far from the North Star of building fault-tolerant universal quantum computers but may possess sufficiently large numbers of qubits, of sufficiently high quality, to be able to outperform classical computers for certain specific tasks. Creating practical applications for NISQ computers is a relatively new area of research and will require work on new types of quantum algorithms. Demonstrating quantum advantage via NISQ machines is key to maintaining the momentum of the industry and keeping investors and the industry interested. Many companies have thus adopted a two-pronged approach to quantum computing—they work on NISQ computers and algorithms to demonstrate quantum speed-ups in the short term while maintaining long-term focus on building fault-tolerant universal quantum computers.

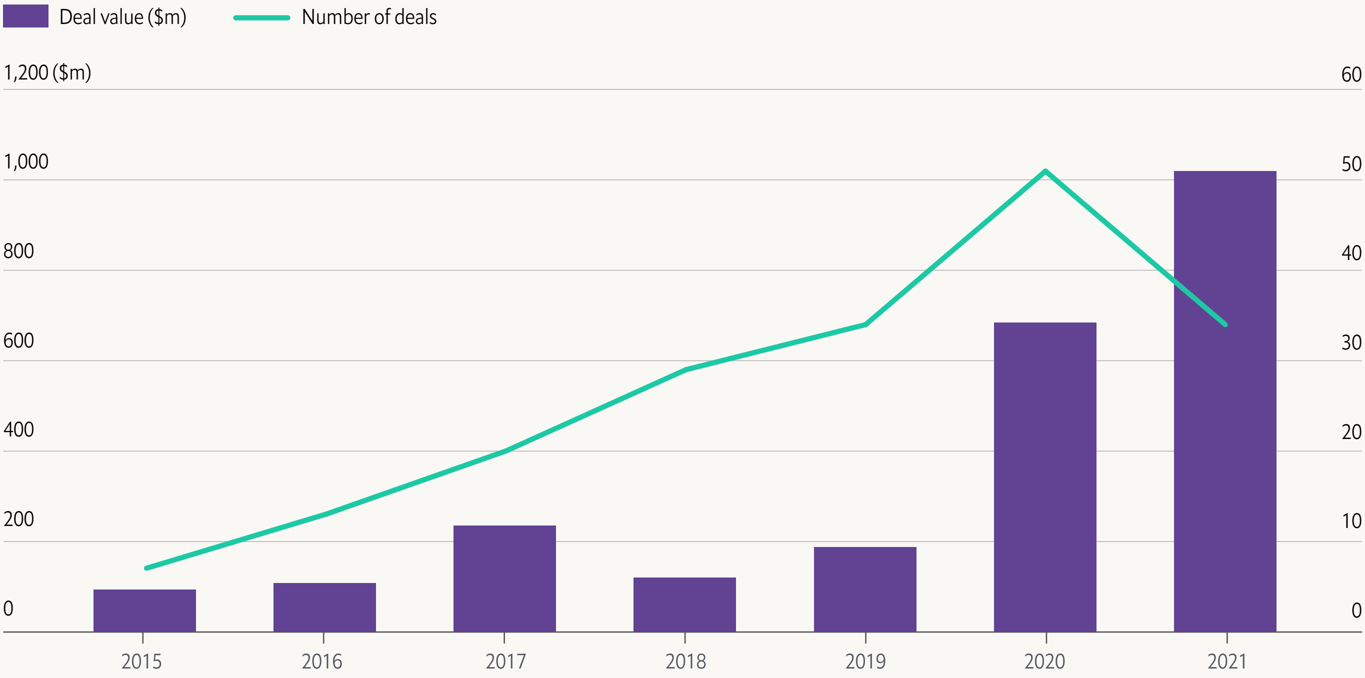
Distribution of quantum capability

Given the promise it holds, quantum computing is a hotbed of activity among startups, established technology firms, investors and pioneering businesses.

Large technology companies such as Google, IBM, Microsoft, Intel, Honeywell and Amazon are racing to create larger and faster quantum computers and establish their dominance in an emerging ecosystem. Independent companies like Rigetti, D-Wave, IonQ, Pasqal, Alice & Bob and QuantWare, among others, are also employing a variety of concepts to create stable quantum computers and achieve quantum advantage.

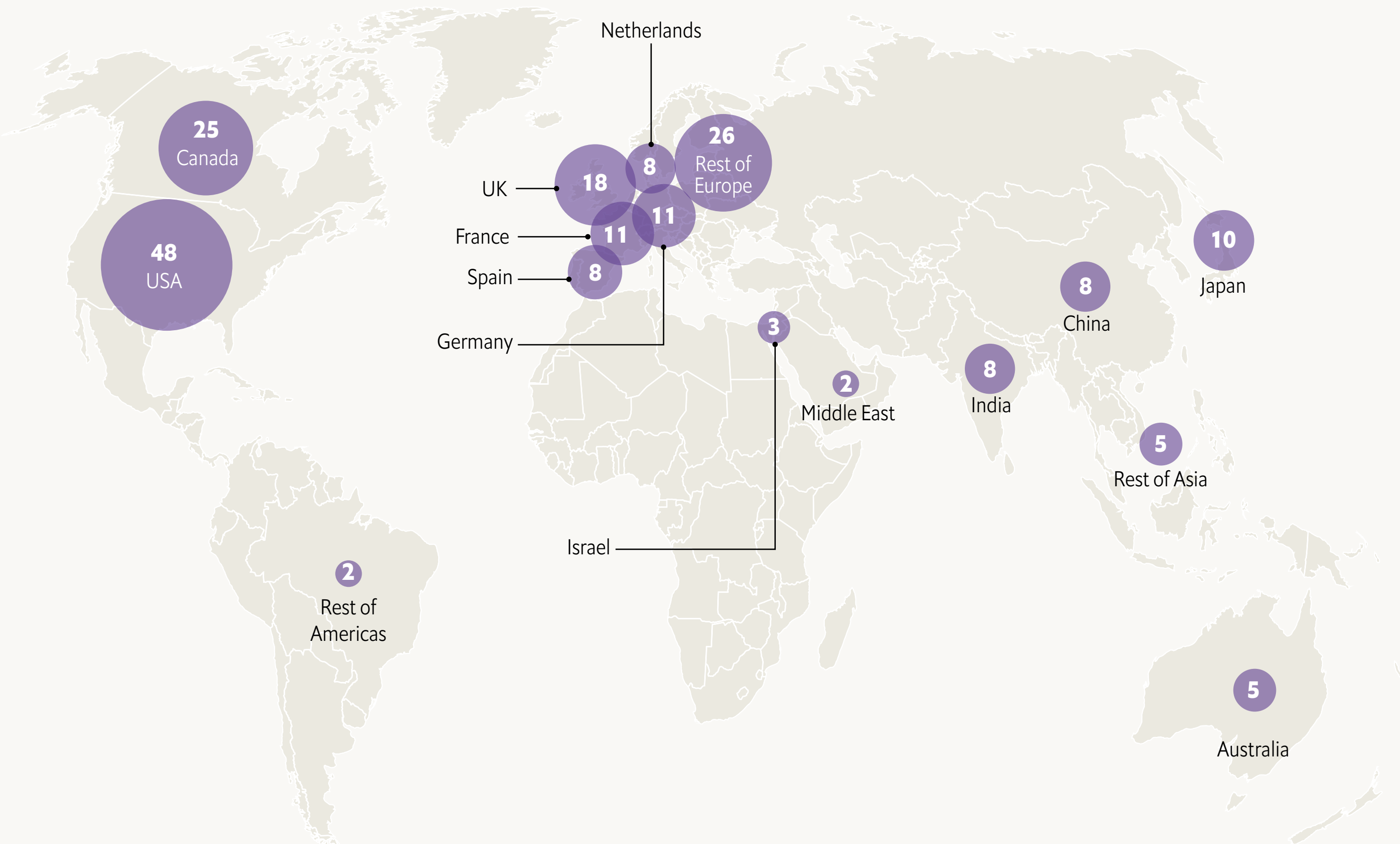
[5] Fault tolerance is the ability of a computer to detect errors or component failures and correct or mitigate them so that normal operation can continue as if no error had occurred. Definition from: Krupansky, Jack. "Quantum Computing Glossary — Part 2 — D-G." *Medium*, 20 July 2018, www.jackkrupansky.medium.com/quantum-computing-glossary-part-2-d-g-c94f54565ce4.65ce4

FIGURE 1. VC funding in quantum computing



Source: Temkin, Marina. "VCs Make Record Bets on Quantum Computing." *PitchBook*, 13 Sept. 2021, www.pitchbook.com/news/articles/quantum-computing-venture-capital-funding.

FIGURE 2. Number of quantum computing startups by country/region



Source: Finke, Doug. "Private/Startup Companies." *Quantum Computing Report*, 2017, www.quantumcomputingreport.com/privatestartup.

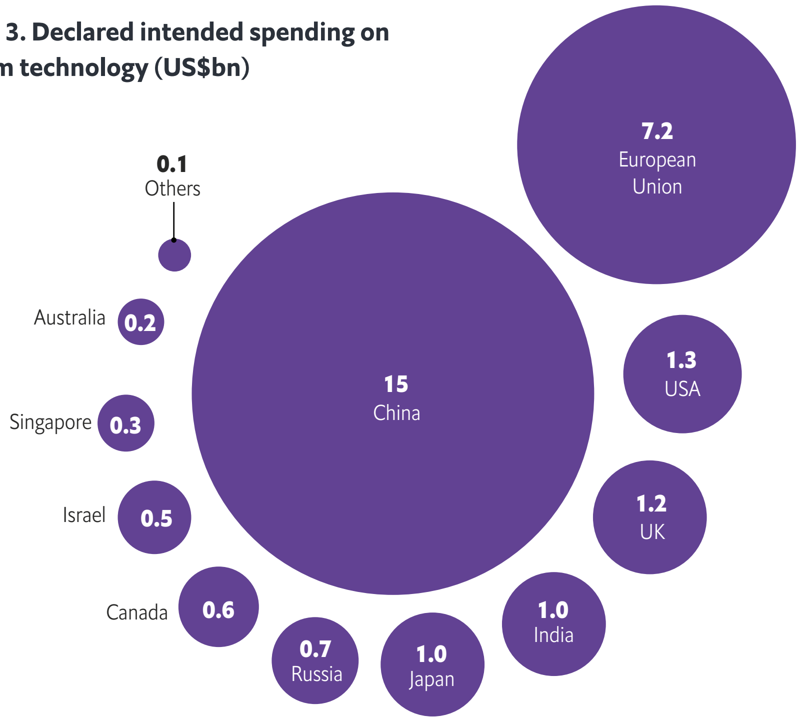
Aside from these large firms, there were about 200 active quantum computing startups worldwide in 2021. In the same year, venture capital firms invested more than a billion dollars into quantum computing. A plurality of startups are based in the US with Canada, the EU and the UK also witnessing vibrant startup activity. There is limited transparency on startup activity in China, but it is likely to be comparable, if not more advanced, than what is happening in other leading regions.

In the next half-decade, industry insiders expect a wave of consolidation as the industry matures, leaving only about 15 companies at the top that are either vertically integrated across software and hardware development or have a competitive advantage in a niche. "These [large] players will buy up the smaller pieces to fill in the gaps in their supply chain or value chain or technology roadmap," says Benno Broer, chief commercial officer at Pasqal.

Although quantum computing is still in its infancy, some countries are already emerging as leaders while others are at the risk of lagging behind. Some governments, such as those in China and the EU, are pouring resources into developing quantum capabilities. The US has allocated comparatively less public funding but has been able to maintain technological leadership given the scale and quality of activity in the private sector and in academia.

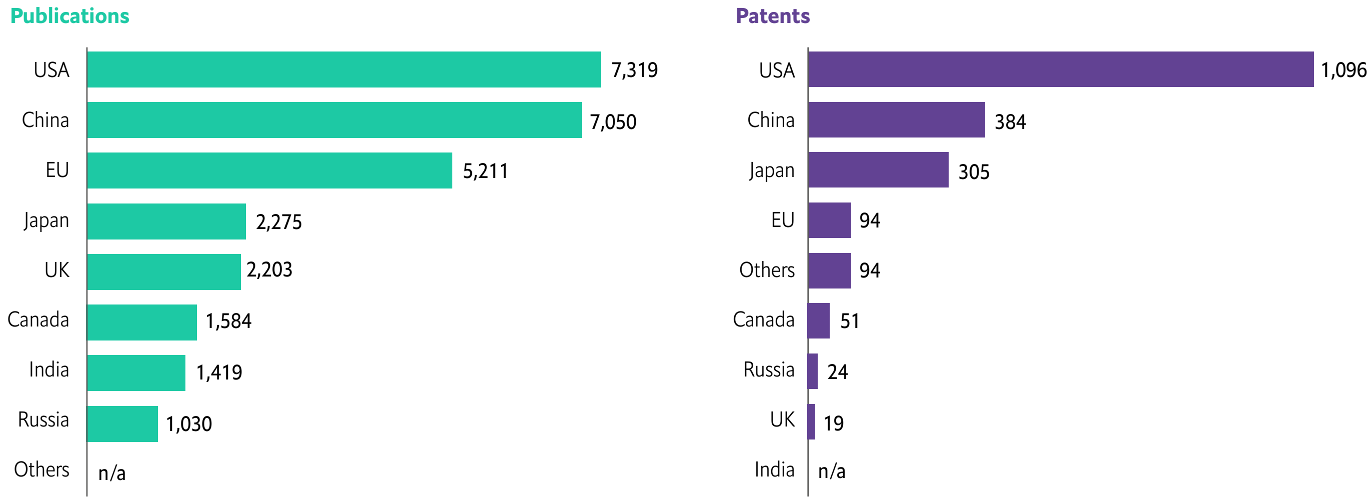
There are several quantum tech clusters in North America, including the San Francisco Bay Area, Chicago, the Toronto-Waterloo corridor and Vancouver. Europe is also witnessing the emergence of clusters in Paris, TU Delft-TNO in the Netherlands and in Munich, while the UK has several prominent startup spin-outs in the university towns of Cambridge and Oxford. Outside of these clusters, activity is high in academic institutions such as the University of

FIGURE 3. Declared intended spending on quantum technology (US$bn)



Source: Kung, Johnny, and Fancy, Muriam. *A Quantum Revolution: Report on Global Policies for Quantum Technology*. CIFAR, April 2021, www.cifar.ca/wp-content/uploads/2021/05/QuantumReport-EN-May2021.pdf.

FIGURE 4. Estimated technological advances in terms of research publications and patents filed



Sources: (1) Mason, Elliott. "Trends in Quantum Computing Patents." *QED-C*, 24 May 2021, quantumconsortium.org/blog/trends-in-quantum-computing-patents. (2) Parker, Edward, et al. *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*. RAND Corporation, 2022, www.rand.org/pubs/research_reports/RRA869-1.html.

$1.5trn

Use of quantum computing in the finance industry could boost its output by up to US$1.5trn

$1.1trn

Use of quantum computing in the high-tech industry could boost its output by up to US$1.1trn

Maryland in the US, the University of New South Wales in Australia, Weizmann Institute of Science in Israel and the National University of Singapore. Japan, South Korea and India have also dedicated public funds to research in quantum computing.

Both public spending and startup activity have yielded technological progress. China and the US lead other countries in both the number of research publications and patents filed in quantum computing.

Despite its opacity around the quality of technological advances, experts believe that China is only slightly behind the US and Europe, if not at technological parity, in quantum technology.

Applications of quantum computing

Most algorithms for quantum computing (but not all[6]) fall into four broad classes: factorisation, simulation, linear algebra and optimisation. While quantum computers do not currently exhibit any quantum advantage over the most powerful classical computers, they may be able to solve some previously intractable, critical industry problems as they get more powerful.

Factorisation of large numbers is a key concept underpinning current **digital cryptography** methods. In 1994 Peter Shor, an American mathematician, devised Shor's algorithm, which, if run on a sufficiently powerful quantum computer, could factorise these large numbers efficiently. The implication is that if this algorithm is deployed on a perfect quantum computer, it would be able to break RSA—currently the most widespread encryption technology in use. The implications of quantum computing for cryptography and potential mitigation approaches are discussed in Section 3.

Academic and industry researchers believe that **simulation** algorithms could be the first "killer app" where quantum computers provide higher speed-ups compared to classical computers. Quantum computers are well suited to simulate molecules because they directly exploit the quantum properties of real particles. Simulation at this level is beyond the scope of classical computers. Modelling quantum systems is a critical process in many industries such as chemistry, material science, fertilisers, clean energy, condensed matter, nuclear physics and high-energy physics. Quantum players hope

[7] For example, Monte Carlo simulation algorithms, which could be useful for developing applications in the finance industry, do not fall into any of these four categories.

that simulation will lead to the development of a wave of revolutionary drug molecules, materials and high-efficiency batteries. Indeed, industry insiders expect that the first instances of quantum advantages will be demonstrated in industries such as pharmaceuticals and material science, where molecule simulation is at the heart of research and development (R&D). According to a model created by Economist Impact, in an optimistic scenario, quantum computing could make direct and indirect contributions of US$360bn (~19% increase in output) to the global pharmaceutical industry and US$390bn (~5%) to the global chemical industry in 2035.

Linear algebra is important across a host of computational problems in industries including **artificial intelligence, machine learning**, computer graphics and recommendation algorithms. Powerful enough quantum computers could provide exponential speed-ups and use fewer resources compared to classical computers to solve a system of linear algebra problems. Use of quantum computing to solve these problems in the finance and high-tech industries could boost output in these industries by up to US$1.5trn (~16%) and US$1.1trn (~9%) respectively in 2035 under the optimistic scenario according to Economist Impact's model.

Quantum **optimisation** is a good candidate for a problem that is split between a classical computer and a quantum computer. The optimisation step that progressively approaches a true solution could be performed by a quantum machine while a classical computer could decide whether to perform another iteration. Such optimisation algorithms could find applications in many industries, including chemistry and materials, and in machine-learning algorithms.

The long-term view

We do not know what we do not know. It is conceivable that as the field reaches maturity, researchers will discover more classes of algorithms and apply existing algorithms in ways not foreseen today. Any of the following scenarios could play out. Please refer to Appendix I for more details on the scenarios and the modelling methodology for each scenario.

1

Scenario 1: Quantum computing becomes mainstream (optimistic scenario)

Quantum computing fulfils all promises it portends and more. Quantum computing could be at the stage where the first modern computers were in the 1960s. No one could have foreseen the evolution of personal computers, the internet, the cell phone, and their myriad applications and takeover of all aspects of life today. If, tech firms, academics, investors and businesses are bullish on the technology and plan for this scenario, they should not look at only the next decade or half. Planning for the advent of quantum computing and its corresponding investment window must span the next half-century, not just the next decade.

2

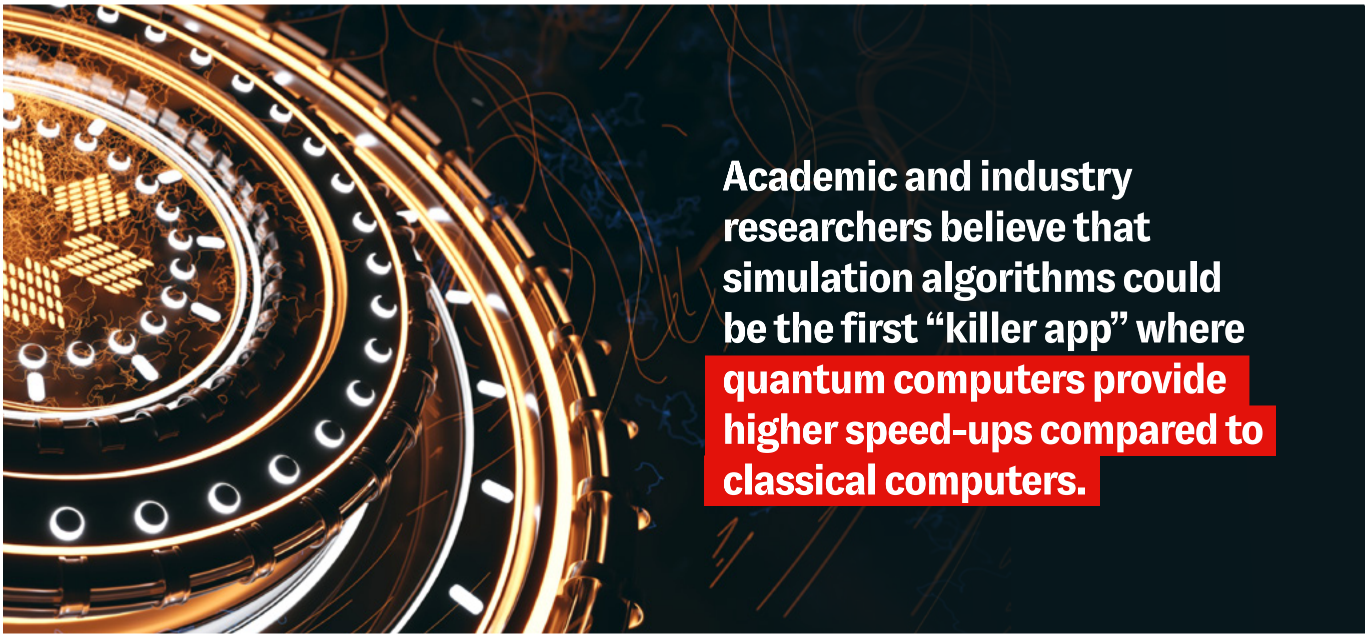
Scenario 2: Quantum computing finds niche industry applications (realistic scenario)

Quantum computing continues to find applications in different niches under a business-as-usual scenario. In this scenario, quantum computing will not be ubiquitous in the global economy like the internet is today. Instead, it will be integrated into key niches across sectors—for example, in determining how robotics is heavily employed in manufacturing but has not found widespread use elsewhere.

3

Scenario 3: Quantum computing enters a "quantum winter" (pessimistic scenario)

Under a slow-uptake scenario, quantum computing may end up in a state similar to technologies like artificial intelligence: perpetually on the cusp of disruption and becoming mainstream but without being able to fulfil its potential, despite massive interest and investment.



> **Academic and industry researchers believe that simulation algorithms could be the first “killer app” where quantum computers provide higher speed-ups compared to classical computers.**

However, if quantum computing does reach maturity, it will have a sizeable impact on the global economy. According to the model, in an optimistic scenario, quantum computing could contribute as much as US$21trn to global GDP in 2035. East Asia (led by China) could see gains of US$5trn (17%), while the Americas (led by the US) could gain US$8trn (30%) and Western Europe could gain US$2.5trn (13%). If businesses and countries want to place a bet on quantum computing, they must actively prepare their workplaces and economies to reap the full benefits of the technology as it reaches fruition. If businesses and countries want to place a bet on quantum computing, they must actively prepare their workplaces and economies to reap the full benefits of the technology as it reaches fruition.

The role of stakeholders in creating a thriving ecosystem

Businesses: how to stay ahead of the curve

As of early 2022 quantum computing is yet to demonstrate any advantage in practical applications. However, many companies are betting that quantum computing could bring disruptive changes to their industries in the near future. The technology promises much and could indeed have a transformative impact on the global economy if it meets its potential. However, it still needs to surmount significant physics and engineering challenges before it goes mainstream.

"This is a classic 'high-risk, high-gain' situation," says Yuval Oreg of the Weizmann Institute of Science, and scientific co-founder of Aspen Quantum Consulting. Companies and investors with a higher risk appetite could invest more resources than their peers in expectation of higher rewards. Many major companies across sectors have already made investments and set up dedicated quantum research teams to explore potential competitive advantages that they could extract from quantum computing.

Although industry insiders and quantum computing specialists are yet to identify any specific quantum advantages, the next five years could be crucial as the field enters the NISQ era and quantum computers begin to outperform classical computers. The crucial race is towards building the first algorithms for NISQ computers that demonstrate clear quantum advantages for important R&D and business processes in industry.

Firms with the resources and vision to invest in the technology could reap handsome benefits but could also see a write-off. Companies should define their own risk appetites and take suitable steps. Any technological breakthroughs are not likely to instantly transform these industries and create clear winners and losers. However, initial advantages for early investors could snowball into an insurmountable technological gap that late entrants may not bridge.

To make their organisations quantum ready, corporate leaders could start by educating themselves about the value of quantum technology in their industries and gradually expand the scope of experimentation with the technology as it matures.

Become quantum-smart

The low-risk action that business leaders could take is to educate themselves on quantum computing and its potential ramifications in their industries. Chief information officers (CIOs), chief technology officers (CTOs) and other equivalent office bearers must pay especially close attention to developments in the field and be able to inform any executive assessments or decisions to take a more active role in adopting quantum computing in their operations.

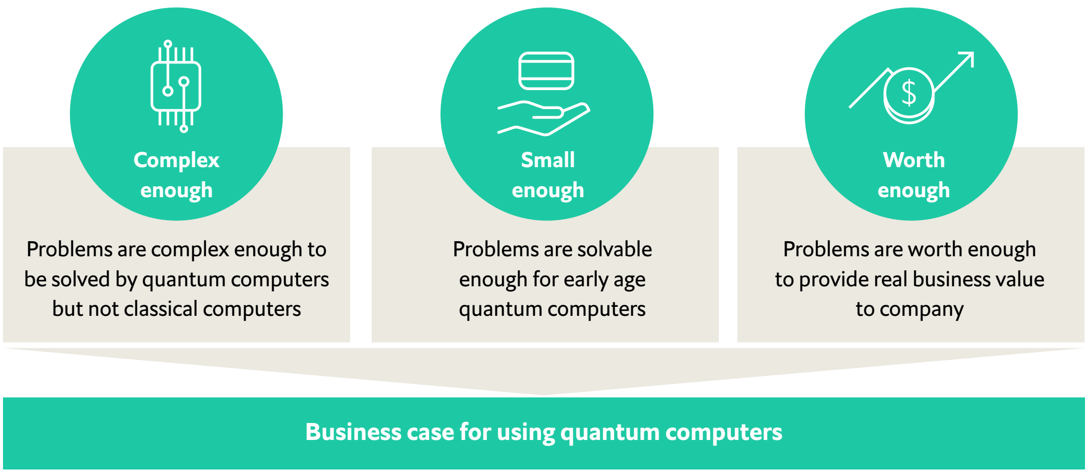
Corporate leaders should examine **where quantum computing is headed** in their sectors. Executives in sectors that hold early promise such as pharmaceuticals, chemicals and automotives should be on the lookout for investment deals that catalyse technological breakthroughs and, therefore, yield some competitive advantage. Executives who are loath to invest scarce resources in an unproven technology could, at the very least, stay abreast of developments in the field via white papers, industry reports, industry-related publications, research papers and other technology publications.

CIOs and CTOs could **open communication channels with quantum scientists** and engineers in universities and technology firms involved in quantum research and development in areas related to their industries. They could schedule regular conversations to stay apprised of developments in the industry and even invite them to their offices to hold conversations with R&D teams.

Tinker with the technology

While quantum computers with enough power are still some years away, companies could **start identifying problems that are beyond the scope of classical computing**. They could explore whether such problems are worthy of quantum computing. Businesses must clearly define which operations in the businesses' workflow are complex enough to be able to benefit from quantum computers, says Robert Marino, chief executive of Qubit Pharmaceuticals. "These operations must be relatively small enough to be computable within the next five to ten years [with limited quantum power], and valuable enough so that companies [devote resources] to the development of the quantum algorithms."

Business case for using quantum computers today



$21trn

Quantum computing may contribute up to US$21trn to the global GDP in 2035 under an optimistic scenario

Partnerships between industry and quantum computing firms are critical to the development of practical applications for industry. Encouraging in-house R&D engineers, mathematicians and scientists to work with startups in the field could create mutually beneficial relationships. "Even in the short-term [before the emergence of universal quantum computers], simply experimenting with the hardware can lead to innovations that can help with the algorithms that you're using", says Francesco Bova of the University of Toronto's Rotman School of Management.

The cost of experimentation is fairly low compared to the material resources that large companies devote to R&D. Firms could allocate a small portion of their research budgets to experimenting with quantum computers. Industry researchers, compared to generalists, would better appreciate the value that quantum computing conceivably provides in the short and long term and may learn how to design quantum algorithms. On the flip side, quantum engineers would better understand the burning questions that researchers are trying to answer in specific industries, and would tailor their software and hardware accordingly.

The EU has made **quantum computers available for public use**.[7] Companies based in Europe could take advantage of this opportunity by encouraging its researchers to leverage these machines. These researchers could work either in-house or with software developers to create algorithms and execute them on publicly available machines and save some hardware costs.

Companies could also organise and **participate in hackathons** organised by the quantum industry and exchange ideas and problems with startups eager to gain experience and explore what is possible. QuantX, an industry networking organisation based in France, organised a four-day hackathon in October 2021 that saw enthusiastic participation and identified some potential areas of collaboration between tens of technology firms (including IBM, Pascal, AWS, Microsoft, Xanadu, Google and QCWare), industry stalwarts (such as EDF, Airbus, L'Oreal and BMW), investors and, MBA students from top-ranked business schools such as Insead.[8]

Manage expectations

Quantum computing technology has not and, as understood today, may yet never come to fruition. If corporate leaders decide to invest in quantum investments, they should be aware that there is a possibility that they may not get an early return on their investment, if at all.

"I think the really tricky part for many people in this space is to make a distinction between what's real—what's already proven, what you have—and the aspirations, what you'd like to have," says Christophe Jurczak, managing partner at quantum-focused investing firm Quantonation. The field of quantum computing is witnessing many entrants who are out to make a quick buck by making unrealistic promises underpinned by dubious technological claims. Before making any investments in quantum computing, executives should **conduct due diligence** to weed out

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[7] The EU and Germany have sponsored the installation of quantum computers manufactured by D-Wave and IBM computers at Forschungszentrum Jülich Supercomputing Centre and Fraunhofer-Gesellschaft respectively. The project envisions the active use of these computers by enterprises, universities and governments.

Refer to: (1) Miller, Joe. "IBM to Build Europe's First Quantum Computer in Germany." *Financial Times*, 13 Mar. 2020, www.ft.com/content/83bfbfd3-0cd6-4f3a-9d98-4996f9295984. (2) "D-Wave and Jülich Launch First In-Region Commercial Quantum Computer for European Access." *Scientific Computing World*, 18 Jan. 2022, www.scientific-computing.com/news/d-wave-and-j-lich-launch-first-region-commercial-quantum-computer-european-access.

[8] For more details on the format and participants, refer to: *BIG Quantum Hackathon by QuantX*. www.quantx.fr/big-quantum-hackathon/

$360bn

Potential direct and indirect contribution of quantum computing to the global pharmaceutical industry in 2035

$390bn

Potential direct and indirect contribution of quantum computing to the global chemical industry in 2035

dubious technology. This research could be outsourced to quantum computing specialists who know how to evaluate advanced technology and are in a position give executives a realistic estimation of the technical soundness and potential benefits touted by startups.

"**In-house teams could be a help, but it's not necessary in the beginning**," says Mr Broer. "If I were [the business], then I would avoid setting up such teams until I've really identified the use cases and have taken first steps on working towards these use cases and making them practical quantum tools." If businesses hire a team now and discover that the machines needed to implement the algorithms will not be available for ten years, then they may end up with a redundant team.

Executives must also ensure that the incentives for any partnerships in quantum computing must align with those of the firm. Businesses should trust quantum researchers enough that they do not "overstate their results, or over-promise what they can bring in the short term," adds Mr Broer.

Policymakers: leading from the front

Contrary to their popular image as tech Luddites, policymakers have fostered some of the greatest innovations of modern times. The primary goal of government is rarely to make a return on its investments; therefore, it can afford to pour resources into unproven technology with little to no concern for achieving profitability. It was governments that invested in the research, development and rollout of game-changing technologies that we take for granted today. The internet, GPS, modern aviation and, more recently, COVID-19 vaccines are just a few modern marvels that were funded by government largesse. When private investors were loath to bet on unproven, untested technology and unwilling to play the long game, governments stepped in.

Quantum computing is at the same place where the internet was in the 1960s when the US government was nurturing the technology in its embryonic stage. Disruptive, revolutionary technologies such as the internet or quantum technology take decades to reach fruition. Bearing this in mind, the primary goal of policymakers in quantum technology's stage of infancy should be to signal their belief in the technology by creating a cohesive, long-term strategy covering funding, workforce development, and multi-sectoral and multidisciplinary collaboration while setting up safeguards against misuse and misappropriation.

Develop a clear vision

Policymakers should develop similar **clear-eyed roadmaps** that specify clear, measurable objectives, a funding plan and an accountability mechanism. For example, the European Commission has recognised the potentially pivotal role that quantum technology could play in the near future and has created a €1bn programme to maintain the EU's role at the forefront of quantum computing R&D. The bedrock of this programme is the European Commission's Strategic Research Agenda, which has laid out a medium-term (three years) and long-term (6-10 years) vision consisting of the goals that it wants to achieve.

To ensure accountability and measure progress, government strategy should establish s**pecific, measurable, achievable, relevant and time-bound (SMART) indicators** for each project and initiative under the wider programme to drive the programme towards its goal. The EC has published the key performance indicators that it will use to benchmark the progression of European efforts in quantum computing against those of its peers.[9]

[9] *Key Performance Indicators for Quantum Technologies in Europe.* Quantum Flagship, 2022, qt.eu//app/uploads/2022/04/KPIs-for-QT-in-Europe.pdf.

> **“Even in the short-term [before the emergence of universal quantum computers], simply experimenting with the hardware can lead to innovations that can help with the algorithms that you’re using.”**
>
> Francesco Bova of University of Toronto’s Rotman School of Management.

Quantum computing is evolving, with new developments taking place frequently. Policymakers and policy advisors should **react rapidly** to notable developments and revisit the strategy every six months or once a year to reorient their vision and modify goals accordingly.

Create a culture of (practical) innovation and ideas

A thriving technology ecosystem should allow frictionless exchange of ideas among academic institutions, research centres, startups, established tech firms, industry end-users and investors. Technology such as quantum computing that requires talent spanning many disciplines is an ideal breeding ground for the transmission and exchange of ideas.

For a technological cluster to have substantial socioeconomic impact—every policymaker’s ultimate goal—it must create strong linkages between all players and promote the development of a coherent set of interrelated strengths that over time transform into deep-rooted competitive advantages. Only then would they witness meaningful economic activity and yield a corresponding growth in productivity, employment and other indicators of socioeconomic success.

Policymakers should **nudge industry-academia linkages at all steps of the process**. The UK is a good example of doing just that. It has dedicated departments that direct R&D funding into advanced education and the startup landscape; both academia and industry co-operate with each other as well as with large companies in relevant industries in the country. It is really important that industry be engaged at an early stage, says Katharine Dunn, joint head of quantum technologies at the UK government’s Engineering and Physical Sciences Research Council. “Although we fund universities, in most of our projects that we support, they have industrial collaborators already engaged at that stage. It might just be early-stage, but that can also move up to real collaborative projects or people exchange [very quickly].”

The EU’s flagship technologically advanced firms (for example, Airbus, SAP, Schneider and Siemens) work closely with the European Commission to create R&D policy roadmaps that are oriented towards solving technical problems in their industrial workflows.

Purely academic research is valuable and should be supported. However, at each step of the R&D process, policymakers could nudge researchers to **think of potential practical applications** of their research. Industry-academia partnerships are advantageous because companies can create a short feedback loop on which problems they are working on and where they need support. Policymakers should set up a mechanism with participation from academia, industry and investors to test the proof of concept.

Any promising ideas could be spun out into startups with dedicated funding and a specific mandate to pilot the technology.

Streamline procedures

Startups and industry tend to move and react quickly in a fast-developing field with intense competition. On the other hand, policymaking and funding decisions are time-consuming activities: disbursement is conditional on the merits of research or business proposals that are technically intensive and require time to be comprehensively screened. However, policymakers should realise that startups and researchers may not be able to wait for six months or a year to hear back from the government at critical junctures in their programmes. Policymakers could explore ways of cutting the processing time, for example, by limiting the rigour of the screening process or running some processes in parallel.

Policymakers could devise different formats and mechanisms to **match funding to needs** and, simultaneously, incentivise the reorientation of R&D goals towards practical needs. For example, an increasingly ambitious funding pyramid could include prize-based competitions for nimble startups and small student teams, proposal-based grants for small and medium-sized startups, and tender-based procurement processes for large-scale projects.

To maintain leadership in quantum computing, creating and nurturing fresh cohorts of skilled STEM graduates should be a key ambition for those defining policy.

Manage workforce

The quantum technology field is already experiencing a shortage of skilled workers. Quantum computing requires specialised workers from across STEM fields, including quantum scientists; physicists; mathematicians; and computer, electronic and electrical engineers. Apart from the intensive training required to make workers ready for the job, policymakers should also worry about brain drain to companies and countries that are able to lure qualified workers with the promise of lucrative salaries and other benefits. To maintain leadership in quantum computing, creating and nurturing fresh cohorts of skilled STEM graduates should be a key ambition for those defining policy.

In Europe and the US, even high school students gain early exposure to basic concepts of quantum computing. "The US government has funding programmes to put together courseware ... even reaching down to the high school and junior high school level," says Doug Finke, managing editor of Quantum Computing Report. Policymakers in other constituencies should explore the type of courseware and programmes that could **provide early exposure** to high school and young college students and orient them towards quantum computing.

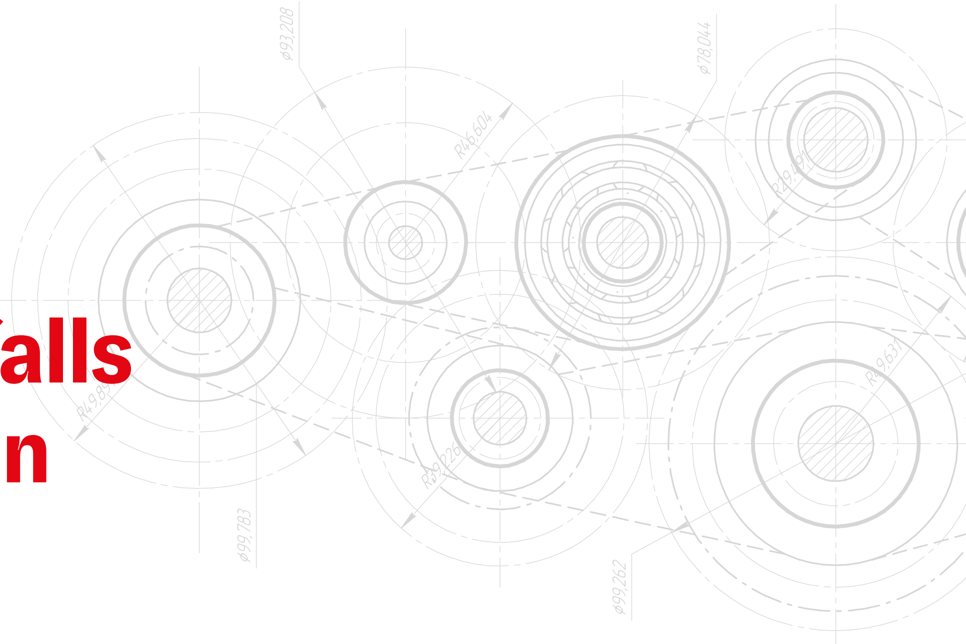
Startups affected by worker shortages suggest that scientists and engineers in related fields could be retrained and deployed relatively quickly. Industry and academia could co-operate to design programmes ranging from a six-month full-time certificate course to a two-year part-time graduate degree programme to upskill STEM professionals. Quantum computing firms could also design **industry apprenticeships for advanced students** that lead to a full-time job upon graduation. This way, companies could hire the best workers straight out of academia and train them to their unique needs.

Strike a balance between protection and promotion of quantum tech

While collaboration and cross-pollination of ideas and innovation across countries are vital to the growth of the field, policymakers should be **cautious about the misuse of such potent technology**.

Currently, as the technology is far from mature, benefits from collaboration and exchange of ideas outweigh security concerns. However, policymakers should **monitor the field** for significant breakthroughs. They should also be on the lookout for strategic acquisition attempts of domestic startups by foreign companies and any trending movement of skilled workforce outside of the country. Policymakers should be **ready to deploy safeguarding measures** that prevent the theft, transfer or leakage of critical knowledge that may provide a strategic advantage to rival powers.

Potential pitfalls and mitigation



Winners and losers: lopsided funding and advancement

While the countries that have seen the biggest advancement in quantum computing—mostly rich, developed western economies, China being the exception—have benefitted from underlying advantages stemming from technological leadership in classical computing and other high-tech areas, less prepared countries could be at risk of missing out on significant socioeconomic gains if quantum computing was to fulfil even a fraction of its potential. There is ample evidence that unequal technological innovation and development exacerbate inequality both within and between countries—the so-called digital divide.[10] The advent of quantum computing may lead to shifts in the global economy and workforce in unforeseen ways. Policymakers should be cognizant of these potential shifts and ensure that their citizens are well equipped and well positioned to adapt to the potential technology disruption. Policymakers should also treat quantum computing as an opportunity to play catch-up with technologically advanced nations and bridge the digital divide both domestically and globally, rather than enlarging it.

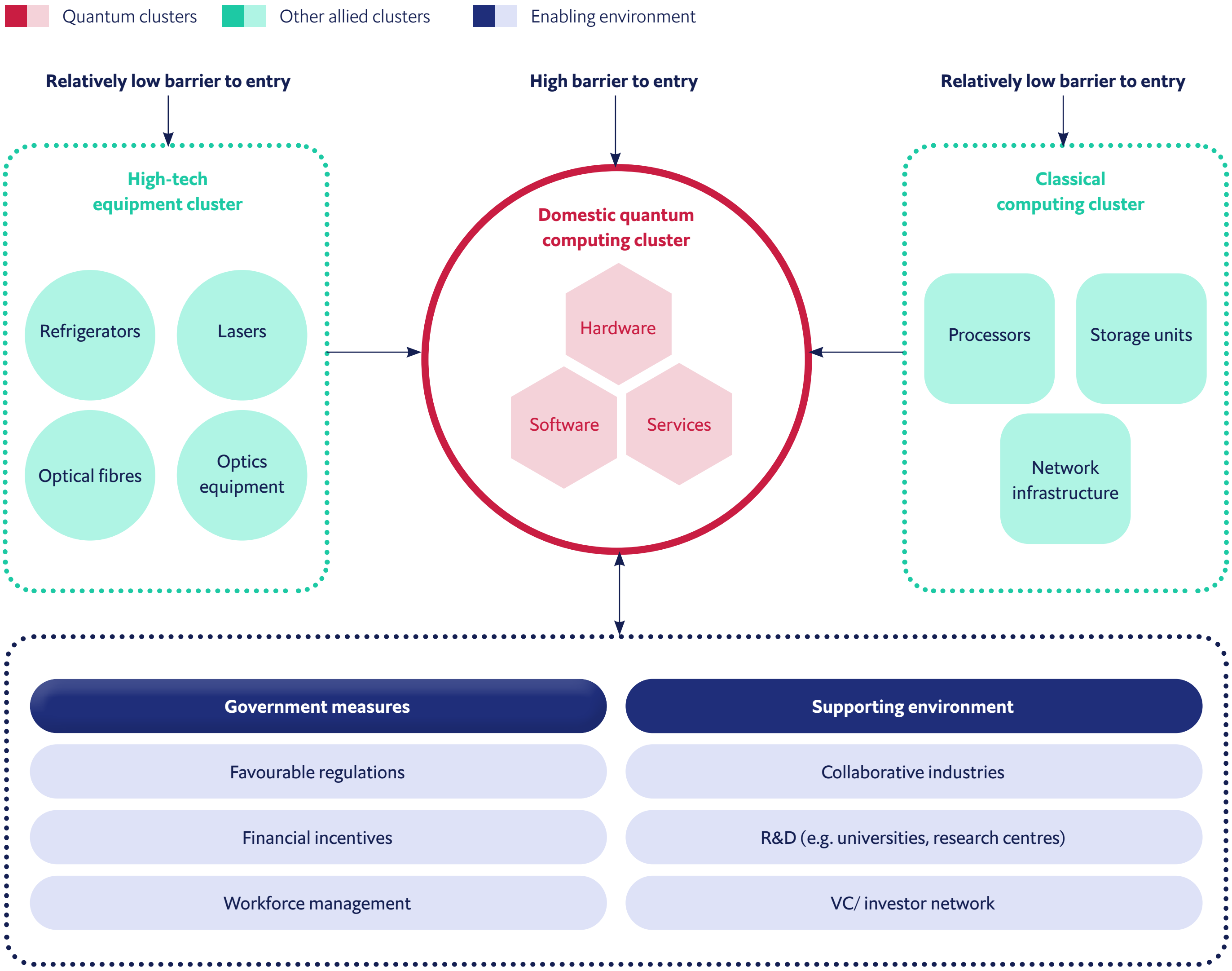
Mitigation: A cluster-driven approach?

Policymakers could explore some ideas to seed nascent ecosystems in their domains. A promising approach could be to enter the quantum computing value chain at different points that do not require the most advanced specialisation or pre-existing technology infrastructure. Since the field is far from maturity, countries that take a long-term view could still find many opportunities to reap benefits from the technology. "[Given] the rate at which the whole market is currently growing and the level of segmentation or specialisation that is happening, I think there's room for a lot of new entities," says Niels Bultink, CEO and co-founder of Qblox.

Once an industrial cluster (a network of interplaying small and medium sized companies) has taken root in a niche area of the quantum computing value chain, policymakers and

[10] Derviş, Kemal, and Laurence Chandy. "Are Technology and Globalization Destined to Drive up Inequality?" *Brookings*, 5 Oct. 2016, www.brookings.edu/research/are-technology-and-globalization-destined-to-drive-up-inequality.

FIGURE 5. Illustrative cluster map with different points of entry



the industry itself could nudge it towards specialisation in that niche and develop global competitiveness. Alternatively, the cluster could leverage its competitive advantages in the niche to expand up and down the value chain and become a generalist leader with a concentration of talent, infrastructure and ideas that drive innovation and growth. The choice, says Mr Bultink, is "If this market grows so fast, we should be smart and perhaps focus a bit" or "[we] pick one level lower and let another company do the rest."

Although setting up new industrial clusters from the ground up is not easy in countries with little to no record of leadership in science and technology, history shows that countries could still take these technological leaps by implementing cohesive economic policy and dedicating human and financial capital with an eye at gaining a competitive edge in specific niches. Japan (automotives), South Korea (consumer electronics) and China (manufacturing at large) are prominent examples among many others of countries that have bridged the technological gap with more advanced western nations in a relatively short period of time.[11]

Countries that want to establish a foothold in the field should create achievable yet ambitious goals and **allocate dedicated funding and resources**. The US government funds 17

[11] For an in-depth analysis of these economies, see, for example: Studwell, Joe. How Asia Works. Grove Press, 2014.

$8trn

Quantum computing could contribute up to US$8trn to the GDP of the Americas in 2035

national laboratories that support scientists and engineers by providing access to specialised equipment, world-class research facilities and skilled technical staff to solve complex scientific problems. Another example that policymakers could draw inspiration from is the Apollo space programme, where the US government sought to achieve moon landings by the end of the 1960s with single-minded dedication, pouring significant resources and its best scientists and engineers into the endeavour.[12] The advantage of government funding is that it is less driven by profit and gives researchers breathing room and time to focus on truly advancing fundamental research.

Governments and industry bodies could also explore **entering the value chain at a point where barriers to entry are lower**. Aside from highly trained scientists and engineers and exotic materials, quantum computing also requires **resources that are relatively less high-tech** to support the development of the industry. For example, policymakers could look at setting up classical computer chip fabricators. In addition to quantum processing units, quantum computers also require classical chips that are embedded in the quantum computer control units. Setting up chip factories is a technologically advanced and resource-intensive endeavour but could be a good long-term investment: the world has been experiencing an acute shortage of these chips over the past few years and demand is only going to rise with the ever increasing, universal proliferation of electronic devices.[13]

Another idea could be to set up **manufacturing facilities for hardware accessories**. For example, quantum computers require dilution refrigerators–vital pieces of equipment that maintain a cryogenic environment and keep qubits stable. Currently, only three companies globally manufacture these refrigerators, and they are all based in Europe. There could be room for other entrants as the industry expands and demand increases.

In terms of workforce, the field requires more than only doctorate holders in quantum physics and engineering. Creating an army of **well-trained STEM college graduates or postgraduates** that could be upskilled in quantum computing via short graduate programmes, part-time courses or apprenticeships will require less time and resources than training PhDs. Professionals who undergo about four to six years of training rather than the ten typical for PhD students could play supporting roles for primary quantum researchers who do have doctorate degrees. "You don't necessarily need a PhD to work in quantum technologies if you don't intend to become an academic or lead a big technology programme in industry", says Dr Dunn. "We need a range of skillsets and levels of training to ensure that the technology pipeline can continue to develop at the research and innovation stages, and then other levels of support such as technician skills to support the devices working across a range of applications and sectors." Countries that create such low-investment but high-demand talent pools will fill a vital gap in the industry.

Policymakers should not be hesitant about making these sizable investments. Even if quantum technology does not fulfil its potential, the establishment of an **R&D culture creates a virtuous cycle**. The history of science is littered with examples of inventions and discoveries that were unrelated or unintended consequences

[12] Dreier, Casey. "An Improved Cost Analysis of the Apollo Program." *Space Policy*, 2022, p. 101476. *Crossref*, www.doi.org/10.1016/j.spacepol.2022.101476.

[13] Hollinger, Peggy. "Chipmakers Face Two-Year Shortage of Critical Equipment." *Financial Times*, 21 Mar. 2022, www.ft.com/content/763c9e15-44ab-43bc-b3e9-0d03bf27e841.

of scientific pursuits in other directions.[14] While these developments were unforeseen, they were certainly not a product of luck or coincidence. A group of very smart people with dedicated resources are bound to come up with ideas that make the world a better place. "It's not that you invest for nothing. Even if quantum computers will not work, something useful will come out of that [investment]," says Mr Oreg. "What you do in one field, even if you didn't think about it, is very good for another application. So, sometimes you go and look for that and this—there is a click in your mind and you realise that it's very relevant for other [purposes]."

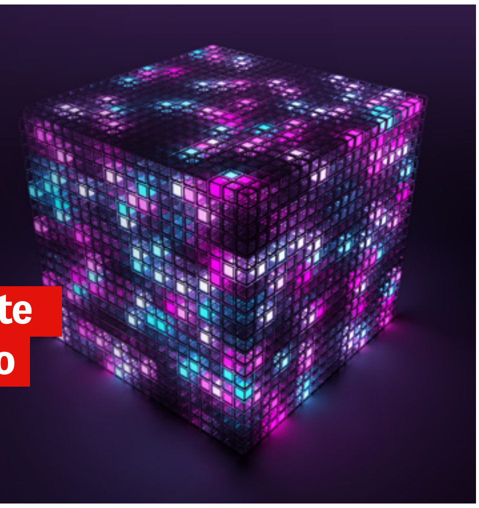
Cybersecurity risks: paranoia or possibility?

Current encryption techniques rely on the ability of classical computers to solve hard mathematical problems such as integer factorisation in a relatively long amount of time. RSA, a widely used cryptography algorithm, uses integer factorisation maths problems to encrypt information. Classical computers would take a long time to factorise a large number and obtain the "key" to break encryption. According to some estimates, the most powerful classical computers today employing brute force would require more time than the calculated lifespan of the universe to break RSA-2048 key encryption.[15]

Quantum computers, however, are a different beast. Shor's algorithm could, if run on a sufficiently powerful quantum computer, break popular encryption such as RSA quickly. Experts are still divided on when, if ever, quantum computers would become powerful enough to run Shor's algorithm. The timeline, as for other applications of quantum computers, depends on how soon organisations could build a powerful enough quantum computer. Timeline estimates range from an implausible five years to a more realistic two decades.

Irrespective of the uncertainty, major geopolitical players are viewing the threat seriously, given the extreme sensitivity of national classified information that is at stake in the long term. China, the EU, the UK and the US are all involved in a cat-and-mouse race to build quantum computers that are able to break encryption

The US National Institute of Standards and Technology (NIST) estimates that it will take at least two decades to develop and deploy the requisite cryptographic infrastructure to safeguard its systems



[14] For a deeper discussion and a list of breakthroughs, see, for example, Loosemore, Martin. *Innovation, Strategy and Risk in Construction.* Amsterdam University Press, 2013.

[15] Keylength. www.keylength.com

systems of rival powers and, at the same time, make their own communication systems resistant to attacks from quantum computers.

The US National Institute of Standards and Technology (NIST) estimates that it will take at least two decades to develop and deploy the requisite cryptographic infrastructure to safeguard its systems—coinciding with the most realistic estimates of the development of requisite quantum computing power to break current encryptions.[16] In such a scenario, policymakers will not be remiss about managing the threat urgently.

Businesses are also exposed to the risk. Companies in industries such as banking, insurance, healthcare, aerospace and defence that store sensitive information for the long term could be among the first targets of bad actors with access to powerful quantum computers. To mitigate this risk, business leaders should start quantum-proofing their networks as soon as possible, as it could take many years to build defences capable of withstanding quantum computing attacks around vast technological infrastructure and information systems.

Mitigation: devil in the details

The good news is that the **technology that makes networks quantum-resistant already exists**. The two best-known examples of quantum-resistant approaches are a post-quantum cryptography software-based class of algorithms that could be implemented by classical computers today to make networks quantum-resistant, and quantum key distribution (QKD), which is hardware-based technology that uses fundamental quantum properties of particles to detect anomalies that an eavesdropper invariably creates in a communication channel when intercepting a communication signal.[17]

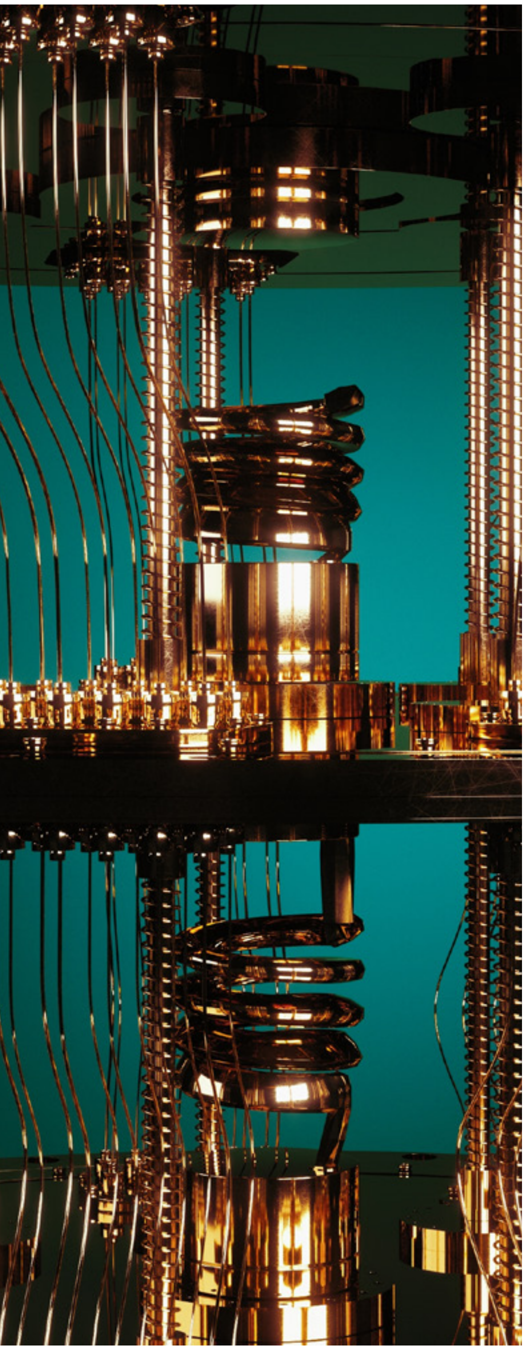
Both the US and the EU are in the process of adopting measures to make their networks quantum-resistant. NIST is developing the Post-Quantum Cryptography Standard and expects to complete the process in 2022. In 2022 the president, Joe Biden, also signed a National Security Memorandum that directs American federal agencies to adopt a whole-of-government and a whole-of-society approach to transition to quantum resistant cryptographic standards and safeguard American interests from quantum -led attacks. The EU has set up the European Quantum Communication Infrastructure Initiative to develop its own standards, based on QKD, and upgrade its infrastructure to make it quantum-resistant.

Corporate and IT security leaders must **monitor the development of these cryptographic standards**. Once they have been established, they should react with agility and decisiveness to revamp the security infrastructure of their organisations. Upgrading decades-old, sprawling security infrastructure will be a mammoth, resource-intensive task, but it is worth undergoing this transition to prevent the potentially cataclysmic impact of a quantum attack on their customers and bottom lines.

[16] "Post-Quantum Cryptography | CSRC." *National Institute of Standards and Technology Computer Security Resource Center*, csrc.nist.gov/Projects/post-quantum-cryptography/events. Accessed 19 Apr. 2022.

[17] It must be stressed that quantum key distribution is a quantum communication technology and not a quantum computing technology, although both make use of quantum properties of systems.

Conclusion



Quantum computing is an exciting and promising technology. It has the potential to affect a wholesale transformation of the global economy at the same scale as digitalisation has over the past few decades. Whether it does so is an open question. The scale of challenges and pitfalls is vast but so are the tenacity and ingenuity of the scientists and engineers working on them.

In the past few years the rate of advancement has picked up. Optimists are confident that we will continue to witness the same rate of development and successfully build the first universal quantum computers by the end of the 2020s. Others are more cautious and urge patience: according to them, the challenges ahead lie at the very edges of our knowledge of quantum physics and could take a long time to address adequately.

Policymakers and the private sector could play instrumental roles in supporting the sector. At the very least, learning about the technology and disseminating insights could be key to unleashing or rejuvenating a culture of knowledge and innovation in their ecosystems. By ignoring the hype and relying on expert advice, leaders would be better enabled to take science- and data-informed decisions on the pathway towards preparation.

Quantum computing offers a pathway to businesses and policymakers that missed the last wave of digitalisation of the economy and want to ensure that they do not lag in the next one. Creating the infrastructure for quantum computing and developing a knowledge ecosystem around it will unleash socioeconomic development irrespective of how quantum computing fares over its life cycle.

In the event that quantum computing languishes and remains perpetually on the cusp of becoming mainstream but does not see widespread application, the investments in human resources, collaboration and infrastructure will not go waste. Creating a cohort of multidisciplinary, smart STEM graduates will be an investment that helps to establish a virtuous cycle driving unforeseen advancements in science and technology even outside of quantum computing.

However, if quantum computing indeed turns out to be a revolutionary technology that remakes entire industries, leaders who invest in the ecosystem, security and infrastructure now will be lauded as visionaries who set their businesses and society on the path to prosperity and success, reaping benefits for decades to come.

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