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Assessing the quantum computing landscape

Market readiness, levels of investment, and implications for the future

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ABSTRACT

This paper presents the findings of a study examining the quantum technology landscape from a market perspective. The findings cover the market readiness of quantum computing technologies and the reported levels of investment in them. These findings are based on a highly targeted scan of available literature to develop an initial, exploratory perspective on the state-of-play. The paper specifically considers the role of 'big tech' companies, the start-up ecosystem, and funding by nation states to identify key implications for the future of quantum computing developments. It highlights that although quantum computing technologies offer scope to revolutionise computing hardware and software, the development of a universal quantum computer will require breakthroughs in several areas including improvements in the quality of qubits, error correction, and a demonstrable set of practical applications. The findings are expected to be of interest to computing researchers, policy makers, market players, and those interested in the future of computing.

CCS CONCEPTS

• Social and professional topics~Professional topics~Computing industry • Hardware~Emerging technologies~Quantum technologies • Social and professional topics~Computing / technology policy

KEYWORDS

Quantum computing, Quantum computing state-of-play, Future of computing

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1 Introduction

There is now emerging discourse about the potentially game-changing impact of quantum computing and quantum communications in popular and academic literature [6] [18]. Perceived returns on investment in quantum computing and its potential to disrupt the current classical digital computing landscape has intensified competition for delivering a functional quantum computer amongst the so-called 'big tech' companies and selected high-performing start-ups [15] [17]. Although several software tools have been made available either freely or on open source-basis, most of the research and development on hardware by 'big tech' companies and the start-ups remains proprietary. This makes it challenging to realistically assess the quantum computing capabilities currently available and distinguish the hype surrounding quantum computing from market realities [23] [1]. Despite the increasing, potentially unrealistic expectations and timelines associated with quantum computing [14] [38], there appear to be limited number of studies assessing the technology landscape from a market perspective as of 2021-22.

This paper is aimed at assessing quantum computing developments with a focus on the market readiness of the technologies developed and the reported levels of investment in them by following key players: the 'big tech' companies, the start-ups, and the nation states. It draws on desk research to present this market assessment. The discussion in this paper is intended to be an initial, exploratory review of the current state-of-play rather than a comprehensive investigation of the market players. The aim is to provide a more informed understanding of the current capabilities of quantum computing technologies and the implications they hold for the future of computing. The findings are expected to be of interest to quantum computing researchers, policy makers, market players such as venture capital investors, technology companies, and nation states investing resources in quantum computing, and those who follow emerging technology trends.

The next section (2) discusses the research approach for the paper and the limitations of the approach. Section 3 provides a description of key terminology used in the paper. The analysis on market readiness of quantum computing hardware and software is included in section 4. A discussion on the reported levels of investment in quantum computing technologies is provided in section 5. Section 6 considers the implications for the future of quantum computing landscape. The paper concludes with reflections on the findings in section 7.

2 Research approach

To understand the current state-of-play on quantum computing technology developments, this paper used a highly targeted form of literature review based on a scan of available literature via Google Scholar and Google.

As part of the initial scan, the literature searches covered peer-reviewed journal articles and conference papers on Google Scholar using combinations of following search terms: ‘quantum computing’, ‘market readiness’, ‘level of investment’, ‘technology readiness’, ‘cost of development’, ‘total addressable market’, ‘market size’, ‘*big tech*’, ’start-up*’, ‘start up*’. Grey literature was excluded from the initial searches conducted on Google Scholar. However, the initial scan on Google Scholar for these search terms primarily yielded technical literature on quantum computing. In consequence, the search criteria were broadened to include grey literature (technology consulting and policy reports, blogs, technology magazines, and news articles). The second round of searches were conducted on Google instead of Google Scholar. Search results after 2010 were prioritised and only articles published in English were considered as part of both rounds of literature scans.

For the literature identified through this scan of Google and Google Scholar search results, the abstracts and executive summaries were reviewed at high-level to short-list 48 articles based on their relevance to the aims of this paper. The short-listed articles were then reviewed in detail to categorise the findings based on following parameters relevant to this paper: definitions, approaches to quantum computing, market readiness of the technology, reported levels of investment, and implications for the future development of quantum computing technologies. The information extracted as part of the review of the final short-list of articles forms the basis of the discussion presented from section 3 to 6. 43 additional articles were identified through scanning relevant references in the short-listed articles (i.e. snowballing) to cross-check and triangulate the findings. The articles most relevant to the narrative in this paper are cited and included in the References section.

Given the highly targeted nature of the literature scan, some caveats to the findings provided in this paper need to be considered:

- The literature scan relied on information in the public domain and resulted in primarily qualitative literature being identified. The data sources were secondary in nature and commercially available quantitative information on quantum computing developments was excluded due to the cost of acquiring the data. The resultant analysis in sections 3 to 6 is therefore exploratory rather than a comprehensive coverage of the available literature.
- Although there is a growing body of literature focussed on the applications of quantum computing technologies to the field of security and encryption, the discussion in this paper is focussed on general-purpose quantum computing. Extensive coverage of topics related to quantum encryption and quantum security methods is out of scope for this paper.
- Literature on quantum communications i.e. the application of quantum physics to information processing, networks, and communications, is also excluded from the analysis in sections 3 to 6. This is to facilitate a calibrated discussion on the state of quantum computing technology developments in this paper.
- The discussion in this paper is focussed on ‘big tech’ companies, start-ups, and nation states. Although the literature identifies market players in investment banking, automobile manufacturing, oil and gas production, insurance, and multinational retail banking as key investors in the technologies, such market players are excluded from the discussion.
- Although China is a leading investor in quantum computing technologies along with the United States of America (US), English-language literature appears to mainly target developments in North America, Europe, and other countries in Asia-Pacific region such as Singapore and Australia [15]. As a result, this paper presents only a partial picture of the market developments in China with a focus on the following Chinese ‘big tech’ companies: Alibaba, Baidu, and Tencent.
- One of the main challenges facing the small-scale quantum computers operational today is that when the hardware is scaled up, the hardware errors also scale up exponentially. The quality of qubits, including their ability to retain the qubit state in a persistent manner, is unproven [16] [17]. Decoherence, in which the qubits interact with the external environment, change their quantum states, and lose information stored in the qubits, is also a key contributing factor to the errors [28]. If breakthroughs in error correction, noise reduction, or quantum transistors occur earlier than currently forecast, the timelines for mainstream adoption of technology can be expected to change significantly.
- The findings in this paper are a snapshot of the state-of-play as of 2021-2022. These findings would need to be re-assessed in case of unforeseen breakthroughs.

3 Description of key terms

This section provides a brief description of key terms related to the discussion on quantum computing.

- A quantum bit or a qubit is the quantum computing equivalent of the bit in classical computing. To understand the difference, it helps to visualise a classical bit and a qubit as plotted on a 3D sphere [18]. A classical bit has only two values 0 or 1, and therefore can take only the value of the north or the south pole on this sphere. In contrast, a qubit can take a value of any point of the surface on the sphere, including every possible pair of latitude and longitude measurement. The qubit can also simultaneously take intermediate positions between 0 and 1. As a result, for n qubits, the same operation can be done on all the possible combination of 0 and 1 for all the qubits i.e. 2^n combinations are possible [18].
- A quantum algorithm is a set of instructions solving a problem that can be performed on a quantum computer [4].
- Quantum supremacy (also quantum primacy or quantum advantage in some publications) is achieved when a quantum device is proven to be able to carry out a task that a classical computer would find impossible, or take too long to complete, and is unlikely to be overturned by algorithmic or hardware improvements to classical computers [26].
- A 'universal' quantum computer is identified as one which would be capable of full set of capabilities of a classical computer using quantum algorithms and hardware [10].
- Existing proposals for building quantum computers focus on using ion traps, nuclear magnetic resonance (NMR), optical / photonic, and solid state techniques [33]. Of these NMR and ion trap technologies are the most advanced so far with optical and solid state techniques considered promising in the future [33]. All of these approaches suffer from quantum noise and scaling problems to go beyond tens of qubits to hundreds of qubits [33]. Experts suggest that for quantum computers to be useful in solving real-world problems, the devices need to be scaled up to millions of qubits [25].
- Current-day quantum computers are referred to as Noisy Intermediate-Scale Quantum (NISQ) computers. This term signifies that current-day quantum computers have few qubits, limited gate depths, and short coherence times [18].
- The term 'big tech' refers to world's largest information technology companies in terms of market availability, revenues, operational footprint, and tangible/intangible socio-economic-political-legal influence. For the discussion in this paper 'big tech' refers to the following companies: Alibaba, Amazon, Apple, Baidu, Facebook (parent company: Meta), Google (parent company: Alphabet), IBM, Intel, Microsoft, and Tencent.
- The term 'start-up' is used to describe a company or project undertaken by an entrepreneur or a group of entrepreneurs to develop a viable business model based on developing quantum computing software or hardware capabilities either in conjunction with or independent of the 'big tech' companies.

4 Market readiness of current-day quantum computing technologies

As of 2021, a universal quantum computer capable of performing operations equivalent to the current day computers, smartphones, and other smart devices remains decades away. Most of the notable breakthroughs reported in the literature have been about hardware devices. This indicates that the focus of quantum computing investments has been on hardware development. The following discussion takes this into consideration to use two parameters to assess the market readiness of quantum computing hardware and software:

- Published results or public demonstrations of the technology; and
- The extent to which access is available to the hardware or software.

In the literature reviewed, the atomic clock capable of split second precision is commonly cited as the earliest demonstrable example of the technology [31] [2]. Other notable examples of quantum computing hardware from the 1990s include:

- A simple two-qubit NMR quantum computer built by researchers in IBM Almaden Research Center in San Jose, the Massachusetts Institute of Technology in Cambridge, and the University of California in 1997 [20].
- Three-qubit NMR quantum computers demonstrated in 1998 by researchers at Los Alamos National Laboratory in New Mexico [20]; and
- A simple two-qubit quantum computer built by researchers in the University of Oxford in 1999 [20].

The use of quantum sensors in devices such as atomic clocks, gravimeters is considered a practical, useful contribution of the technology in 2021 [31] [2]. In particular, quantum sensing is expected to become a key component in quantum Positioning Navigation and Timing (PNT) devices and quantum radar technologies in the next five to seven years [2].

4.1 Market readiness of quantum computing hardware

When hardware developments in quantum computing are considered, several technology demonstrations have been made by 'big tech' companies such as Google, IBM, and Intel along with academic researchers. Some notable examples include:

- Early 2015, Google demonstrated a linear array of nine qubits in operation [36].
- In late 2015, demonstrations by [39] and [22] highlighted breakthroughs in solid-state spin qubits

which potentially make quantum computing more practical [36].

- In 2016, Google simulated a hydrogen molecule with a nine-qubit quantum computer [25].
- In 2017, Intel reached 17 qubits, and IBM built a 50-qubit chip that could maintain its quantum state for 90 microseconds [25].
- In 2018, Google unveiled Bristlecone, its 72-qubit processor [25].
- In 2019 IBM launched its first commercial quantum computer – the 20-qubit IBM Q System One [25].
- As of 2019, IBM and Canadian firm D-Wave Systems were reported to sell access to quantum-enhanced calculators. [3]. This source [3] also reported that Google, Microsoft, and Intel had plans for similar offerings in three to five years.
- As of 2020, IBM had built Q System One, a 53-qubit quantum computer for which it was reported to have reached sales agreements with Germany and Japan [32].

Each of these demonstrations indicate incremental growth in the qubit capabilities of the available quantum machines. Most of these quantum machines have at best a few dozen qubits [9]. Due to the computation-destroying noise inherent to the current technology, most of these demonstrations have limited practical uses [9]. For example, although Google's biggest quantum computer had 72 qubits as of 2019, a general-purpose quantum computer will require around one million qubits to be functionally useful [15].

An important breakthrough in the market readiness of the technology was reported by Google in 2019 when it claimed to have reached quantum supremacy [21]. Google reported that its quantum computer ('Sycamore') performed a calculation in 200 seconds which it argued would require a classical supercomputer 10000 years [15] [17] [21]. IBM however questioned this and argued that a classical supercomputer could do that calculation in 2.5 days [18] [15] [17] [12]. Setting aside the debates of performance, from the perspective of large-scale, general-purpose quantum computing, Google's Sycamore quantum computer represents an important step since it can detect and fix computational errors [35]. However, although an essential step for large-scale quantum computing, Sycamore's current system generates more errors than it solves [35].

Despite the challenges of error correction and decoherence however, in September 2020, IBM announced a road map for the development of its quantum computers, including its goal to build a quantum computer with 1000 qubits by 2023 [2]. Google has also indicated it plans to build a million-qubit quantum computer by 2029 [2]. Intel is reportedly readying a superconducting quantum computer [18].

When the hardware built by start-ups in the quantum computing space is considered, D-Wave, a Canada-based company is often cited as an outlier [4] [25] [36]. D-Wave has been selling commercial quantum computers since the late 1990s and claims to have several thousand 'annealing qubits' in its devices [25]. However, 'annealing qubits' are only useful in certain types of problems, and therefore quantum annealers are not general-purpose computers [25]. Given the current state of development of the technologies, the quantum annealers are energy intensive and very expensive. For example, the D-Wave 2XTM computer (a quantum annealer) built in 2015 had 1,000 qubits, consumed 25 kilowatts of power, and cost in the region of U$15 million [36].

Other notable examples of quantum computing hardware start-ups include IonQ which plans to produce a device roughly the size of an Xbox videogame console by 2023 [23]. One source cites Rigetti and IonQ as having developed integrated chips suitable for quantum computing [18]. PsiQuantum, a United Kingdom (UK)-based start-up expects to be building fault-tolerant quantum computers with fully manufactured components capable of scaling to a million or more qubits by mid-2020s [23]. For this, PsiQuantum has partnered with the semiconductor manufacturer GlobalFoundries to build machines which will be comparable to supercomputers or data centres in terms of their size and will be accessible to users remotely [23] [37]. Rigetti Computing based in Berkeley, California (US), has built its own 31-qubit machine [27]. Amongst companies providing specialised hardware capabilities, Janis Research Company, is the only US-based commercial manufacturer providing cooling solutions for superconducting quantum computers, and the Swiss Federal Institute of Technology (ETH)-led Quantum Engineering Initiative (QEI) provides analogue and digital control electronics and device fabrication [18].

When general purpose quantum computing hardware is considered, the developments in China are also significant in assessing the market readiness of the technology. The Chinese government has decided to allocate US$10 billion for the country's National Laboratory for Quantum Information Sciences [40]. In 2020, a team of researchers from the University of Science and Technology of China reported to have achieved quantum supremacy by completing Gaussian boson sampling (a problem considered intractable for classical computers) in just 200 seconds through a device named 'Jiuzhang' [26] [40] [12]. The research team behind Jiuzhang suggested that the same calculation would take the 'Fugaku' (a supercomputer built by Fujitsu at the Riken Center for Computational Science in Kobe, Japan) 600 million years to complete [26]. They argued that when the metrics of performance around Gaussian boson sampling were considered, Jiuzhang was up to ten billion times faster than Google's Sycamore [40]. Another Chinese quantum computer, 'Zuchongzhi', a two-dimensional programmable computer composed of 66 functional qubits has been reported to perform random quantum circuits sampling (another reportedly intractable problem for classical computers) [12].

4.2 Market readiness of quantum computing software

An important challenge facing the development of quantum computing software is that the current hardware is highly targeted in terms of functionality i.e., a general-purpose quantum computer does not yet exist. This results in a paradoxical scenario where the software currently being written is for hardware capabilities which are not yet fully available [20].

When the software developed by 'big tech' is considered, Microsoft, IBM, Baidu, and Google have all created tools. These tools Q# (Microsoft), Qiskit (IBM), QCompute (Baidu), and Cirq (Google), are primarily based on the Python programming language, and include development environments with supporting documentation for software programmers [27]. Amazon, Microsoft, IBM, Alibaba, and Baidu have also started offering cloud computing services with quantum computing resources as back-ends in limited preview mode for developers [25] [32] [40] [34].

Through Amazon Web Services (AWS), Amazon is one of the leading providers of cloud services worldwide. As of 2019, Amazon started offering quantum computing through an AWS cloud service to researchers and developers to experiment [32] [40]. Named Amazon Braket, the service is available in an early preview with quantum computers from D-Wave, IonQ, and Rigetti as the back-ends [32]. Amazon is reported to be exploring mass-produced quantum computers through its new Center for Quantum Computing [32]. Amazon is also said to be analysing some of the leading start-ups in the sector for either future partnerships or acquisitions [40].

Microsoft's tools take the form of a quantum development kit (QDK), containing code libraries, a debugger and a resource estimator [27]. Microsoft has also developed Azure Quantum, a cloud computing service with IonQ's trapped-ion quantum computer, superconducting qubits being developed by Connecticut-based Quantum Circuits Incorporated (QCI), and Honeywell's quantum computer as the back-ends [25] [32]. This service is currently available in private preview with Microsoft indicating that it plans to build its own quantum computing hardware [32]. Azure is second only to AWS in cloud computing as of 2021-22 [32]. Microsoft's Azure Quantum is therefore considered to reduce the gap on Amazon's leading position in quantum cloud services [40].

Microsoft has also developed LIQUi|>, a Language Integrated Quantum Operations Simulator platform as part of which a quantum algorithm written in the form of a high-level program can be translated into low-level machine instructions for a quantum device [31]. It includes a compiler, optimisers, translators, various simulators, and examples for developers [31].

Along with Microsoft, IBM was one of the first 'big tech' companies offering public access to an experimental quantum computing platform [36]. In 2016, IBM offered access to 'IBM Quantum Experience' which enabled cloud-based access to a 5 qubit quantum computer virtual lab for researchers and students [36]. IBM also offered access to the IBM Q premium service as part of which it was reported to be working with more than 100 companies, including ExxonMobil, Barclays, and Samsung, on practical applications [25]. One source identifies IBM as a leader in the field overall with a full complement of hardware and software in addition to the most assigned patents [40].

Amongst Chinese 'big tech' companies, Alibaba appears to lead Baidu and Tencent when quantum computing investments originating in China are considered [11]. In 2018, Alibaba's cloud service subsidiary Aliyun ('Alibaba Cloud') and the Chinese Academy of Sciences jointly launched an 11 qubit quantum computing cloud service [34]. Alibaba is reportedly developing quantum processers at its US$15 billion science and technology research centre [40]. Baidu has declared its interest in building a hardware-agnostic software stack with quantum artificial intelligence, quantum algorithms, and quantum architecture as the three priority areas [34]. In 2020, Baidu announced 'Quantum Leaf', which it describes as the first cloud native quantum computing platform in China [34]. Tencent has created a Tencent Quantum Lab (tasked with building a Quantum Computing Cloud) as part of its planned 500 billion yuan (US$70 billion) expansion into artificial intelligence, blockchain, supercomputing centres, Internet of Things operating systems, 5G networks, and quantum computing [29].

In addition to 'big tech' efforts, several start-ups have released software development kits for quantum computing. Notable examples include Rigetti Computing which has released a quantum-software development kit called Forest, which includes a Python library called pyQuil [27]. UK-based Cambridge Quantum Computing (now Quantinuum, part of the Honeywell Group) has launched tket, along with an associated pytket library [27]. Companies such as QxBranch and 1Qbit act as intermediaries between the quantum experts and industry, examining whether and how a given firm's business might be improved by quantum methods [31]. Example services offered by them include optimising trading strategies or supply chains or monitoring network activity to spot cyber-attacks [31]. Other notable examples of software include, Silq, a language released in 2020 by a team at ETH in Zurich [27], QuTip, open-source software packages funded by a number of research organisations in Asia [31], and Quantum Algorithm Zoo at the National Institute of Standards and Technology in Maryland which is a comprehensive collection of known quantum computing algorithms [31]. QuTip uses Python to make programming quantum computing easier and more accessible using high-level languages [36].

5 Reported levels of investment in quantum computing technologies

As of 2021, based on the available information on reported levels of investment in quantum computing, the following discussion covers two strands of investment activity:

- Investments by nation states into research and development at universities, public sector research organisations, and industry; and
- Private sector investment including investments by 'big tech' companies and other private sector operators, and investments in start-ups by venture capital companies.

National and supranational funding bodies appear to be the main investors in quantum computing research [31]. Given the security implications of quantum computing, defence departments in many nation states appear to be the main drivers of funding [31]. Although many 'big tech' companies are also reported to be heavily investing in quantum computing, very few companies appear to have publicly disclosed the amounts involved [15]. When venture capital funding activity is considered, North America is the leader [15].

5.1 Investments by nation states

Among the nations reported to be investing in quantum computing, the US, Canada, the European Union (EU), the UK, China, Russia, and Australia are the leading nations [3] [36].

In the North American context, the US$250 billion US Innovation and Competition Act has designated quantum information science and technology as one of ten key focus areas for the National Science Foundation [5]. The US National Quantum Initiative Act provides US$1.2 billion to promote quantum information science over a five-year period [8]. As part of this initiative, five new National Quantum Information Science Research centres have been created by the US Department of Energy researchers with participation from academia, US national labs and industry to help catalyse quantum information science research [8]. In the 2021 budget, the US federal government strengthened this funding with other initiatives including US$237 million [19]. As part of the Canada First Research Excellence Fund, the University of Waterloo, one of the major research hubs in North America was awarded CA$76.3 million [36].

In 2018, the EU launched billion-dollar investment programmes including the ten-year Quantum Technologies Flagship programme [31] [3]. In 2020, Germany also announced a €2 billion investment in quantum technology research and development over the next five years in addition to the European Commission's €1 billion fund for quantum technologies [19].

The UK's total public and private investment in quantum technology research and development since 2014 is reported to have exceeded US$1 billion [3]. The UK also launched a programme worth £270 million (US$337 million) in 2017 [31].

In 2019, China declared its intent to open the world's largest quantum-research laboratory in 2020 at a cost of US$10 billion [3]. The Chinese government reportedly spends at least US$2.5 billion a year on quantum research [19].

Russia is reportedly coordinating private and government research and development of quantum technology as part of which large projects are expected to receive up to US$300 million in the first phase [3].

When other notable investments are considered, in 2016 the Australian government made an AU$46 million investment into a quantum computing programme based at the University of New South Wales [36]. This included the ARC Centre of Excellence for Quantum Computation and Communication Technology (CQC2T) which was awarded AU$33.7 million; and the University of Queensland's Centre for Engineered Quantum Systems (EQuS) which received AU$31.9 million for a duration of seven years [36]. India and South Korea are the other nation states which have declared their intention to invest tens of millions of US dollars per year [3].

5.2 Private sector investments

Although most of the 'big tech' companies (with the notable exception of Apple and Facebook) have announced quantum computing initiatives, none appear to report actual levels of investment as part of their annual reports. The evidence suggesting that 'big tech' companies are making investments worth millions of dollars in quantum computing research and development, is therefore mainly anecdotal. A number of 'big tech' companies including IBM, Microsoft, Intel, along with other industry behemoths such as Applied Materials and Lockheed Martin have been reported as being participants in the new National Quantum Information Science Research centres created as part of the US National Quantum Initiative Act [8].

Unlike the 'big tech' companies however, there is significant evidence highlighting the levels of venture capital funding in start-ups working on quantum computing hardware and software. More than 80 percent of these investments have been allocated to quantum computing hardware or its components [15]. Start-ups focussed on software and applications are likely to be the next area of growth.

In 2015, McKinsey reported that a combined investment of US$1.5 billion had been made worldwide on quantum technology research [31]. Private sector investments in quantum computing are projected to grow exponentially in the years ahead. Globally, equity investments in quantum computing were reported to have tripled in 2020 and 2021 [37]. Some sources have projected that the investments in quantum computing will grow from US$260 million in 2020 to US$9.1 billion by 2020s [32]. Honeywell anticipates that quantum technologies will lead to a US$1 trillion industry in the decades ahead [6].

North America is a world leader in attracting venture capital funding, and it also dominates private quantum investment [15]. These investments are not restricted to the Silicon Valley. Firms in Canada have attracted US$243 million resulting in an ecosystem to support quantum companies around academic hubs in Waterloo and Toronto [15]. As of 2019, Canadian quantum-computing pioneer D-Wave Systems was reported to have raised US$177 million [15].

By late 2021, venture capital investors have reportedly funded 180+ quantum computing companies globally since 2015 with the cumulative investments exceeding US$2.4 billion [37]. The number of venture capital deals in the North American market rose 46% in 2020 compared with 2019, despite the total amount raised in the quantum computing sector falling by 12% to US$365 million [40]. Although the financial value of some of these investments remains undisclosed, Nature's analysis suggests that in 2017 and 2018, companies received at least US$450 million in private funding [15]. This is more than four times the US$104 million investments disclosed in 2015 and 2016 [15]. The number of start-ups being funded due to advances in quantum computing technology are likely to increase in the years ahead [40].

Notable start-ups which are reported to have raised tens of millions of dollars each include Zapata Computing in Cambridge, Massachusetts (US); 1QBit in Vancouver, Canada; and UK-based Cambridge Quantum Computing [15]. Chinese firms QuantumCTek (in Heifei) and Qasky (in Wuhu), leaders in the field, have raised significant private funding which has not been disclosed [15].

6 Implications for the future of quantum computing landscape

The discussion in this paper has focussed on the market readiness of the quantum computing technologies when correlated with the reported levels of investment in the technology. Based on this evidence, some key implications can be identified for various stakeholders - researchers, technology companies, investors, nation states, and policymakers interested in the technology:

- Any current day assessments on the market size of quantum computing, its transformative effect on various sectors, valuations of the impact of quantum computing, and predictions on mainstream availability of the technology are early, optimistic projections. The actual addressable market of the technology in practice is highly limited as of 2021-22 [37].
- Since quantum computing technologies are in early stages of development, some sources suggest that there is a risk of the research talent moving away to start-ups too early. This may fragment the market and limit potential breakthroughs the research could yield [3] [30]. Given the growth in patent activity by start-ups, whether the transition of publicly funded research talent to start-ups is hindering fundamental research in the field is also open to question [3]. For example, one source states that due to issues of scaling up technology development in the UK, the UK's best-known quantum computing scientists have already moved to the Silicon Valley [30].
- Although quantum computing technologies are still developing, the development of algorithms for quantum computers has led to advances in solutions to large-scale combinatorics problems on the existing classical computers [7]. This suggests that developments in quantum computing are likely to prove complementary and may help augment and upscale current capabilities of classical computers.
- Given the potential capabilities of quantum computing to process raw, complex datasets at a scale and pace unmatched by classical computers, industry verticals where data, particularly big data and data analytics, plays a crucial role, are likely to be early adopters of the technology. This suggests that industry verticals such as healthcare, finance, commerce, communications, security, cybersecurity & cryptography, energy, space exploration, and other industries where data is a crucial ingredient will be the main industries driving the investment in the technology in the near-term [8]. Understanding the role of data will be crucial to any analyses of the next stage of market developments.
- Due to the hype surrounding the technology, there is a risk that quantum computing research may suffer the same fate as AI research did in the 1980s, resulting in a quantum equivalent of the AI winter. Experts warn that unrealistic expectations of possible breakthroughs could result in the research funding being prioritised to address other immediate-term technology research and the research talent moving away before full-scale machines can be built [15] [9].
- Based on the state of quantum hardware capabilities circa 2016, one source estimated that constructing a full-fledged universal quantum computer would cost around US$10 billion, equivalent of a next-generation chip fab at Intel [10]. As a result, it is highly likely that instead of a single universal quantum computing platform, quantum computing platforms relying on different approaches or hybrid uses of quantum and classical platforms may prevail in the interim depending on their efficacy for different tasks [16].
- Compared to classical computers, quantum computers draw on the unpredictable attributes of quantum particles and therefore, may better suited to a different, narrower range of outcomes such as simulating systems dominated by quantum effects [23]. The quantum hardware and software being developed by 'big tech' and start-ups is mainly aimed at solving computational problems using a fundamentally different paradigm

than a classical computer [21]. The expectations of what quantum computing can or cannot deliver need to be independent of the capabilities of classical computers.

- Without undermining the role of market-led innovation, there is potential for industry and public sector stakeholders to start discussing the role of technical standards and codes of conduct as regulatory tools for quantum computers [24]. At an early stage, these discussions could be industry-led and focus on the security concerns posed by quantum computers in the form of quantum cyberattacks, including the use of postquantum cryptography [24].
- Given the known limitations of the technology in terms of its need for error correction, uncertain quality of qubits, and the challenges in managing decoherence (to name a few), the first market-ready applications of real quantum computers are likely to be discrete, focussed on specific uses or outcomes such as verifying random numbers [31] [25]. Related to the niche hardware capabilities of quantum computers, the focus on software and algorithm development is also likely to shift to the smaller quantum machines which are expected to be available in the near future [31].
- Although most of the reported funding for quantum computing research has been provided by nation states and public sector authorities, most of the available quantum computing capabilities on the market are through private technology firms (either 'big tech' or start-ups). In particular, the access to quantum computing hardware is available almost exclusively through private technology firms [27]. When contrasted with comparable stage of development to classical computers (1940s and early 1950s) [13], this suggests a different, more market-led trajectory for the development, deployment, and adoption of quantum computers.
- Most of the notable access to quantum computing capabilities is in the form of cloud offerings of 'big tech' companies such as Amazon, Microsoft, IBM, Alibaba, or Baidu [25] [32] [40] [34]. Most private technology firms (either 'big tech' or start-ups) have developed software development kits or application programming interfaces (APIs) to access the hardware capabilities in private preview mode mainly on subscription basis. It is quite likely that until the capabilities of quantum computers exceed their current day niches uses, cloud computing will remain the prevalent form of mainstream access to quantum computers.

7 Reflections on the findings

This paper highlights that although much of the promised capabilities of quantum computing could revolutionise the field, the current set of quantum computing hardware and software does not yet deliver this promise.

Whilst some hardware capabilities have been demonstrated by companies such as D-Wave, Google, and IBM, they have yet to provide definitive timelines for commercial availability of a quantum computer. Start-ups such as Rigetti and IonQ have reportedly developed integrated chips suitable for quantum computing with Intel readying a superconducting quantum computer.

On software front, the offerings by Google, IBM, Microsoft, and Baidu, and start-ups such as Rigetti, and Cambridge Quantum Computing (now Quantinuum) have been in the form of application programming interfaces, software development kits, simulations, and quantum machine learning capabilities. Companies such as Amazon, Microsoft, IBM, Alibaba, and Baidu have begun offering cloud services with the prospect of quantum computing capabilities being available on demand. However, most of these services are currently available in private preview mode. Quantum computers built by companies such as Honeywell, IonQ, and QCI appear to have been at the core of the cloud services offered by Amazon, Microsoft, and IBM.

Efforts by Chinese 'big tech' such as Alibaba, Baidu, and Tencent indicate an increasingly competitive marketplace with developments dominated by advances being made by organisations headquartered in the US and China. On the one hand, Google has indicated that it wants to build a useful quantum computing offering by the end of the decade. On the other hand, critics highlight challenges in error correction, decoherence, and potential niche remit of the quantum computing to argue that the transformative capabilities of the technology are being over-stated based on current development status.

When the overall market readiness of the software and hardware powered by quantum computing and the reported levels of investment in the underlying technologies is considered, a complex picture of raw potential, promising early developments, and misleading hype emerges. Available evidence suggests that a demonstrable universal quantum computer is at least a decade away. It may be too early to speculate about widespread commercial availability of universal quantum computing capabilities. In the interim, a hybrid computing approach drawing on classical computers and advancements in quantum computing hardware and software is likely to prevail. Due to the disruptive potential of the technology, interest in funding fundamental research in quantum computing and commercial investments in the hardware and software development is likely to persist in the near term. However, based on the current state-of-play, making any definitive assessments on the timeframes for mainstream adoption and deployment of general-purpose quantum computing capabilities remains challenging.

REFERENCES

[1] Scott Aaronson. 2021. What Makes Quantum Computing So Hard to Explain? *Quanta Magazine*. Retrieved December 7, 2021 from https://www.quantamagazine.org/why-is-quantum-computing-so-hard-to-explain-20210608/

[2] Michiel van Amerongen. 2021. Quantum technologies in defence & security. *NATO Review*. Retrieved September 13, 2021 from https://www.nato.int/docu/review/articles/2021/06/03/quantum-technologies-in-defence-security/index.html

[3] Jacob D. Biamonte, Pavel Dorozhkin, and Igor Zacharov. 2019. Keep quantum computing global and open. *Nature* 573, 7773 (September 2019), 190–191. DOI:https://doi.org/10.1038/d41586-019-02675-5

[4] Jacob Biamonte, Peter Wittek, Nicola Pancotti, Patrick Rebentrost, Nathan Wiebe, and Seth Lloyd. 2017. Quantum machine learning. *Nature* 549, 7671 (September 2017), 195–202. DOI:https://doi.org/10.1038/nature23474

[5] Jean-François Bobier, Matt Langione, Edward Tao, and Antione Gourévitch. 2021. What Happens When 'If' Turns to 'When' in Quantum Computing? *United Kingdom - EN*. Retrieved September 13, 2021 from https://www.bcg.com/en-gb/publications/2021/building-quantum-advantage

[6] Francesco Bova, Avi Goldfarb, and Roger Melko. 2021. Quantum Computing Is Coming. What Can It Do? *Harvard Business Review*. Retrieved September 13, 2021 from https://hbr.org/2021/07/quantum-computing-is-coming-what-can-it-do

[7] Francesco Bova, Avi Goldfarb, and Roger G. Melko. 2021. Commercial applications of quantum computing. *EPJ Quantum Technol.* 8, 1 (December 2021), 1–13. DOI:https://doi.org/10.1140/epjqt/s40507-021-00091-1

[8] Chuck Brooks. 2021. The Emerging Paths Of Quantum Computing. *Forbes*. Retrieved September 13, 2021 from https://www.forbes.com/sites/chuckbrooks/2021/03/21/the-emerging-paths-of-quantum-computing/

[9] Michael Brooks. 2019. Beyond quantum supremacy: the hunt for useful quantum computers. *Nature* 574, 7776 (October 2019), 19–21. DOI:https://doi.org/10.1038/d41586-019-02936-3

[10] Edwin Cartlidge. 2016. Quantum Computing: How Close Are We? *Opt. Photonics News* 27, 10 (2016), 30–37.

[11] Yi-An Chang. 2021. Quantum Wars. *Cheung Kong Graduate School of Business (CKGSB) Knowledge*. Retrieved March 31, 2022 from https://english.ckgsb.edu.cn/knowledges/quantum-wars/

[12] Charles Q. Choi. 2021. Two of World's Biggest Quantum Computers Made in China. *IEEE Spectrum*. Retrieved April 13, 2022 from https://spectrum.ieee.org/quantum-computing-china

[13] Michael A. Cusumano. 2018. The business of quantum computing. *Commun. ACM* 61, 10 (September 2018), 20–22. DOI:https://doi.org/10.1145/3267352

[14] Mikhail Dyanokov. 2018. The Case Against Quantum Computing. *IEEE Spectrum*. Retrieved October 22, 2021 from https://spectrum.ieee.org/the-case-against-quantum-computing

[15] Elizabeth Gibney. 2019. Quantum gold rush: the private funding pouring into quantum start-ups. *Nature* 574, 7776 (October 2019), 22–24. DOI:https://doi.org/10.1038/d41586-019-02935-4

[16] Elizabeth Gibney. 2019. Hello quantum world! Google publishes landmark quantum supremacy claim. *Nature* 574, 7779 (October 2019), 461–462. DOI:https://doi.org/10.1038/d41586-019-03213-z

[17] Elizabeth Gibney. 2020. Quantum computer race intensifies as alternative technology gains steam. *Nature* 587, 7834 (November 2020), 342–343. DOI:https://doi.org/10.1038/d41586-020-03237-w

[18] John Gomes, Arjun Bhalla, and Carlos Oliver. 2021. *Why quantum computing is a big deal.* Retrieved from https://www.kearney.com/documents/20152/72556498/Why+quantum+computing+is+a+big+deal.pdf/9f1d3d11-1b05-539e-e85f-1c3189f39571?t=1613514406000

[19] Clothilde Goujard. 2021. Germany unveils powerful quantum computer to keep Europe in global tech race. *POLITICO*. Retrieved September 13, 2021 from https://www.politico.eu/article/germany-unveils-europes-first-quantum-computer/

[20] Lov K. Grover. 1999. Quantum Computing. *The Sciences* July/August, (1999), 24–30. Retrieved September 13, 2021 from https://cryptome.org/qc-grover.htm

[21] Kevin Hartnett and The Quanta Magazine. 2019. Why Two Tech Giants Are Arguing About Quantum Computers. *The Atlantic*. Retrieved September 13, 2021 from https://www.theatlantic.com/technology/archive/2019/10/why-google-and-ibm-are-arguing-about-quantum-computing/600625/

[22] B. Hensen, H. Bernien, A. E. Dréau, A. Reiserer, N. Kalb, M. S. Blok, J. Ruitenberg, R. F. L. Vermeulen, R. N. Schouten, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, M. Markham, D. J. Twitchen, D. Elkouss, S. Wehner, T. H. Taminiau, and R. Hanson. 2015. Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres. *Nature* 526, 7575 (October 2015), 682–686. DOI:https://doi.org/10.1038/nature15759

[23] John Horgan. 2021. Will Quantum Computing Ever Live Up to Its Hype? *Scientific American*. Retrieved September 13, 2021 from https://www.scientificamerican.com/article/will-quantum-computing-ever-live-up-to-its-hype/

[24] Walter G. Johnson. 2019. Quantum Supremacy and the Regulation of Quantum Technologies | The Regulatory Review. *The Regulatory Review*. Retrieved September 13, 2021 from https://www.theregreview.org/2019/12/30/johnson-quantum-supremacy-regulation-quantum-technologies/

[25] Amit Katwala. 2019. Inside big tech's high-stakes race for quantum supremacy. *Wired UK*. Retrieved September 13, 2021 from https://www.wired.co.uk/article/quantum-supremacy-google-microsoft-ibm

[26] Daphne Leprince-Ringuet. 2020. Quantum supremacy "milestone" achieved by light-emitting quantum computer. *ZDNet*. Retrieved September 13, 2021 from https://www.zdnet.com/article/quantum-supremacy-milestone-achieved-by-light-emitting-quantum-computer/

[27] David Matthews. 2021. How to get started in quantum computing. *Nature* 591, 7848 (March 2021), 166–167. DOI:https://doi.org/10.1038/d41586-021-00533-x

[28] Katherine McCormick. 2020. Decoherence Is a Problem for Quantum Computing, But … *Scientific American Blog Network*. Retrieved December 16, 2021 from https://blogs.scientificamerican.com/observations/decoherence-is-a-problem-for-quantum-computing-but/

[29] Sebastien Moss. 2020. Tencent plans $70bn investment in cloud, AI, blockchain, quantum computing, and more. *AI Business*. Retrieved April 1, 2022 from https://www.aibusiness.com/document.asp?doc_id=761444

[30] Madhumita Murgia. 2019. British quantum computing experts leave for Silicon Valley. *Financial Times*. Retrieved September 24, 2021 from https://www.ft.com/content/afc27836-9383-11e9-aea1-2b1d33ac3271

[31] Jason Palmer. 2017. Here, there and everywhere. *The Economist*. Retrieved September 13, 2021 from https://www.economist.com/news/essays/21717782-quantum-technology-beginning-come-its-own

[32] Corinne Reichert. 2020. How the quantum computing race will change our lives. *CNET*. Retrieved September 13, 2021 from https://www.cnet.com/tech/services-and-software/amazon-ibm-and-microsoft-race-to-bring-global-access-to-quantum-computing/

[33] Eleanor Rieffel and Wolfgang Polak. 2000. An introduction to quantum computing for non-physicists. *ACM Comput. Surv.* 32, 3 (September 2000), 300–335. DOI:https://doi.org/10.1145/367701.367709

[34] Craig G. Smith. 2021. Competing Visions Underpin China’s Quantum Computer Race. *IEEE Spectrum*. Retrieved March 31, 2022 from https://spectrum.ieee.org/alibaba-baidu-quantum-computer-race

[35] Matthew Sparkes. 2021. Google demonstrates vital step towards large-scale quantum computers. *New Scientist*. Retrieved September 13, 2021 from https://www.newscientist.com/article/2283945-google-demonstrates-vital-step-towards-large-scale-quantum-computers/

[36] Rupesh Srivastava, Iris Choi, and Tim Cook. 2016. The Commercial Prospects for Quantum Computing. (2016), 48. Retrieved from https://nqit.ox.ac.uk/sites/www.nqit.ox.ac.uk/files/2018-10/Commercial%20Prospects%20for%20Quantum%20Computing%20Dec%202016.pdf

[37] Marina Temkin. 2021. VCs make record bets on quantum computing | PitchBook. *Pitchbook*. Retrieved April 7, 2022 from https://pitchbook.com/news/articles/quantum-computing-venture-capital-funding

[38] Moshe Y. Vardi. 2019. Quantum hype and quantum skepticism. *Commun. ACM* 62, 5 (April 2019), 7. DOI:https://doi.org/10.1145/3322092

[39] M. Veldhorst, C. H. Yang, J. C. C. Hwang, W. Huang, J. P. Dehollain, J. T. Muhonen, S. Simmons, A. Laucht, F. E. Hudson, K. M. Itoh, A. Morello, and A. S. Dzurak. 2015. A two-qubit logic gate in silicon. *Nature* 526, 7573 (October 2015), 410–414. DOI:https://doi.org/10.1038/nature15263

[40] Lara Williams. 2021. Is Big Tech on the verge of taking a quantum leap? *Investment Monitor*. Retrieved September 13, 2021 from https://investmentmonitor.ai/analysis/big-tech-quantum-computing-startups