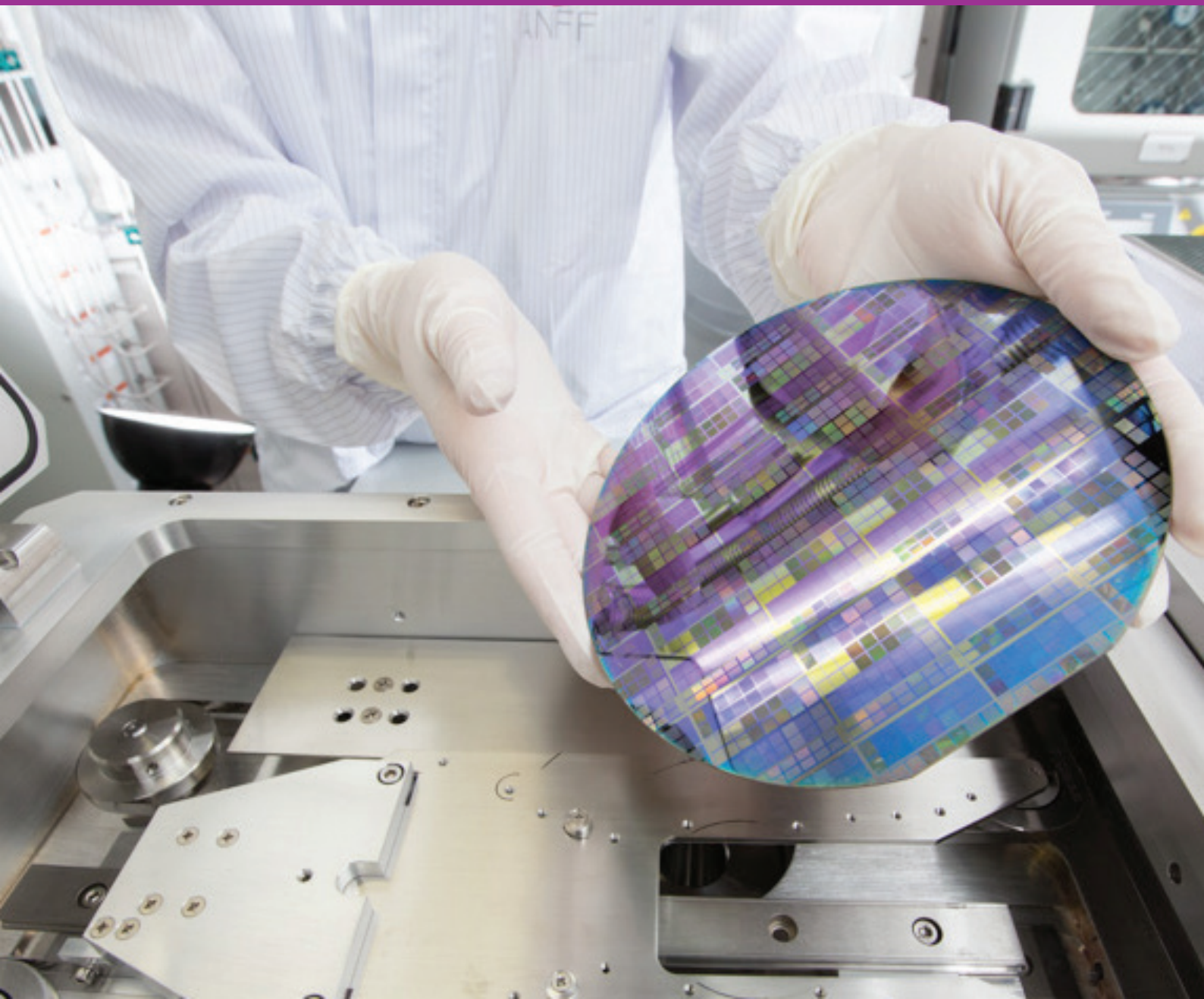




An Economic Analysis of Quantum Computing

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01

Introduction: What This Report Is, and Is Not

Quantum computing is going to make someone a lot of money. It is unlikely to be any of the major players in the industry today. Unless the quantum industry can deliver a *commercial* quantum computing system that can be installed in many hundreds of private and government owned data centres the forecasted trillion dollars of value generation will never be realised¹. Huge, monolithic quantum computers built at the scale of whole office blocks; single dedicated sites across hectares of commercial land capable of servicing clients one at a time via cloud services (the dominant business model of today) will always be too expensive to run, maintain and refresh for any commercial enterprise.

Read any news article on quantum computing today and you will see claims of quantum supremacy², or that a specific system is doing commercially useful calculations³. While technically interesting, such milestones are a long way from a profit-generating quantum computing service.

A genuinely commercial quantum system needs to provide compute services to many clients at a price point that those customers can afford within the context of their own operating margins. This requires the quantum computers to hold millions, and eventually billions, of qubits in single contained systems. These systems need to be power efficient, operationally easy to manage, and able to be configured into, and alongside standard compute infrastructure.

In short, to be a viable investment, a quantum computing hardware provider must describe their path to utility in the same way a hyperscale data centre is a utility for many concurrent customers, or an AI inference data centre serves many paying clients.

1.

Commercial usefulness:

The ability of a quantum computer to solve a problem for a commercially valuable use-case.

2.

Commercial viability:

The ability of a quantum computer to solve a problem for a much lower cost than the value of the solution in an appropriate timescale.

3.

Utility scale quantum computer:

A quantum computer which can be applied to a range of problems and provide computational value that is greater than its cost.

¹ <https://www.mckinsey.com/featured-insights/the-rise-of-quantum-computing>

² When a specific algorithm run on a quantum computer delivers a result that is impossible on a classical computer.

³ It solves a problem such as route optimisation for a logistics firm, or protein-molecule design for a drug company.

01 Introduction: What This Report Is, and Is Not (Continued)

The final design of any quantum computer is primarily driven by the choice made as to what type of qubit to use.

Quantum computing companies can choose from a range of qubit *modalities* to act as their core technology. We believe that of all the ways in which to build a qubit and by extension a full-scale quantum computer currently in development, only the spins in silicon method can deliver a commercially viable system. This may read as a bold claim given the hundreds of millions of dollars being poured into other qubit modalities by governments around the world.

A bold claim also given the strong investor support for such modalities as superconducting qubits (Google, Rigetti, IBM, IQM, Alice & Bob), photonic qubits (PsiQuantum, Xanadu, Quandela), trapped-ions (IonQ, Quantinuum) and neutral atoms (Pasqal, Atom Computing, QuEra). However, having tracked this sector for a decade we believe that none of these ways to build a quantum computer can be commercially viable. This paper outlines why.

We continue to track the sector closely and remain eager to see the promise of quantum computing realised irrespective of qubit type; so, our views will be updated regularly.

We seek to convey a venture capitalist's analysis of this highly viable sector. Even for specialists the quantum computing market remains a complex one to navigate. It may appear full of conflicting statistics, competing performance benchmarks and hyperbolic claims from founders and backers who exude legitimacy and charisma.

We do not set out to provide a detailed review of the deep technical specifications of each competing quantum computing companies' platform (although we have done that). Nor is this paper intended to be a beginner's guide to quantum computing (although we do provide background). Rather, it should be read as a guide for those looking to make sense of all the claims and counter claims made by the industry, and a tool for those who are seeking to deploy venture capital into it. At the very least we hope it arms venture investors with some of the questions they should ask the charismatic quantum computing founder standing before them.

01 Introduction: What This Report Is, and Is Not (Continued)

1.1 Questions to Ask a Quantum Computing Hardware Company

1. How many qubits (physical and logical) do you expect to need for utility scale quantum computing?

2. What algorithms and use cases will justify buying your quantum hardware?

3. When do you expect to reach utility scale quantum computing?

4. Once you reach utility scale quantum computing, what are your plans to scale performance beyond that point?

5. What would the energy consumption of one of your utility scale quantum computers be?

6. What would the physical size of your utility scale quantum computer be?

7. What is the cost of the classical hardware to your QPU (compilation, real time error correction, electronics drive, signals analysis)?

8. How much would a utility scale quantum computer cost to build?

9. How much would a utility scale quantum computer cost to run?

10. Do you expect to sell quantum computers themselves i.e. on-prem machines or do you expect to sell time-for-use of a quantum computer i.e. cloud-access, or both? How much do you expect to sell machines or access for?

11. Who are your target customers? How much do you expect they would allocate to utility scale quantum computing if available?

12. How long do you expect it would take to build a utility scale quantum computer, assuming the blueprint was available?

13. How many utility scale quantum computers would you be able to produce in a year?

14. If you do not have a rate card for time-on-machine when will you have?

15. If your exit plan is an IPO (or SPAC) how much recurring revenues from customers accessing your service via the cloud will you have at that time?

02

About Quantum Computing

Quantum computing is a rapidly evolving field of technology that seeks to revolutionise computation by leveraging the principles of quantum mechanics – the fundamental rules that govern the behaviour of matter and energy at the smallest scales. Unlike classical computers, which use binary bits (0s and 1s) as the unit of information, quantum computers use quantum bits or qubits which utilise quantum mechanical properties like entanglement, superposition and interference to perform calculations in ways that classical computers cannot.

Quantum computers are expected to excel in solving specific problems much faster than classical computers, particularly those problems which are quantum mechanical in nature. Example problems where quantum computers may unlock use cases include artificial intelligence, chemical simulation, optimisation and cryptography. These are well documented and can be viewed in reports from many sources including McKinsey⁴, or the WEF⁵.

The global quantum computing market could **add a total of more than \$1 trillion to the global economy** between 2025 and 2035, according to analysis from The Quantum Insider⁶ and McKinsey⁷:

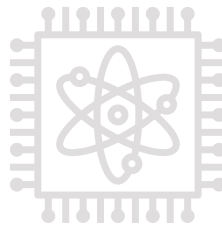
Economic value forecasts that **QUANTUM COMPUTING** will contribute

\$1 TRILLION
in value creation by **2035**



The **quantum computing market** may approach

\$131 Billion by **2040**



Quantum computing vendors expected to generate

\$50 BILLION



in revenue by **2035**

QUANTUM COMPUTING WILL CREATE AN ESTIMATED



840,000 new jobs
by **2035**, with
250,000 by **2030**

⁴ <https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/quantum-computing-use-cases-are-getting-real-what-you-need-to-know>

⁵ <https://www.weforum.org/publications/quantum-economy-blueprint/>

⁶ <https://thequantuminsider.com/2024/09/13/the-quantum-insider-projects-1-trillion-in-economic-impact-from-quantum-computing-by-2035>

⁷ <https://www.mckinsey.com/featured-insights/the-rise-of-quantum-computing>

02 About Quantum Computing (Continued)

To deliver this windfall requires there to be a quantum computer; ideally many of them. Commercial quantum computers will be embedded within computing infrastructure and will work alongside classical computing architectures to deliver services via the cloud or on-premises.

Despite the economic advantage of having access to a quantum computer this market remains out of reach until such a time a fault tolerant quantum computer is available. A fault tolerant quantum computer ('FTQC') is one that has reduced errors to an acceptable level to the algorithms which are being run. This is possible through error correction, a technique that reduces the effective errors in a system.

Fault tolerance:

The ability of a system to continue working even when there are faults or failures of qubits (a common occurrence when dealing with such sensitive systems)

Quantum error correction:

A technique that protects quantum information by encoding it into a larger quantum system

Quantum information:

Fragile information that is susceptible to noise and decoherence

FTQC uses sophisticated techniques and architectures to allow quantum computations to continue reliably. These techniques include quantum error correction, which can reduce the impact of errors on the overall computation.

There are a variety of definitions for a system meeting the *commercial usefulness* bar, to *begin* solving useful problems we are looking at least many millions of physical qubits providing many thousands of logical qubits (being the sustained processing base unit of a quantum computer)⁸. A typical ratio of physical to logical qubits is 1000:1^{9,10}. This means that systems that can claim hundreds, or even thousands of physical qubits operating together are scientifically interesting, but they fall far short of the minimum requirements for a commercially useful system.

Preliminary results from the US government's DARPA show that quantum computers can be commercially useful but show that high-value problems will be solved with 600 to 10M logical qubits reflecting physical qubit numbers of 10,000 to 10M depending on hardware architecture. Most of the DARPA problems require system sizes with more than 4,000 logical qubits which we see as the baseline for a commercially useful quantum computer. It should be noted that quantum systems will need to scale past this number to deliver on market demand. This sets a baseline of 4M physical qubits for most hardware architectures to perform useful computations.

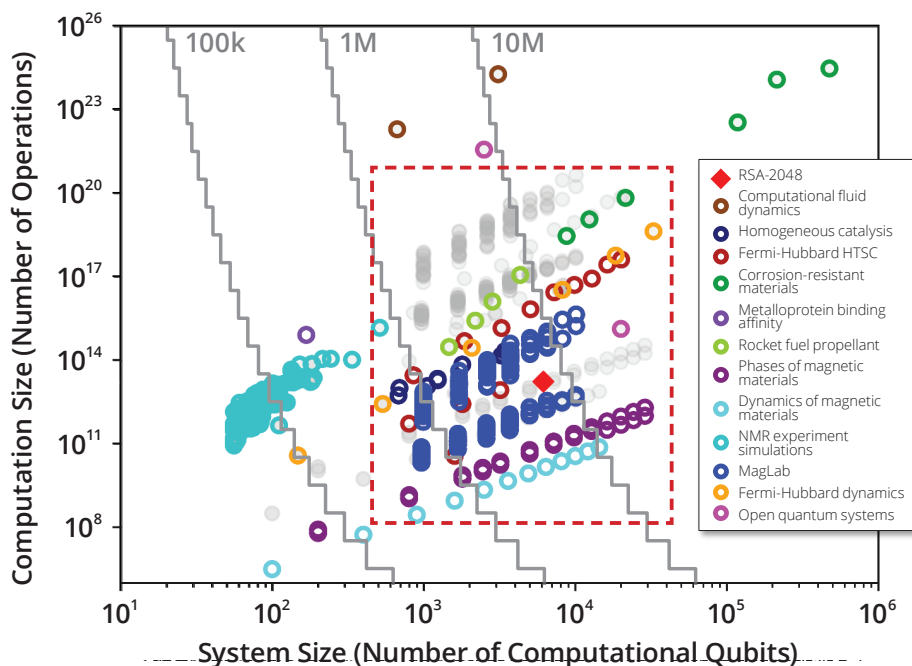
⁸ Figure 1. DARPA QBI Proposers Day Presentation. September, 2024.

⁹ Assuming a surface code approach to error correction and a fidelity of 99.9% for 2-qubit operations. The physical qubit overhead also depends on connectivity between qubits. We note that autonomous error correction qubits like cat-qubits (Alice&Bob, AWS) or GKP qubits (Nord Quantique) could reduce this physical qubit overhead.

¹⁰ Some groups claim that their roadmaps will increase fidelities enough such that the physical qubit overhead decreases. While this is theoretically correct, increasing fidelities is difficult and we are sceptical of groups that assume a roadmap with 2-qubits fidelities well above 99.9% (e.g. Quantinuum).

02 About Quantum Computing (Continued)

Figure 1 DARPA Commercial Application Benchmarking¹¹



Grey solid circles represent pessimistic resource estimates. Coloured circles are optimistic resource estimates based on known improvements. All points supported by detailed published pre-prints.

Additional to commercial usefulness (the ability to solve a commercially relevant problem), there is also a question of commercial viability (the ability for quantum computing to be delivered for a much lower cost than the value of the solution). Most announcements today focus on usefulness and not viability. Such a quantum computer can be deemed "utility scale"¹².

Commercial usefulness: The ability of a quantum computer to solve a problem for a commercially valuable use-case.

Commercial viability: The ability of a quantum computer to solve a problem for a much lower cost than the value of the solution in an appropriate timescale

Utility scale quantum computer: A quantum computer which can be applied to a range of problems and provide computational value that is greater than its cost.

Many of the pitch decks and projects currently being funded replicate this focus and neglect commercial viability. Much attention and capital is spent on teams that may deliver FTQCs but are massive physically and prohibitively expensive to run for all but the largest of government budgets. This might make sense for governments looking to protect national interests¹³ or strategic investors protecting their competitive positions, but even financial investors are funding projects hoping to get venture style returns on eventual full-scale systems that even in an optimistic analysis, cannot deliver commercially viable quantum computing.

At ICM, we have been **infrastructure investors for over 30 years** and are focused on teams that can deliver many millions of quality qubits in a single system and can deliver these utility-scale systems profitably.

¹¹ Figure 1. DARPA QBI Proposers Day Presentation. September, 2024.

¹² <https://www.darpa.mil/research/programs/underexplored-systems-for-utility-scale-quantum-computing>

¹³ Governments are particularly interested in the cryptographic threat of quantum computing

03

ICM's Quantum Computing Core Thesis

The quantum computing sector **will only be commercial once fault-tolerance is achieved** and when these machines can be provided in a form and at a price point that is rational.

The following sections detail the criteria for how we compare modalities from a both a commercial and technical perspective and evidence why we have concluded that **only quantum computing that can be delivered in a single module (or few) can deliver on the promise** of commercial quantum computing.

Acknowledging that science is in constant development, **we continue to challenge** our assumptions and to seek out other modalities which have line of sight to commerciality.

04

Our Core Principles

As long term, value investors we built our thesis on the last decade of research into quantum technology. **Our core principles when evaluating companies are:**

1. There is limited evidence that near-term, early uses cases of quantum computing (so-called “NISQ”) will deliver much, if any, value to businesses or government^{14, 15}. We do not believe these will be at the level required for venture-style returns.

2. Significant commercial value will only be realised with fault tolerant quantum computing (“FTQC”) and more value will be unlocked as the underlying hardware improves from that point.

3. Given current technical specifications, including minimum operations required and gate speeds, many millions of physical qubits with low errors (<1%) will be required to solve commercially useful problems¹⁶.

4. To be commercially viable, quantum computers must solve a problem in a meaningful time and for much less cost than the value created by the solution¹⁷. This means we need to consider the capex and opex of a “utility scale” quantum computer, not just if it’s technically possible to deliver.

5. Quantum computers will need to work in partnership (both physical location and in a computing workload sense) with classical computers, and the closer a quantum computer can be to a High-Performance Computer (“HPC”) or data centre, the better. Physical size, operation temperature, form factor and power consumption are all considerations here.

6. Time-to-market is increasingly important as progress made in AI threatens the marginal improvement that quantum computers can make to some high-value problems in optimisation and chemical simulation (for example, AlphaFold can now predict the structures of proteins, DNA, RNA and how they interact¹⁸). How much better would a quantum computer need to be to justify its premium cost?

7. However, there will remain problems where optimal “good enough” solutions (i.e. generated by AI) are not sufficient, including cryptanalysis.

¹⁴ Most case studies are on highly specific non-commercial physics simulations like Ising models and High Energy Physics

¹⁵ <https://quantumzeitgeist.com/nisq-dead-john-preskill/>

¹⁶ Figure 1. <https://www.darpa.mil/sites/default/files/attachment/2024-12/qbi-proposers-day-2024-program-manager.pdf>

¹⁷ We note that the DARPA Quantum Benchmarking Initiative (“QBI”) pursues a quantum computing solution that meet this criterion.

¹⁸ <https://blog.google/technology/ai/google-deepmind-isomorphic-alphafold-3-ai-model/>

05

Qualification Criteria

We use the following criteria to qualify any potential investment in the sector.

5.1 Unit Economics: the envisaged FTQC must be commercially viable

The most efficient way to assess the suitability of a quantum computing hardware company for investment is to assume the technology and roadmap hold as proposed^{19,20} and estimate the unit economics of these machines at utility scale.

End-users do not have unlimited budgets to spend on quantum computing and quantum computers need to be appropriately priced to attract demand and to be profitable such that the company can deliver venture-style²¹ returns to investors.

Additionally, appropriate pricing is an important competitive advantage over competitors using other modalities that may succeed in reaching fault-tolerance but do not have a commercially viable offering. We summarise some of the capex and opex **cost drivers** below.

5.1.1

Capex – very large-scale systems are unlikely to be commercially viable due to the capital cost. The primary cost driver for the capital expenditure of a quantum computing system is the **number of qubits that can fit onto a single Quantum Processing Unit “QPU”** because this number determines the **number of modules** required for a fault tolerant system.

Quantum Computing Module:

Quantum Computing Module: the infrastructure setup required to operate one QPU.

The major cost drivers for a module are the cooling requirements (e.g. cryogenic fridges and cryoplants) but other costs include the quantum processing units (“QPUs”) itself, and the room temperature and cryogenic electronics required for the control and readout of the system. Classical compute including GPUs may also be required in a module.

¹⁹ Most companies have not followed their announced roadmaps and are late on delivery.

²⁰ A check of the reputation of the team, anecdotally and in the literature, identifies parties that are not worth pursuing.

²¹ We specify venture-style returns, because for some governments it may make sense to pursue FTQC at any cost.

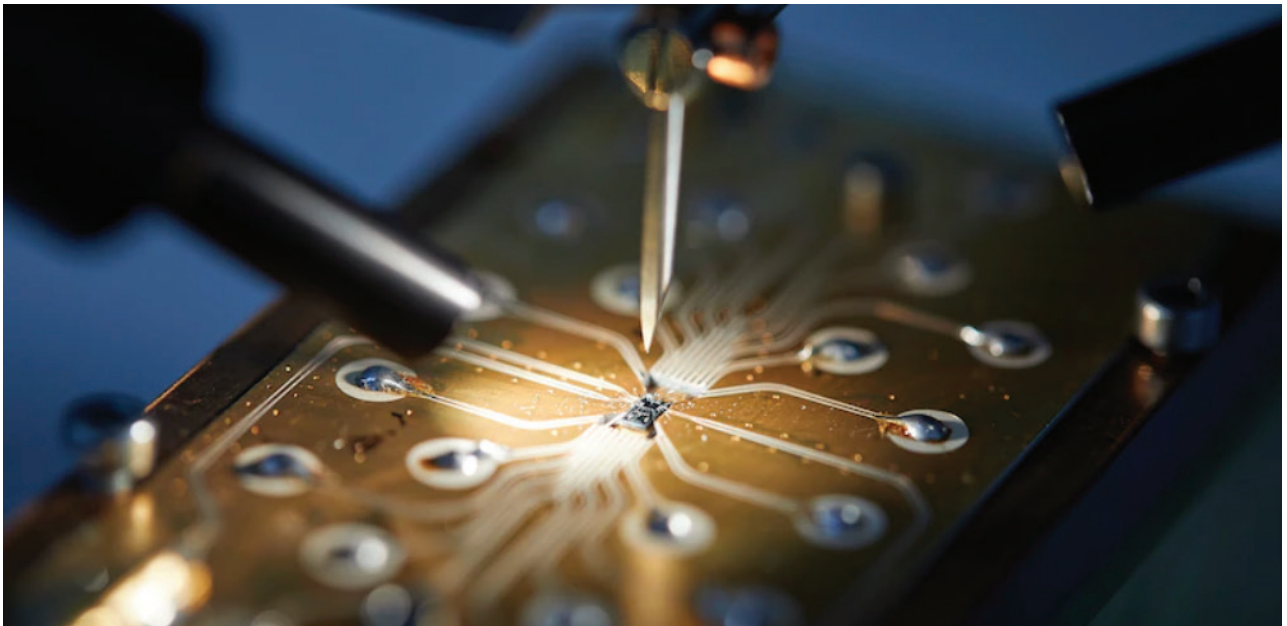
05 Qualification Criteria (Continued)

If a quantum computing system contains multiple modules, there is also the cost of the networking equipment to maintain and transfer information between modules. Some modalities require network architecture tailored to the modality, and in some cases designed and manufactured from the ground up, adding again to the costs to build and run a full-scale quantum computer. Networking costs are out of scope for this analysis but this would significantly increase capex and opex spend.

We assume in this analysis that component costs are equal across modalities such that cost scales only with the number of modules. In reality, most modalities cannot make use of existing semiconductor foundries or tools and therefore are likely to face higher capex costs for the QPU which will factor in the investment of building a dedicated, single-purpose foundry for to build QPUs²² (haven't we learnt this lesson already?²³). Notably, only silicon spin qubits are native to the semiconductor foundry, having been invented for this specific purpose, but other modalities have also adapted some or all of their designs to utilise these fabrication techniques as much as possible²⁴.

5.1.2

Opex – Operational costs are primarily electricity usage which are driven by the **cooling requirements**, the **operating temperature** of the cryogenics, and the **heat dissipated on the qubit stage**. Control electronics are also significant. Other factors to consider are the staffing/personnel costs and building rental and maintenance, costs which increase proportionally to the number of modules required and size of the full system.



²² For example Seeqc (<https://seeqc.com/chip-foundry-services/chip-fabrication>), IonQ (<https://ionq.com/news/ionq-opens-doors-to-first-dedicated-quantum-computing-manufacturing-facility>)

²³ <https://www.investopedia.com/terms/f/fablesscompany.asp>

²⁴ PsiQuantum uses GlobalFoundries silicon photonics platform, QoLab is experimenting with 300mm production lines for its superconducting chips

5.2 Qualifying technical criteria: the technology must have a realistic roadmap to provide commercially useful solutions

The underlying qubit technology must meet these necessary (but not sufficient) conditions. Unless a quantum computing modality can demonstrate all of the criteria below they are outside the risk and return ratios of even deep tech investment timelines and likely should remain in the domain of university-based R&D. These criteria reduces the list of modalities we need to assess from a commercial viability lens.

5.2.1

A Prototyped Qubit – only technologies which have demonstrated prototypes that work according to the minimum basic rules for quantum computation and have mapped out all the challenges for building a full-scale quantum computer. There may be early-stage theories²⁵ for new types of qubits but due to the pressure of market timing, the unknown unknowns, and the difficulties to get to a prototype, we disqualify un-prototyped qubits for investment.

5.2.2

Fidelities of >99% – errors in quantum computers build up quickly. Existing error mitigation and correction protocols assume that errors occur somewhat rarely, so that they can be detected and corrected. This assumption leads to a minimum fidelity for the operations that, in an optimistic analysis, sets the threshold for usefulness at 99% fidelity in all operations. Ultimately, companies will need to achieve fidelities above 99.5% and should have a clear engineering plan to achieve this.

5.2.3

Consistent Fabrication Process – A realistic pathway for useful quantum computation must include a plan (even if that plan is optimistic) for how to integrate, control and measure qubits in a repeatable manner. Qubits that were demonstrated in system with properties that are difficult to repeat, such as randomly positioned qubits make it unlikely that these technologies will ever achieve a high qubit count. This is because to make qubits at the scale of millions there needs to be a fabrication process that can be repeated consistently millions of times and that the variability between QPUs are minimal.

5.2.4

Universal Gate Set – we need to know if the qubit will be useful -- this relates to whether a technology promises a “quantum advantage” or the ultimate goal of universal quantum computation. Only with a universal set of basic quantum operations (or gates) can a quantum computer tap into the provably efficient quantum algorithms known at present. This property is achieved once all operations are performed in at least a pair of qubits (one and two qubit operations are sufficient for universal quantum computation).

²⁵ <https://link.springer.com/article/10.1007/s11128-024-04498-4>

06

The Commercial Reality of Different Modalities

Analysing the potential capex and opex costs of different systems shows how important the commercial consideration of a quantum computer is. We have directionally compared the five major quantum computing approaches.

We compare at the level of 4,000 logical qubits²⁶. This number is the departure point for utility scale quantum computers to solve the problems demanded by the market.

Cost estimates are presented only as a magnitude as to capture error and uncertainty. This is also a point in time analysis where we have used, to the best of our knowledge, the most optimistic inputs (i.e. the number of qubits that can fit on a single chip). We have not considered multiple QPUs in one module for simplicity.

Table 1:

The Cost to Build a Quantum Computer – comparing the capital cost for different modalities at 4,000 logical qubits

Modality	Example Companies	Physical Qubits Required (#)	Max Qubits Per QPU (#)	Modules (#)	Total Capital Cost (\$)
Superconducting	Google, IBM ²⁸ , Rigetti	20M ²⁹	20K	1K	Tens to Hundreds of Millions
Photonics	PsiQuantum, Xanadu	20M	5K	4K	Hundreds of Millions to Billions
Ion Traps	IonQ, Quantinuum	20M	32K ³⁰	625 ³¹	Tens of Millions to Hundreds of Millions
Neutral Atoms	Pasqal, QuEra	20M	100K	200	Tens of Millions to Hundreds of Millions
Spins in CMOS	Diraq, Intel, Quantum Motion, Quobly, SemiQon	64M	1B	1	Millions

Table 2:

The Cost to Run a Quantum Computer – comparing the yearly costs (opex + capital depreciation) for different modalities at 4,000 logical qubits

Modality	Example Companies	Physical Qubits Required (#)	Max Qubits Per QPU (#)	Modules (#)	Annual Running Costs (\$)
Superconducting	Google, IBM, Rigetti	20M	1K	20K	Millions to Tens of Millions
Photonics	PsiQuantum, Xanadu	20M	5K	4K	Tens of Millions to Hundreds of Millions
Ion Traps	IonQ, Quantinuum	20M	32K	625	Millions to Tens of Millions
Neutral Atoms	Pasqal, QuEra	20M	100K	200	Millions to Tens of Millions
Spins in Silicon	Diraq, Intel, Quantum Motion, Quobly, SemiQon	64M	1B	1	Hundreds of Thousands

²⁶ Figure 1. DARPA QBI Proposers Day Presentation. September, 2024.

²⁷ The number of modules required for each modality is a technical challenge in itself as companies pursue different ways to network QPUs together. This is a point in time analysis and something we continue to track.

²⁸ IBM plans to use different error correction codes than Google, which would enable them to reduce the error correction overhead, potentially by an order of magnitude.

²⁹ Alice and Bob use cat qubits, which they claim means they require 100,000 cat qubits for 4000 logical qubits, reducing the number of modules required.

³⁰ The number of physical qubits to deliver 4,000 logical qubits may be lower for trapped ions and neutral atoms, at the expense of slower gates.

³¹ There are startups like Oxford Ionics that are trying to solve the module problem in ion traps by using techniques to increase the number of qubits on a single QPU to tens of millions which would reduce the cost of a system to a few million, similar to a spins in silicon system.

06 The Commercial Reality of Different Modalities (Continued)

A conclusion from Table 1 and Table 2 is that if companies are not successful in delivering quantum computing in a single, or possibly a handful of modules (as the number of modules is the biggest cost driver), quantum computers will never be commercially available at the scale required to deliver on the trillions of dollars of value generation the industry is excited about. In other words, it would be difficult to achieve venture-style returns from most quantum computing modalities³². Spins in silicon therefore stand out as one such approach that is pursuing a commercially viable pathway to quantum computing³³.

These large numbers will not come as a surprise. Companies have been self-reporting on these estimates for years. The following quotes are either from companies themselves, or external estimates from reputable sources:

“ Superconducting

Google is aiming to cut the cost of components by a factor of 10 by the end of the decade, putting the cost of a fully functional quantum system at that point at around \$1B. ”

Head of Google's Quantum Programme³⁴

i.e. with current designs and components costs, Google's fault tolerant quantum computer would cost \$10B to build.

“ Photonic

\$940 million investment into [PsiQuantum]...won't cover the cost of building a useful quantum computer ”

Co-Founder of PsiQuantum³⁵

i.e. at least a billion dollars is required to cover the cost of building a PsiQuantum quantum computer.

“ Ion Traps

... the cost estimate for running the \$1 million quantum simulation on the superconducting devices increases to over \$1 billion on an ion trap device. We conclude that under the current pricing model, ion trap devices will be too expensive to reach the scale of practical quantum advantage ”

Lawrence Berkeley Lab Analysis, 2023³⁶

In line with our estimates, an ion trap computer would cost billions to run.

We were unable to find a self-reported estimate from a neutral atom company. We challenge these groups to publish a view.

³² Venture capital funds require large multiples on the initial investment to justify other losses in the portfolio. Depending on the fund, this might mean an investment needs to have the potential to return the value of the entire fund, or a >10x return.

³³ This does not mean spins in silicon do not face technical and engineering challenges but the ultimate goal is a system that is commercially viable. We refer you to <https://www.oezratty.net/wordpress/2024/understanding-quantum-technologies-2024/> for one view on technology challenges.

³⁴ <https://www.ft.com/content/f1d26918-67c5-4b11-b47b-4904606a002f>

³⁵ <https://www.capitalbrief.com/article/psiquantum-needs-even-more-cash-to-build-brisbane-computer-2e70bd23-12a4-44cc-b6fb-4df3061a7559/preview/>

³⁶ <https://dl.acm.org/doi/fullHtml/10.1145/3624062.3625533>

06 The Commercial Reality of Different Modalities (Continued)

Table 3 shows what an example cost to run a commercially useful algorithm might cost. The inputs are T-Gates, Logical Qubits (which impacts the capex and opex) and Gate Speeds (which impacts the opex). Note that ion trap solutions are much higher than the other modalities, this is because the lower clock speeds mean problems need to be run for a longer period of time.

This presentation of the commercials suggests that spins in silicon has a competitive pricing advantage and that modalities outside of spins in silicon may not even be viable when considering the value of the algorithm to an end-user.

Table 3: Costs per Example Problem

Problem	T-Gates ³⁷	Logical Qubits	Supercon.	Photonic	Ion Traps	Neutral Atoms	Spins in Silicon
Nitrogen Fixation Catalysis	1.00E+11	2500	\$0.4M	\$12M	\$791M	\$4M	\$164
Propellant	2.58E+13 ³⁸	4333	\$177M	\$5B	\$353B	\$1.7B	\$43K
Amyloid Beta	1.17E+14	4728	\$876M	\$27B	\$1.7T	\$8.8B	\$199K
Corrosion Mitigation	1.00E+15	10000	\$16B	\$495B	\$31.6T	\$158B	\$2M

6.1 Practicality – Form Factor

The form of the quantum computer itself is also important as it determines its applications and how close it can be to classical compute. A smaller, more portable system has a greater number of use-cases including on prem system, data centre co-location, defence and industry applications including operation at the edge.

Large quantum computers also limit the number of customers because they are expensive, cumbersome and have a long lead time³⁹ and would therefore act as a throttle on the total market (a World Economic Forum panel in 2024 suggested there would only be a market for a handful of quantum computers in the world based on an assumption that utility scale quantum computers must be very large⁴⁰) whereas small quantum computers mean customers can buy many quantum computers i.e. hundreds or even thousands to co-locate in an HPC or data centre.

Table 4: Footprints of Different Modalities at 4,000 logical qubits

Modality	Company Examples	Footprint (m2)
Superconducting	Google, IBM, Rigetti	20,000 (a large data centre)
Photonics	PsiQuantum, Xanadu	4,000 (a small data centre)
Ion Traps	IonQ, Quantinuum	625 (a tennis court)
Neutral Atoms	PASQAL, QuEra	200 (half a basketball court)
Spins in Silicon	Diraq, Intel, Quantum Motion, Quobly, SemiQon	5 (a king-sized bed)

These footprints are likely underestimates, given the size indication from the companies themselves.

³⁷ DARPA, Quantum Benchmarking. <https://www.darpa.mil/research/programs/quantum-benchmarking>.

³⁸ Assumes 1 T-Gate = 1 Operation

³⁹ How long can a customer wait for a quantum computer to be built?

⁴⁰ <https://www.weforum.org/meetings/world-economic-forum-annual-meeting-2024/sessions/quantums-black-swan-event/>

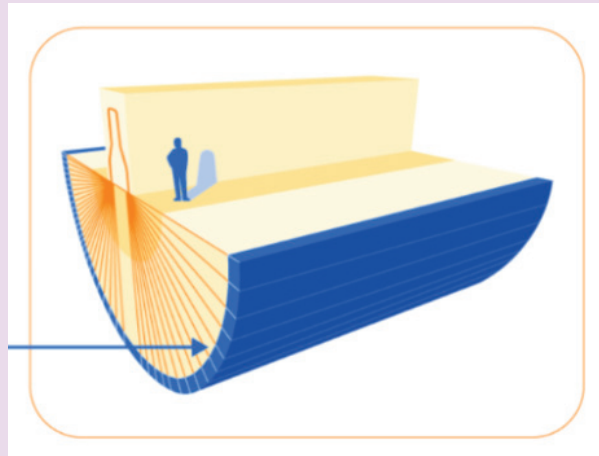
06 The Commercial Reality of Different Modalities (Continued)

Table 5: Self-reported Fault-Tolerant Size Estimates

Superconducting

“ If one were to build a quantum control and measurement system for a million transmon qubits using present Google technology, it would occupy over 15,000 m² of floor space and dissipate about 40 MW ”

(IEEE, 2021)



Google's million physical qubit quantum computer⁴¹ pictured at scale next to a person.

Photonics



PsiQuantum envisages a data-centre-sized quantum computer⁴², recently moving into a 440-acre site to build a quantum computer in Chicago.

PsiQuantum's quantum computer will have

“ hundreds of cabinets, each with hundreds of chips, optically connected and electrically wired and cooled to low temperatures. It will look like a data centre or HPC ”

(Jeremy O'Brian, Co-Founder, PsiQuantum @ Commercialising Quantum 2024)

Xanadu estimated it would need “tens of thousands of server racks”⁴³ for 100K logical qubits, reflecting ~9,000m². This is likely an underestimate as it assumes they achieve a 100:1 error correction overhead.

⁴¹ <https://thequantuminsider.com/2023/02/23/google-quantum-ai-researchers-say-error-correction-milestone-is-an-important-step-toward-practical-quantum-computing/>

⁴² <https://www.psiquantum.com/news-import/psiquantum-envision-data-center-sized-quantum-computer>

⁴³ Scaling and networking a modular photonic quantum computer | Nature

06 The Commercial Reality of Different Modalities (Continued)

Ion Traps

Self-dubbed as a

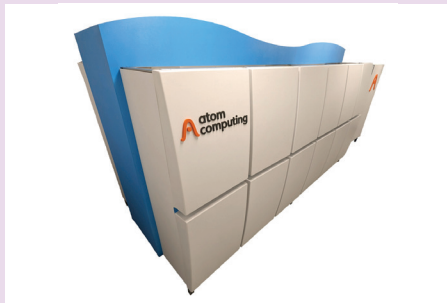
“data-centre form factor”,

IonQ also anticipate a large-sized quantum computer.

This is **larger than our estimates**, suggesting there are more modules required than we have estimated.



Neutral Atoms



Neutral atom companies are quieter about their estimates however the picture here shows **Atom Computing's 1,000-physical qubit device**.

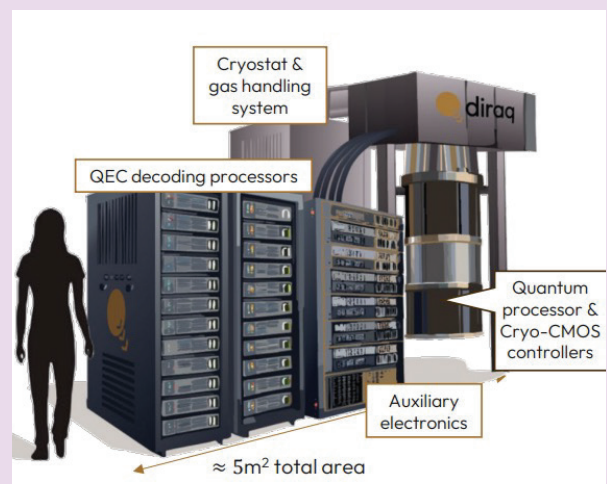
10,000x bigger would bring it closer to a data centre size rather than a basketball court size as estimated.

Spins in Silicon

Most spins in silicon companies see final products as

approx. 5m²

and do not require networking between modules.



6.2 Practicality: Power Consumption

Another consideration is how much power consumption is acceptable. Beyond the impact on operating expenses, power consumption is critical for systems integration. For example, data centres operate in the tens to hundreds of MW range and are already facing challenges in relation to power availability⁴⁴, integrating a power-hungry quantum computer into a data centre is infeasible. Deploying these sorts of fault tolerant quantum computers would require dedicated power grids (or a nuclear power plant) making them inaccessible for most use-cases. It would also put geographical limitations on quantum computers as they would need to be in locations where this level of power is available at an appropriate price (~\$2/kW).

Table 6 – Energy Requirement Estimates at 4,000 Logical Qubits⁴⁵

Modality	Company Examples	MW
Superconducting	Google, IBM, Rigetti	160 ⁴⁶
Photonics	PsiQuantum, Xanadu	100 ⁴⁷
Ion Traps	IonQ, Quantinuum	140 ⁴⁸
Neutral Atoms	PASQAL, QuEra	4 ⁴⁹
Spins in silicon	Diraq, Intel, Quantum Motion, Quobly, SemiQon	0.4 ⁵⁰
Data Centre	Hyperscale	200
Most Power-Hungry HPC	Aurora	40

A high-performance supercomputer like Frontier consumes ~21MW but delivers 1 exaFLOP⁵¹. If a quantum computer requires greater power, it must deliver quantum advantage significantly beyond what classical computing can achieve – otherwise, the cost-benefit trade-off may not justify its use.

Olivier Ezratty⁵² has also done 4,000 logical quantum computer power consumption estimates based on actuals. He sets an acceptability threshold at 40MW which assumes a quantum computer must consume less power than the most power-hungry supercomputer, Aurora. The green line represents a max at 1MW⁵³, assuming the equivalent of a 40MW quantum computer could be split up into 40 machines. A spins in silicon quantum computer would sit well below even the least power hungry QPU Vendor listed here and well below the likely acceptability threshold of 40MW and below 1MW.

⁴⁴ AI data centers causing “distortions” in US power grid – Bloomberg – DCD

⁴⁵ These estimates are based on reported power consumption and assumes linear scaling with number of qubits. This is not a ground up analysis as done with the cost estimates and so we have lower confidence in these numbers.

⁴⁶ Assumes 1M physical transmons dissipate 40MW and that this scales proportionally up. <https://tf.nist.gov/general/pdf/3119.pdf>

⁴⁷ Optimistic analysis based on work from Olivier Ezratty. <https://www.oezratty.net/wordpress/>

⁴⁸ Based on IonQ’s estimate of 35W per qubit. <https://ionq.com/blog/extreme-high-vacuum-xhv-reduces-computational-energy-costs-and-further-reduces-room>

⁴⁹ QuEra estimated a 10kW requirement for 10,000-qubit quantum computer. For 4M qubits, assuming energy consumption scales with number of qubits, is 4MW. We suspect this a major underestimate.

⁵⁰ Assumes 100W per logical qubit.

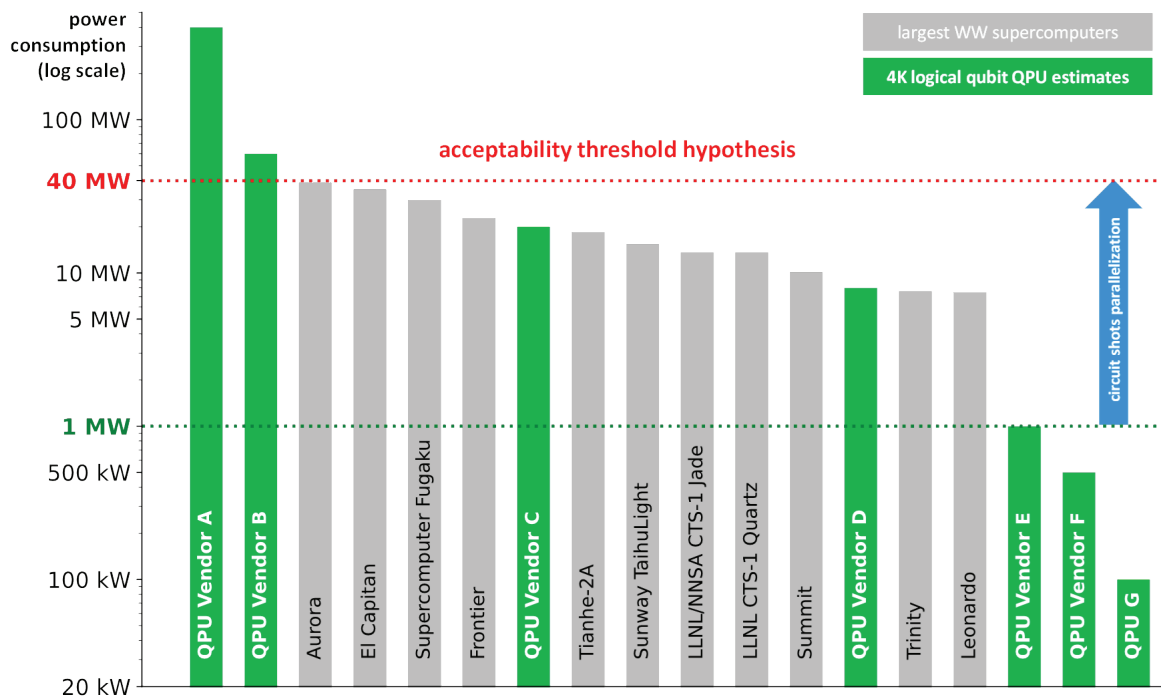
⁵¹ <https://www.datacenterdynamics.com/en/news/frontier-remains-worlds-most-powerful-supercomputer-after-aurora-delays/>

⁵² <https://www.oezratty.net/Files/Conferences/Olivier%20Ezratty%20QEI%20Workshop%20Jan2025.pdf>

⁵³ Quandela estimates its largest quantum computer should keep its power consumption below 1MW. Quandela announces a 100,000-fold reduction in the number of components needed for fault-tolerant calculations, a major breakthrough for photonic quantum computing. We note that Quandela’s roadmap targets 50 logical qubits by 2029 so its “largest quantum computer” is not very large.

06 The Commercial Reality of Different Modalities (Continued)

Figure 2 QPU vs. HPC Power Consumption Estimates



6.3 What would an organisation pay to buy or to use a quantum computer?

We've shown single module quantum computers like spins in silicon have a pricing advantage, we go further to show that most modalities are not commercially viable, even if there were no cheaper alternatives.

In lieu of demand trends for quantum computers, there are few references we can draw on to estimate the maximum an individual or company would pay for to buy or to use a quantum computer.

1. Supercomputing

High Performance Computers ("HPC") are the state of the art, most powerful computers in the world. It cost US\$1B to build the 2020's most powerful supercomputer⁵⁴ and around US\$600M to build 2024's most powerful supercomputer. Although it's possible a government might pay a premium for a quantum computer, quantum computing will only be required for a part of an algorithm and a quantum computer also has less use-cases than a supercomputer, and so a US\$1B price for a quantum computer seems relevant. If we consider two government programmes including the DARPA QBI⁵⁵, which will eventually fund promising groups up to ~US\$300M to build a quantum computer, or the Australian government's investment into PsiQuantum of ~AU\$1B⁵⁶, these programmes are well below the US\$1B threshold and suggest government price expectations sit around the US\$0.5B mark.

⁵⁴ <https://www.dailymail.co.uk/sciencetech/article-8450817/japans-fugaku-crowned-fastest-supercomputer-2-8-times-power-predecessor.html>

⁵⁵ DARPA QBI Proposers Day Presentation, 2024

⁵⁶ <https://www.afr.com/technology/psiquantum-confident-it-has-the-fastest-track-in-quantum-race-20250219-p5ldim>

06 The Commercial Reality of Different Modalities (Continued)

2. Scientific Endeavours

We can look at some of the other projects and programmes that the US government and large organisations fund, to give us an acceptability threshold or a price cap. ChatGPT required 30,000 GPUs to train, for a total cost of \$1B. The entire OpenAI GPU cluster (720,000 NVIDIA H100 GPUs) are worth \$21.6B. The James Webb Space Telescope programme cost \$10B. Launching a space shuttle cost about \$1.6B per launch. The Manhattan Project cost \$30B (in 2023 dollars)⁵⁷ which we can consider as an example of an unconstrained budget i.e. the absolute max, and only if it were critical to national security.

These examples suggest that anything above \$30B is ludicrous and that \$10B would be a (very generous) acceptability threshold.

3. R&D Budgets

Most quantum computing companies suggest that they will offer a pay-by-use service (via a Cloud platform), especially because proposed roadmaps make selling on-prem systems infeasible. We therefore compare in the context of the highest-spending potential customers' R&D budgets to obtain an opex maximum for a quantum computer.

Customers are not able to launch themselves in a multi-million-dollar R&D project that is solely based on computation modelling. The insights gained by quantum computation for drug discovery, chemical process improvements still need to be replicated in the laboratory, so it should only represent a small fraction of the total R&D budget. We have considered 5% as a generous allocation.

Sector	Example Company	R&D Budget	Estimated MAX R&D for QC (5%)
Oil & Gas	Shell	\$1.287B (2023)	60M
Oil & Gas	Saudi Aramco	\$0.573M (2019)	29M
Mining & Resources	BHP	\$0.199B (2022)	10M
Mining & Resources	Rio Tinto	\$0.972B (2022)	49M
Pharma	Merck	\$30.5B (2023)	1.5B
Pharma	Pfizer	\$10.7B (2023)	0.5B
Finance	Goldman Sachs	0.629B (2023)	30M
Finance	JP Morgan	\$17B (2024)	0.9B

If a quantum computer costs a minimum of high tens of millions of dollars a year to run, it is unlikely that it would be attractive for industry.

Conclusion on Max Value

Points 1 and 2 relate to the upfront cost an organisation might pay for a quantum computer and so comparing to *Table 1: Comparing the Upfront CAPEX for Different Modalities at 4,000 Logical Qubits* on page 13. Between Points 1 and 2, there is range of upfront spending an organisation could pay for a quantum computer at \$1B-\$10B. Even with this generous range, we believe an organisation can cross off superconducting systems and photonic systems as commercially viable systems.

Point 3 relates to a yearly cost so we compare to the yearly cost estimated in *Table 2: The Cost to Run a Quantum Computer* – for most industries, all modalities are infeasible except for spins in silicon where the only exceptions to this are the biggest pharmaceutical and financial services companies in the world.

Additionally, if we compare R&D budgets to *Table 3: Costs per Example Problem* we see that for 3 out of the 4 commercially relevant algorithms provided, the cost to run these problems exceeds the estimated MAX R&D spend on quantum computing many times over, and in the many cases exceeds even the total R&D budgets of the biggest spending companies in the world.

⁵⁷ <https://www.nps.gov/mapr/faqs.htm>

07

A Public Proof of the Thesis?

We can look to the public markets to see some support for our thesis that many quantum modalities will not be able to deliver profitable companies. Those quantum companies that have listed, often on the back of speculative earnings projections and market share claims, have failed to return to post-IPO investors. Their annual revenues remain below \$50M USD and are largely made up of government subsidised services contracts. None are profitably selling time on their systems to many clients at scale. This 'failure to launch' stems from:

1. There is no commercial value in systems that have at best a few thousand qubits on offer. These Noisy Intermediate State Quantum Computers ("NISQ") are interesting; they allow groups to set up and run highly specialised algorithm runs that in turn demonstrate the potential for commercial application, but none of them have saved FEDEX millions through route optimisation, or Merck billions through novel drug design, or cracked two-factor authentication on a single encrypted WhatsApp message.
2. The scale projections, that is the unit economic fundamentals, that link users to future profitability are not there yet for any of the listed quantum computing companies. None of the listed companies can show how much their service will cost once at scale, and what they can charge for it in turn. Analysts cannot determine when and if each company will become profitable. User numbers, revenues per service call etc all remain opaque. This is unlikely to change any time soon. The result being that the stocks rise and fall on sentiment – Google announces a superconducting breakthrough in December 2024 and all quantum stocks rise. Nvidia's CEO says he thinks commercial quantum computing is still a decade away and they fall again⁵⁸. Fig 3 highlights some of the recent volatility.

Figure 3 Impact of Sentiment on Rigetti, IonQ and Dwave⁵⁹



⁵⁸ <https://www.reuters.com/technology/quantum-computing-stocks-take-hit-nvidia-ceo-predicts-long-road-ahead-2025-01-08/>

⁵⁹ <https://www.oezratty.net/wordpress/2025/quantum-computing-utility/>

07 A Public Proof of the Thesis? (Continued)

By way of analogy, in the AI space, even OpenAI/ChatGPT with its huge operating costs, requiring many millions of Nvidia's latest chips while currently loss making on an individual service call basis is seeing a lift in value each month. The power and overheads required to deliver a ChatGPT service to a single user are more than that user will pay for the service. But the data centres and stack of Nvidia pods powering the LLMs are generating growing revenues that in turn demonstrate the economies of scale required for per customer profitability. Despite being valued at a staggering \$157 billion⁶⁰, the company is far from profitable: OpenAI reportedly⁶¹ expected \$11.2 billion in revenue by the end of 2025 (its circa \$4B at the start of 2025), but also anticipated spending ~\$14.7 billion to achieve that revenue, equating to a ~\$3.5 billion loss. But the market has calculated that they will clearly get to profitability.

Table 7

The current state of returns for the publicly listed quantum computing companies
(Pitchbook, Retrieved March 2025)

Key Metrics (TTM) Amounts in thousands, USD (except Ratios, Multiples & share items)	QBTS D-Wave	IBM International Business Machines	IONQ IonQ	RGTI Rigetti Computing
Companies (4)	2024-12-... Filed: 14-Mar-2025	2024-12-... Filed: 25-Feb-2025	2024-12-... Filed: 26-Feb-2025	2024-12-... Filed: 07-Mar-2025
Ratios				
EBITDA Margin	-1,563.95%	18.21%	-768.78%	-1,815.94%
Revenue % Growth	0.79%	1.44%	95.41%	-10.14%
EBITDA % Growth		-18.50%		
EBIT % Growth		-29.76%		
Net Income from Continuing Operation...		-5.62%		
Net Income Available to Common Stock...		-5.85%		
Current Ratio	6.14	1.04	10.50	17.42
Quick Ratio	5.95	0.86	9.77	16.39
Debt to Equity	0.58	1.92	0.04	0.05
Total Debt to Equity	0.61	2.13	0.05	0.07
Total Asset Turnover	0.11	0.46	0.08	0.06
Normalized Return on Equity		39.83%	-34.41%	-44.90%
Normalized Return on Assets	-90.22%	7.14%	-29.51%	-28.92%
Normalized Return on Invested Capital	-131.54%	12.34%	-36.38%	-39.04%
Multiples*				
Stock Price	8.40	219.83	41.77	15.26
Market Cap	1,893,271	203,264,744	9,038,704	4,273,554
EV	1,918,626	249,770,744	8,755,227	4,203,464
EV to Revenue	203.59	3.99	233.67	353.47

⁶⁰ <https://sherwood.news/business/openai-is-worth-more-than-snap-dominos-zillow-the-nytimes-levis-and-7-other/>

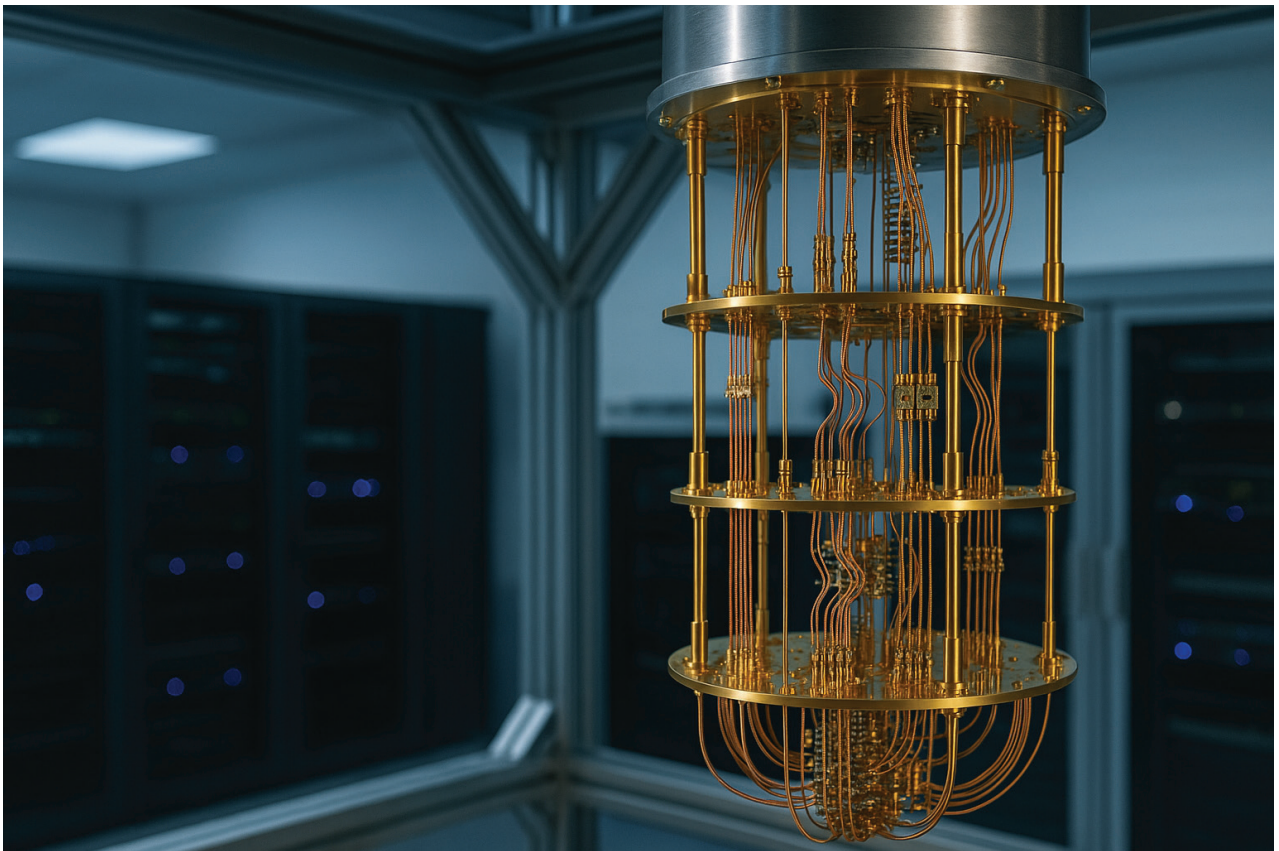
⁶¹ <https://searchendurance.com/chatgpt-statistics/>

07 A Public Proof of the Thesis? (Continued)

This is not the case for public quantum computing companies. D-Wave uses old fashioned annealing for its quantum computer, IonQ employs ion-traps, while Rigetti and IBM provide superconducting systems. In the case of IonQ, Rigetti and D-Wave, we can see from Table 7 that they are far from profitability and have much higher multiples than other technology companies – Nvidia's, for example, peaked at 33.7x in January 2024. IBM is included to show a profitable business that also has a quantum computing programme. While VCs may have made a return by pushing the startups to go public, investors post IPO would have taken a hit. Frustratingly, these companies distract attention and capital from those doing excellent and grounded work at private companies and research labs.

Analysis of the sector at large would suggest the strong returns to early investors will come from the acquisition and merger phase as 'Big Tech' bids for those ventures that can deliver many millions of qubits in single cryogenic fridges.

If a quantum computing company in 2025 tells you they are planning an IPO within three years we would be concerned.



08

Conclusion

We hope that this paper provokes discussion on the commercial viability of quantum computers.

The industry needs to be asking; **how much** would the Utility Scale Quantum Computer **cost to build**, how much would it **cost to run**, how much **power** would it use and **how much space** will it take up?

It seems clear that many of the promises being forecasted by the current crop of late-series or listed quantum companies in respect to commercial viability are particularly challenging – reality is against them. Barring some breakthrough in basic physics there seems significant doubt that a superconducting system can ever provide a commercially viable quantum computer – they will be too big and expensive to run. The same analysis can be seen for photonics, ion traps and neutral atom systems. Even with the ratios between physical and logical qubits falling to less than the current standard of 1,000:1 each of those approaches will eventually require multiple devices in multiple fridges, networked across large physical warehouse sized spaces with enough energy to run a small city.

At current state, we believe only the spins-in silicon approach – still relatively young in their capital journey when compared to the first wave – has a path to commercial profitability. Genuine long-term investors, and government funders looking to establish genuine industries with job creation, should heavily consider commercial viability criteria when looking at quantum computing investments.

Utility scale quantum computing will arrive, and certainly well within the decade marker set down by Nvidia's CEO. When it does a whole new industry sector will open up. The coding talent and smart innovators currently working on AI and robotics will be presented with quantum systems at scale that make economic sense to run. At that point, we can see then the projected trillions of dollars begin to flow.

09

About the Author

ICM Limited is an international fund manager and corporate finance adviser with expertise in listed equity, private equity, and fixed income. ICM manages US\$1.1 billion directly, with a further US\$35 billion held by investee and affiliated companies, and specialises in the following investment sectors: utility & infrastructure, financial services, resources, mobility and technology⁵⁸.

For over three decades, the ICM team has been investing in public, private and capital markets. It focuses on fundamental value generation, relentlessly seeking out opportunities to provide investment opportunities where the market has mispriced the risk in a country, industry, or company.

The ICM Emerging Technologies focuses on investments which bridge the gap between the demand for and the supply of compute. It has investments in quantum computing companies Diraq and Q-CTRL.

9.1 ICM Emerging Technologies Team



Matthew Gould
Portfolio Manager at ICM

Matthew has led data centre and high performance compute projects in the USA and EU across 20 years and drove emerging technology acquisitions for HP. He has founded and listed technology companies including NLP company Arria NLG.



Kate Prebble
Investment Principal at ICM

Kate has a background in science and mathematics and has worked with early-stage deep tech companies for 5+ years. In 2024, she spent the year based in deep tech ecosystems around the world and has an excellent global network of researchers, investors and end-users.

9.2 Acknowledgements

Thank you to all those who provided feedback on this paper namely Prof Andrew Dzurak, Dr Andre Saraiva, Olivier Ezratty, Dr Bill Jeffrey.

⁵⁸ As at 31 December 2024.

10

Appendix

10.1 Quick Overview of Spins in Silicon

Currently we see the spins in silicon modality as the most convincing, commercially viable pathway to build a full scale, fault-tolerant quantum computer.

Spins in silicon can offer quantum computing systems that have a genuine pathway to scale to millions, and eventually billions of qubits on a single chip. In 2025, multiple startups in the space have demonstrated that they are manufacturable on standard semiconductor foundry lines, a fault tolerant system could be offered in a small module (~5m²) and therefore could be used in a range of contexts including in data centres, HPCs, edge and defence. It uses an amount of power that could be supplied without stressing the grid, and it can be built and operated at a fraction of the costs of other modalities. It may be useful therefore to look a little deeper at the history and background of the spins-in-silicon modality.

10.1.1 A short history of spins in silicon

When quantum computing was conceived of in 1980, scientists dove into the challenge by altering existing technologies to create qubits. The four other modalities we have previously mentioned; superconducting, trapped ions, neutral atoms and photonics already existed or were being researched for other applications (e.g. supercomputing, telecommunications, atomic clocks) and so were naturally used as the first qubits. It was not until the early 2000s that scientists confirmed that many millions of physical qubits would be required for the error correction codes that make quantum computers useful and so these early technologies were not necessarily chosen because of their ability to scale but as proof points for a new frontier.

Spin qubits, however, were conceived of as an ideal qubit and developed from scratch because of the appeal of scalability and ability to leverage existing manufacturing capabilities. However, spin qubits' disadvantage was as a late-comer to the quantum computing race; Bruce Kane's initial proposal to use electron spins as qubits using implanted atoms was not until 1998 and Laureate Professor, now Diraq CEO & founder, Andrew Dzurak's discovery of using a modified transistor as a quantum dot was not until 2007, with his group only demonstrating the first qubit in silicon CMOS⁶² in 2014. Because spin qubits were not part of the cohort of technologies already being pursued for other use cases, spins in silicon are in their infancy compared to other quantum processing technologies. As a result, the quantum engineering aspects of this technology are not yet as developed as others. This explains the lag in key metrics, for example, why spin qubit systems only have 8 qubits compared with the 1,000+ qubits now cited by technology giants like IBM.

⁶² The name for the semiconductor process which make the chips in our everyday electronics

10 Appendix (Continued)

Other quantum technologies have acknowledged the clear advantage of silicon for integration and producing millions of components. They are now retrofitting CMOS compatibility e.g. superconducting circuits are being adapted for fabrication on top of silicon substrates, reconfigurable ion traps are being developed with MOS gate electrodes, and photonic circuits are being adjusted from the optics tables to be routed through silicon photonic chips.

Spins in quantum dots are native to silicon and so there is no need to adapt. Diraq for example has developed its designs to obey the very strict fabrication rules that have allowed the miniaturisation of transistors for decades. It already has designs for an architecture that would hold billions of qubits in a similar way to modern electronics holding billions of transistors⁶³. That means that Diraq's qubits can leverage the most advanced fabrication nodes in CMOS foundries. Other spins-in-silicon start-ups are demonstrating similar, sensible commercial approaches.

The size of the quantum computer produced is also important, and spins in silicon is the only modality with a theoretical basis to hold billions of qubits on a single chip in a single unit. This chip will need to be cooled down (to the temperature of outer space), meaning it's unlikely we will ever have a quantum chip in our phones, but a quantum computer in a single unit with the footprint of a king bed makes a lot more commercial sense than one the size of a data centre as is proposed by other modalities.

Putting these two ideas together – manufacturing at scale and small physical size means spins in silicon startups will benefit from economies of scale and lower operation costs, making it difficult for others to compete on price at utility scale.

10.1.2 Key advantages of spins in silicon

Chat with any of the founders of spins-in-silicon companies and they will provide the full detail on the technical benefits of their modality. From our core lens of commerciality, the advantages are obvious and can be conveyed simply.

⁶³ <https://www.nature.com/articles/s41467-017-01905-6>

10 Appendix (Continued)

This is driven by four USPs – Small Size, Manufacturable, Scalable, and Low Power Consumption.

These four USP's can also work as challenge questions to providers of other modalities

1. Small Size

Silicon spin qubits are 20-30nm, similar to the size of real transistors. This simple physical reality has huge implications for the overall architecture of the systems.

2. Manufacturable

Silicon spin qubits are compatible with CMOS foundry manufacturing and this now been proven out by many teams including Intel⁶⁴, Diraq⁶⁵, Quantum Motion⁶⁶ and Quobly⁶⁷. Beyond having a manufacturing process that already exists, silicon spin proponents benefit from the advances that come with them cost cutting edge process nodes, smaller feature sizes, and more advanced manufacturing at a regular cadence. They can also be managed by standard control electronics of the sort used to drive classical computing silicon-based devices. A strong cost advantage.

3. Scalable

In part because of the small size of silicon spin qubits and in part because of the manufacturing advantages of CMOS, many qubits can fit onto a single chip – potentially billions.

4. Low Power Consumption

Silicon spin qubits require much less energy than other modalities, in part because full-scale silicon spin systems would have the form factor of a single module and therefore require limited cryogenic cooling and because the qubits can operate at a higher temperature⁶⁸. Again this simple physical quality drives huge advantages from the single qubit gate up through the architecture to the physical size of the total device.

⁶⁴ <https://www.intc.com/news-events/press-releases/detail/1693/intel-takes-next-step-toward-building-scalable>

⁶⁵ <https://diraq.com/newsdesk/diraq-produces-device-using-semiconductor-infrastructure>

⁶⁶ <https://quantummotion.tech/partnership-with-globalfoundries/>

⁶⁷ <https://quobly.io/news/quobly-announces-key-milestone-for-fault-tolerant-quantum-computing/>

⁶⁸ <https://diraq.com/newsdesk/hot-qubits-cool-logic>



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