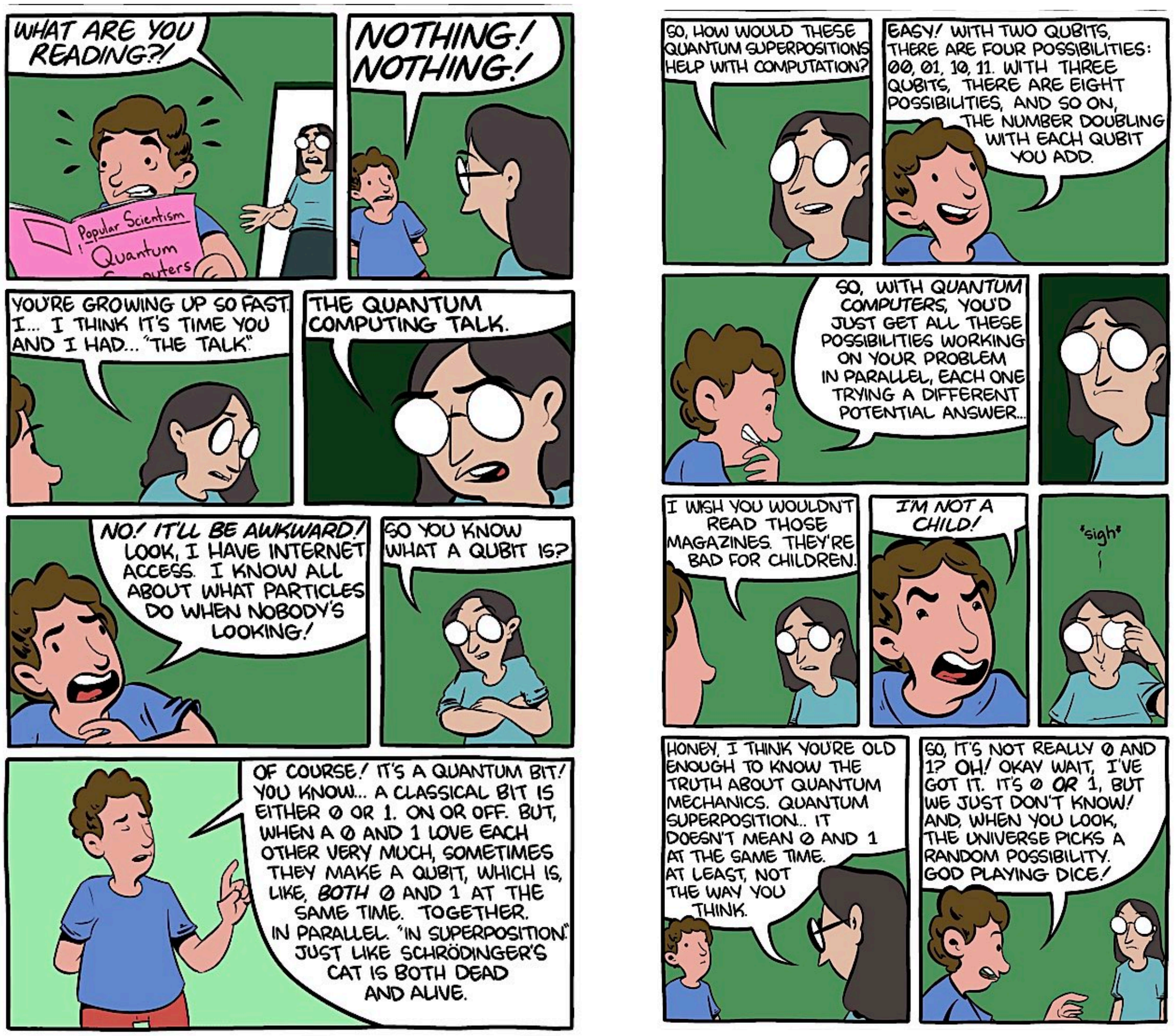
An Environmentalist's Guide to Quantum Computing



Cartoon: https://www.smbc-comics.com/comic/the-talk-3

David Rejeski

Visiting Scholar · Environmental Law Institute · Washington, DC

Associate Researcher · Weizenbaum Institute · Berlin, Germany

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ABOUT THE AUTHOR

David Rejeski is a Visiting Scholar at the Environmental Law Institute in Washington, DC, and an Associate Researcher at the Weizenbaum Institute in Berlin, Germany, where he works primarily on projects designed to improve our understanding of the energy and environmental impacts of the digital economy. He served for over a decade as director of the Science, Technology, and Innovation Program at the Woodrow Wilson Center, where his work focused on understanding emerging technologies, their underlying innovation ecosystems, as well as their impacts and implications for public policy and governance. Study areas included synthetic biology, nanotechnology, and additive manufacturing. Rejeski has published widely, with articles appearing in: *MIT Technology Review, Science, Nature, Journal of Industrial Ecology, Journal of Cleaner Production, Issues in Science & Technology, Technology & Society, Additive Manufacturing, Foresight, Environmental Management, Environmental Science & Policy, Environmental Science & Technology, Environmental Forum,* the *Environmental Law Reporter* and *Wilson Quarterly*. Prior to the Wilson Center, he worked at the White House Office of Science and Technology Policy (OSTP) on a range of topics including the development and implementation of the National Environmental Technology Strategy. He spent three years heading up the Future Studies Unit at the Environmental Protection Agency (Office of Policy, Planning and Evaluation). He is a Fellow of the National Academy of Public Administration (NAPA), and a board member of American University's Center on Environmental Policy. He has also served on EPA's National Advisory Council for Environmental Policy and Technology (NACEPT), EPA's Science Advisory Board (SAB), the National Science Foundation's (NSF) Advisory Committee for Environmental Research and Education, and was a Visiting Fellow at the International Institute of Applied Systems Analysis (IIASA) in Austria. He has graduate degrees in public administration and environmental design from Harvard and Yale universities.

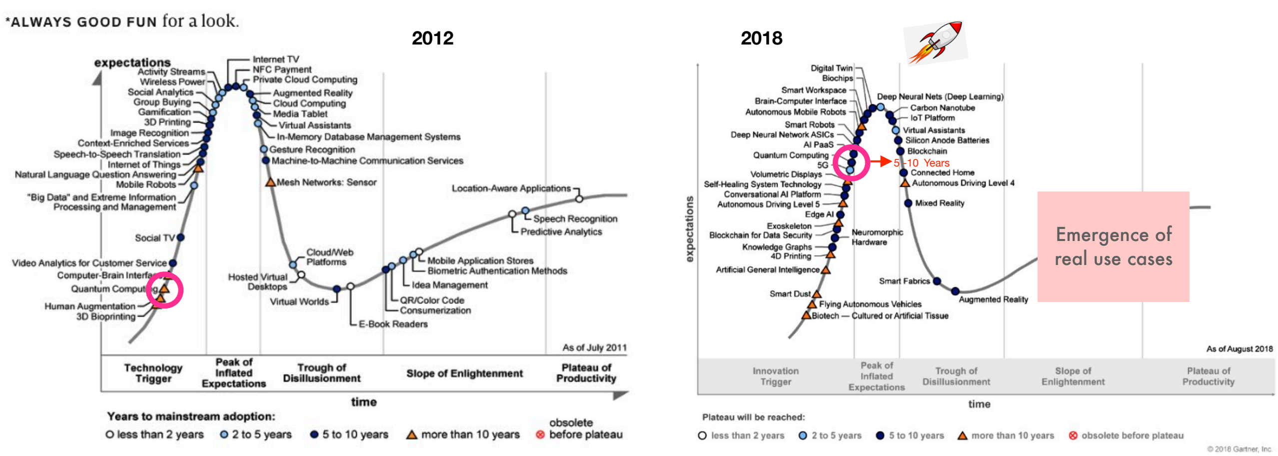
Another Ride on the Hype Cycle

Quantum Computers Could Change the World — Provided They Can Work [1]

Quantum Computing Just Might Save the Planet [2]

The Quantum Era is Arriving, And It Will be Transformational! [3]

Does any of this sound familiar? Remember "AI Could Be A Critical Tool to Save the Planet."[4]. Readers with longer memories may recall: "Can Nanotechnology Save the World?[5]. Or how about: "Saving the Planet with Robots, Microbes, and Nanotechnology."[6] The headline generation algorithm is simple: [Fill in the latest wiz bang technology], then add: 'will save the planet.'



Quantum computing was on Gartner's list of important emerging technologies 11 times between 2000 and 2017, each time with the categorization that commercialization is more than 10 years away. It disappeared after 2018, not appearing in subsequent graphics, and never seemed to reach the 'peak of inflated expectations' or the 'trough of disillusionment'. What happened?

In 2018, Todd Holmdahl, the Microsoft vice president then in charge of their quantum computing efforts, predicted that, "…they would have a working topological qubit by the end

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[1] Walsh, Brian 2022. "Quantum Computers Could Change the World — Provided They Can Work," Vox, May 24. https://www.vox.com/23132776/quantum-computers-ibm-google-cybersecurity-artificial-intelligence-white-house

[2] Cooper, P. et al. 2022. "Quantum Computing Just Might Save the Planet," McKinsey Digital, May 19. https://www.mckinsey.com/business-functions/mckinsey-digital/our-insights/quantum-computing-just-might-save-the-planet

[3] Books, Chuck 2022. "The Quantum Era is Arriving, And It Will be Transformational! " Forbes, July 20. https://www.forbes.com/sites/chuckbrooks/2022/07/20/the-quantum-era-is-arriving-and-it-will-be-transformational-/?sh=3f58e944e7a2

[4] https://www.theguardian.com/ai-for-earth/2019/apr/30/ai-tech-sustainable-planet

[5] https://www.conwayhall.org.uk/blogs/2014/12/can-nanotechnology-save-the-world/

[6] https://wyss.harvard.edu/news/saving-the-planet-with-robots-microbes-and-nanotechnology/

of the year, and a commercial quantum computer based on the technology in five years' time."[7] That didn't happen. That same year, Christian Weedbrook, the founder of the Canadian quantum computing firm Xanadu observed that, "There is still a lot of value being created — it's just a case of whether there is too much hype."[8] A more nuanced assessment of the quantum computing timeline was offered by the cofounder and CEO of PsiQuantum in a discussion with McKinsey that "quantum computing applications once thought to be decades away, could now happen within the next ten years."[9] More recently, Sankar Das Sarma of the University of Maryland observed that, "I'm disturbed by some of the quantum computing hype I see these days, particularly when it comes to claims about how it will be commercialized… quantum-computing hype has apparently convinced people that these systems already exist or are *just around the corner [italics mine]*."[10]

It is important to note that hype fills important functions. As science historian Ed Tenner has noted, "Academic scientists, medical researchers and technological entrepreneurs are taught to avoid extravagant claims and to rely instead on sober peer review. Yet they are also aware that hype can help win research grants and capital funding and can affect share prices."[11]. But in terms of quantum computing's ability to solve our mounting environmental problems — from global warming to addressing fertilizer runoff — there is a significant difference between 'just around the corner' and 'in ten years.' Given existing technological trajectories there is little doubt that quantum computers will improve over time, but the critical question from an environmental perspective is whether they can provide solutions within timeframes needed to solve mounting environmental problems, and achieve results better than other available options. As environmentalist and author Bill McKibben has noted about our worsening climate change challenge, "We're running out of options, and we're running out of decades."[12]

We are at a moment where basic science advances are being turned into technological innovations that could have thousands of potential applications — but which ones will pan out? Predictions are notoriously difficult to make in this space. This challenge is not unique to quantum computing as historians of science and technology have pointed out: "In thinking about the microeconomics of information technology — or, of biotechnology, new materials, and other developing 'generic' and systemic technologies — one often is prone to suffer from a kind of 'telescopic vision': the possible future appears both closer at hand and more vivid than the necessary intervening, temporally more proximate events on the path leading to that destination."[13]

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[7] Ball, Philip 2021. "Major Quantum Computing Strategy Suffers Serious Setbacks," *Quantamagazine*, September 29. https://www.quantamagazine.org/major-quantum-computing-strategy-suffers-serious-setbacks-20210929/#

[8] Quoted in: Gibney, E. 2019. "The Quantum Gold Rush," *Nature*, Vol. 574, October 3.

[9] Hillenbrand, P. & O'Brien, J. 2022. "How Quantum Computing Can Help Tackle Global Warming," May, *McKinsey Leap: Green Business Building Edition*, #4.

[10] Das Sarma, S. 2022. "Quantum Computing Has a Hype Problem," MIT Technology Review, March 28. https://www.technologyreview.com/2022/03/28/1048355/quantum-computing-has-a-hype-problem/ . Also see the critique by Nikita Gourianov, a physicist at Oxford university, summarized in: Greene T. 2022. "Oxford Scientists Says Greedy Physicists Have Overhyped Quantum Computing," *Neural*, Aug. 26. https://thenextweb.com/news/oxford-scientist-says-greedy-physicists-overhyped-quantum-computing

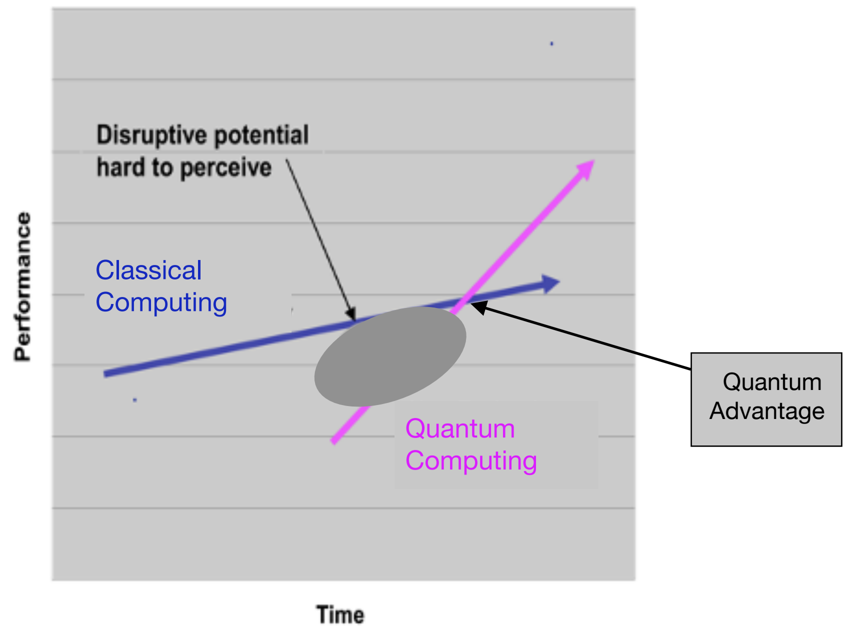
[11] Tenner, E. 2007. "A Place for Hype," *London Review of Books*, May 10. Vol. 29, No. 9. https://www.lrb.co.uk/the-paper/v29/n09/edward-tenner/a-place-for-hype

[12] McKibben, Bill 2018. "A Very Grim Forecast," *New York Review of Books*, November 22. https://www.nybooks.com/articles/2018/11/22/global-warming-very-grim-forecast/

[13] David, Paul 1989. "Computer and Dynamo: The Modern Productivity Paradox in a Not-Too Distant Future," Working Paper #339, Department of Economics, Stanford University.

When disruptive technologies appear, they often perform at a level that is actually below what is already on the market. This is exactly what makes it difficult to perceive their potential. Think about digital photography versus film; e-commerce versus bricks-and-mortar retailing; classroom educations versus internet-based, distance learning – all greeted with yawns and skepticism. But these disruptive technologies created new market opportunities, especially for people focused on higher performance options, and that is what drove their adoption.

The strategic inflection point occurs sometime after the introduction of the new technology but before its advantages are obvious or fully market-tested. The new technology does not replace the old, it provides new capabilities. Schematically, this is represented in the figure to the right (based on the work of Clayton Christensen at Harvard).[14]



Disruptive technological change often leaves the science of risk assessment and management catching up with the risks, outstrips the ability of governments to provide adequate oversight, and leaves little time for democratic deliberation and public dialogue. As Charles Fine at MIT's Sloan School has pointed out, when the "clock speed" of government falls far behind industry, public policies can either become irrelevant or badly designed as policymakers rush to close the governance gap.[15] It makes better sense to assume possible disruptive effects and plan for them rather than react after the fact.

The purpose of this paper to look beyond the 'reality distortion field' surrounding quantum computing, especially in regard to quantum computing's potential contribution to solving our shared environmental challenges.

There are four questions that the environmental community, including funders, should ask of quantum computing, questions that must be revisited and updated as the technology and markets mature:

- Can quantum computing provide unique solutions for our environmental challenges, unavailable through other computing technologies, or, more broadly, other technologies/industries outside the IT sector?

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[14] Christensen, C. 1997. *The Innovator's Dilemma : When New Technologies Cause Great Firms to Fail*, Boston, Massachusetts: Harvard Business School Press.

[15] Fine, C. 1998. *Clockspeed: Winning Industry Control in the Age of Temporary Advantage*, NY: Basic Books. 'Clockspeed' is the evolutionary lifecycle defined by the rate an organization introduces new products, processes, and organizational structures. Also see: Rejeski, D. 2008. "Public Policy on the Technological Frontier," in Marchant, G., Allenby, B., Herkert, J. (eds). *The Growing Gap Between Emerging Technologies and Legal-Ethical Oversight. The International Library of Ethics, Law and Technology, vol 7*. Springer, Dordrecht. https://link.springer.com/chapter/10.1007/978-94-007-1356-7_4

- Can quantum computing provide these solutions in a timely and equitable fashion, overcoming challenges of scaling to address near-term and time urgent problems?

- Could quantum computing exacerbate existing energy and resource use and associated environmental damages?

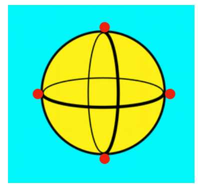
- What policies might be put in place to advance both the technology, its applications, and its access?

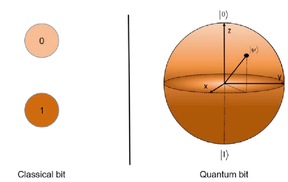
But first, a short detour into the realm of qubits, entanglements, and decoherence.

OK. Quantum Computing: What Is It?

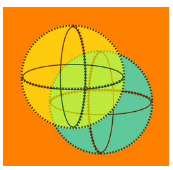
“If you think you understand quantum mechanics, you don’t understand quantum mechanics.” Richard Feynman

Even for people who loved physics in college, quantum computing is a difficult technology to understand, which makes its impacts and implications even harder to unravel and to discuss.

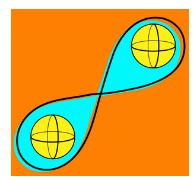




Instead of bits (zeros and ones), which conventional computers use, a quantum computer uses quantum bits—known as ***qubits***. To illustrate the difference, imagine a sphere. A bit can be at either of the two poles of the sphere (red dots), but a qubit can exist at any point on the surface of the sphere, which means that a computer using qubits can potentially store and manipulate an enormous amount of information.

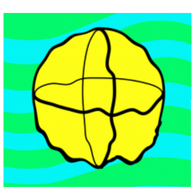


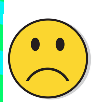
So qubits can represent numerous possible combinations of *1s* and *0s* at the same time. This ability to simultaneously be in multiple states is called *superposition*. This allows a quantum computer to crunch through large numbers of possible outcomes simultaneously.



Now imagine that these qubits are linked (in qu-speak this is called *entanglement*) so they can exchange information. It is not clear how or why this works (it even baffled Einstein) but is the key to the power of quantum computing. With normal computers, doubling the number of bits doubles the computing power but adding extra qubits to a quantum computer results in exponential increases in computational power.

That is the good news. But this state is extremely fragile and can be sustained only if the qubits are effectively isolated from their environment, for instance, by cooling them down to near absolute zero in vacuum chambers. Otherwise the qubits decay and ultimately disappear in what is called *decoherence* (more qu-speak). Because of this challenge, errors creep into the calculations and must be corrected, most often through the use of more qubits. It can take thousands of error-correcting qubits to create one highly accurate logical qubit and, as researchers have noted, quantum error correction (QEC) “is the single biggest problem holding back quantum computing from realizing its great promise… [solving this] is foundational to every effort to build useful quantum computers because it paves the way to building systems of any size.”[16]





A fully error corrected, general purpose quantum computer may be decades away because creating such a device requires controlling qubits in an error free way and, as some have noted, “there is a trade-off: quantum error correction protocols require large number of qubits to operate effectively. This will significantly increase the overheads (energy use, for instance) associated with quantum computing.”[17]

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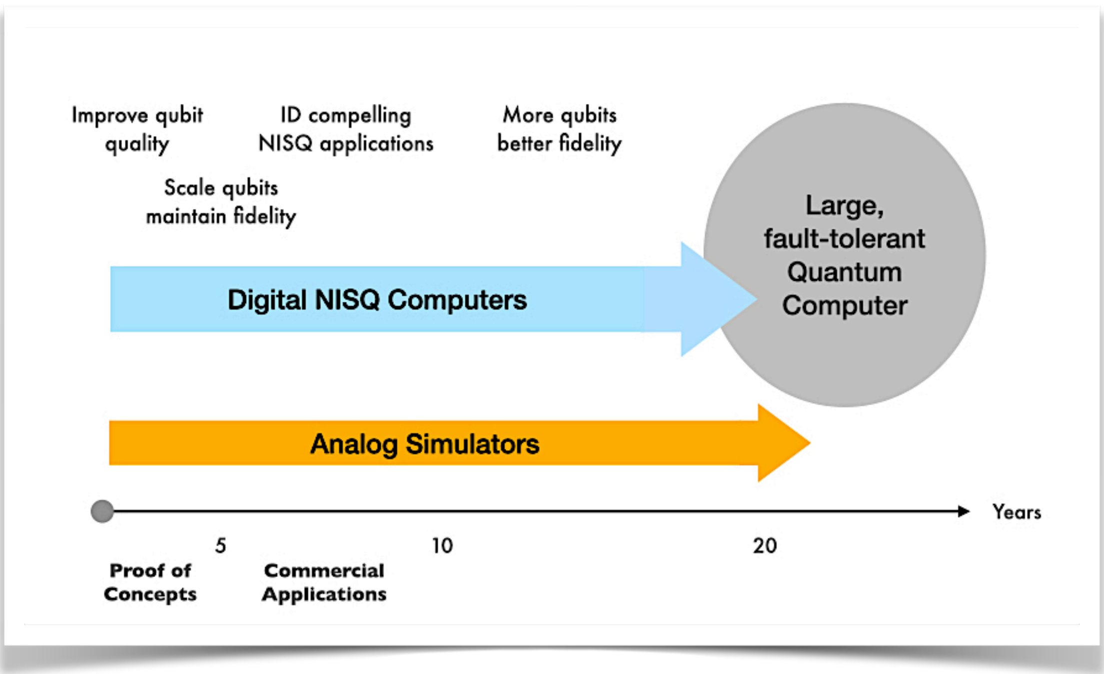
[16] Biercuk, M.J. & Stace, T.M. 2022. “Quantum Error Correction : Time to Make It Work: If Technologists Cannot Perfect It, Quantum Computers Will Never Be Big, *IEEE Spectrum*, June 26.

[17] Roffe, J. 2019. “Quantum Error Correction: An Introductory Guide,” *Quantum Physics*, July 25. https://arxiv.org/abs/1907.11157

In the meantime (probably in the next 5-10 years) there are two options: (1) ***digital noisy intermediate-scale quantum (digital NISQ) computers*** which rely on error correction to improve performance and accuracy, and (2) ***analog quantum computers***, which simulate the dynamics of quantum-mechanical systems, for instance, describing the behavior of electrons in materials or in large molecules. These analog quantum simulators essential map a quantum system, like a molecule or material, onto a programmable quantum system (the quantum computer) are now moving from providing qualitative demonstrations of physical phenomena to providing well calibrated, quantitative solutions for native problems."[18] Analog quantum simulators may continue to provide important information long into the future. We still use (analog) wind and water tunnels for aerodynamic and hydrodynamic modeling despite the power of *in silico* digital options. A notional timeline of these two systems is presented below with some key milestones. If the timeframe seems far off in the future, keep in mind that IBM, founded in 1911, introduced the first mainframe computer in 1964 (after investing $34 billion in 2012 dollars), and did not build the company's first PC until 1981.



Researchers are experimenting with various technologies to produce more powerful and accurate quantum computers that make use of the following approaches (see explanations in Appendix):

- Superconducting
- Trapped ions
- Silicon
- Diamonds
- Two dimensional quasiparticles (anyons)

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[18] Daley, A. et al. 2022. "Practical Quantum Advantage in Quantum Simulation," *Nature,* Vol. 607 July 28. https://www.nature.com/articles/s41586-022-04940-6. Firms are also starting to develop platforms specific to industry-relevant problems, for instance: Quantiuum's Inquanto platform for computational chemistry. https://www.quantinuum.com/products/inquanto

The search for quantum computing platforms will continue. "Researchers around the world are trying to figure out which technologies—such as superconducting qubits, trapped ions or silicon spin qubits, for example—can best be employed as the basic units of quantum computing. And, equally significant, researchers are exploring which technologies will have the ability to scale up most efficiently for commercial use."[19] Recently, researchers explored cuprous oxide found a gemstone from Namibia as a platform for quantum simulators.[20]

But solving the hardware issues does not translate into immediate success. Over 15 years ago, an article on quantum computing in *Scientific American* presciently noted that, "Quantum computers would suffer from many of the same algorithmic limitations as today's classical computers. These limitation are completely separate from the practical difficulties of building quantum computers."[21] Ten years later, a report by the U.S. National Academies stated that, "Progress in quantum algorithms is essential for quantum computing success….The biggest upcoming challenges are algorithmic."[22] Dave Bacon, who leads the Google team's software effort has stressed that, "Quantum code…has to be highly tailored to the qubits it will run on, so as to wring the most out of their temperamental performance. That means the code for IBM's chips won't run on those of other companies, and even techniques for optimizing Google's 53-qubit Sycamore won't necessarily do well on its future 100-qubit sibling."[23] Recently, Ryan O'Donnell of the Computer Science Department at Carnegie Mellon University, speaking about quantum algorithms, observed that, "….progress stalled. It's been a bit of a bummer trajectory. People were like, 'This is amazing, I'm sure we're going to get all sorts of other amazing algorithms.' Nope."[24] Measuring progress on algorithm development is difficult because many remain proprietary, but published algorithms can be found and tracked at the *Quantum Algorithm Zoo*, which contained 262 papers in 2016 and 430 now, an upward trend.[25] The key to remember is that successful quantum computing depends on both hardware and software advances that, together, can address real world, practical problems. But the gnawing question persists: Have we reached the inflection point? Are we there yet?

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[19] Princeton University 2022. "In Race to Build Quantum Computing Hardware Silicon Begins to Shine," April 6. https://phys.org/news/2022-04-quantum-hardware-silicon.html; Also see: Mills, A. et al. 2022. "Two-qubit silicon quantum processor with operation fidelity exceeding 99%," *Science Advances*, April 6. https://www.science.org/doi/10.1126/sciadv.abn5130

[20] University of St. Andrews 2022. "Ancient Namibian Stone Could Hold Key To Future Quantum Computers, *PhysOrg,* April 15. https://phys.org/news/2022-04-ancient-namibian-stone-key-future.html

[21] Aaronson, S. 2008. "The Limits of Quantum Computers," *Scientific American*, March 1. https://www.scientificamerican.com/article/the-limits-of-quantum-computers/

[22] NASEM, 2018. *Quantum Computing: Progress and Prospects*, Washington, DC: National Academies of Science, Engineering and Medicine.

[23] Lichfield, Gideon, 2020. "Inside the race to build the best quantum computer on Earth," *MIT Technology Review*, technologyreview.com/2020/02/26/916744/quantum-computer-race-ibm-google/

[24] Rorvig, M. 2022. "Quantum Algorithms Conquer A New Kind of Problem," *Quantamagazine*, July 11. https://www.quantamagazine.org/quantum-algorithms-conquer-a-new-kind-of-problem-20220711/

[25] https://quantumalgorithmzoo.org/. Searched 8.1.2022.

Are we there Yet?

For 20 years scientists and engineers have been saying that "someday" they'll build a full-fledged quantum computer able to perform useful calculations that would overwhelm any conventional supercomputer. The goal always seemed over the horizon, echoing a standard line among nuclear fusion advocates that fusion was ‘always 30 years away.’[26] This computing milestone was termed *quantum advantage* aka *quantum supremacy* (see box).[27] Much ink has been spilled about whether this goal was reached, by whom, and whether it really mattered, starting with Google’s assertion in 2019 that they had solved a problem that would have taken even the best classical supercomputer 10,000 years to complete.[28] IBM quickly responded that the problem could be solved in just 2.5 days, taking the sheen off of Google’s claim.[29] And so it goes. The supercomputer community has recently come back challenging quantum advantage claims and stressed that,”There’s an urgent need for better quantum supremacy experiments…tasks whose solutions are useful, not just demonstrations of capacity.”[30]

Quantum ‘Advantage’ Please!

Shortly after Google published claims about achieving quantum ‘supremacy’ in October 2019, push back over the choice of words came quickly, including in a letter to *Nature* magazine. The term ‘supremacy’, a phrase coined by physicist John Preskill in 2012, was seen as yet another insensitive grammatical gaff of the techno community with the letter’s signatories noting that, “In our view, ‘supremacy’ has overtones of violence, neocolonialism and racism through its association with ‘white supremacy’.* Others have noted the lack of gender balance in the quantum computing community noting the low representation of female researchers and researchers from the global south at both conferences and in publications. This has spurred some researchers to create the Quantum Gender Initiative [https://twitter.com/quantumgender].

* Carmen Palacios-Berraquero et al. 2019. “We’ll Take ‘Quantum Advantage’” *Nature*, Vol. 576, December 12, p. 213.

It has become clearer that we need to move on to what has been termed *practical quantum advantage* which is, ‘… the point at which quantum devices will solve problems ***of practical interest*** that are not tractable for traditional supercomputers”.[31] This is especially difficult since many of the potential applications of quantum computing have not been discovered and its utility may not be captured by the premature establishment and lock-in of benchmarks. As some have noted, “Bad benchmarking can be worse than no benchmarking at all,” and could incentivize researchers to optimize hardware to perform well on a particular test which may not be relevant to future applications.[32] Despite potential pitfalls, recent benchmarking studies

[26] For an update on nuclear fusion, see: Verman, P. 2022. “Nuclear Fusion Power Inches Closer to Reality,” *Washington Post*, August 26. https://www.washingtonpost.com/technology/2022/08/26/nuclear-fusion-technology-climate-change/

[27] Cho, A. 2020. “IBM Promises 1000-qubit quantum Computer — A Milestone — By 2023,” Science, September 15. https://www.science.org/content/article/ibm-promises-1000-qubit-quantum-computer-milestone-2023

[28] Gibney, E. 2019. “Hello quantum world! Google publishes landmark quantum supremacy claim,” *Nature*, 574, 461–462. https://www.nature.com/articles/d41586-019-03213-z/

[29]https://www.ibm.com/blogs/research/2019/10/on-quantum-supremacy/

[30] Luntz, S. 2022. “Traditional Computers Can Beat Google’s Quantum Computer Thanks to Smart Algorithm Design,” *IflScience*, Aug. 4. https://iflscience.com/traditional-computers-can-beat-googles-quantum-computer-thanks-to-smart-algorithm-design-64748

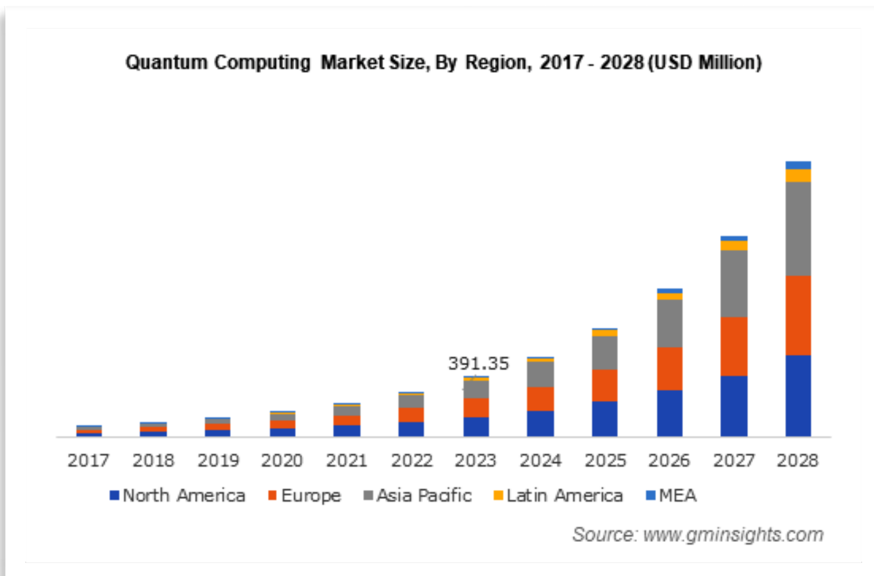
[31] Daley, A.J. et al. 2022. “Practical Quantum Advantage in Quantum Simulation,” *Nature*, Vol. 607, July 27. https://www.nature.com/articles/s41586-022-04940-6

[32] Blume-Kohout, R. & Young, K. 2019. “Metrics and Benchmarks for Quantum Processors: State of Play,” US Department of Energy, Sandia National Laboratory, Technical Report, https://www.osti.gov/biblio/1493362

using a portfolio of application-specific benchmarks has shown the performance of quantum computers is improving over time for specific use cases.[33] More observers are speaking of real, measurable progress, but emphasize that, "One common misconceptions about quantum computing is that industrial application is a binary event — one day soon, we'll flip a switch and the world will suddenly transform. In truth, quantum technology has many facets and timelines…"[34]. This perception is one result of a focus on single targets like achieving quantum advantage.

Some reasons for optimism

Back in 2018 and 2019 there were worries that that the quantum computing field would descend into a 'quantum winter' similar to the 'AI winter' — a plunge into the so-called *valley of death* where funding dries up before meaningful proof of concepts can materialize.[35] But since then, venture capital investments have significantly increased, with over $1 billion in funding in 2021 supporting 30 firms.[36]. More recent data projects a quantum computing market worth over $5 Billion by 2028.[37]



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[33] Baker, J.S. & Radha, S.K. 2022. "Wasserstein Solution Quality and the Quantum Approximate optimization Algorithm: A Portfolio Optimization Case Study," *Quantum Physics*, Feb. 14.

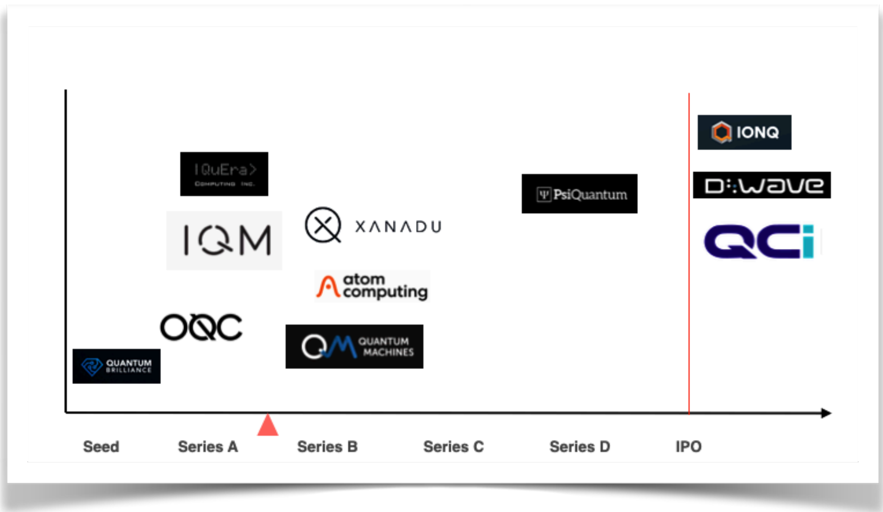
[34] Galitski, V. et al 2021. "Separating the Wheat from the Chaff: Quantum Computing in an Era of Hype," McKinsey Digital, July 1. https://www.mckinsey.com/business-functions/mckinsey-digital/our-insights/tech-forward/separating-the-wheat-from-the-chaff-quantum-technology-in-an-era-of-hype

[35] Gibney, E. 2019. "The Quantum Gold Rush," *Nature*, Vol.574, October 3.

[36] https://pitchbook.com/news/articles/quantum-computing-venture-capital-funding

[37] Published Date: November 1, 2021
https://www.gminsights.com/pressrelease/quantam-computing-market#:~:text=Quantum%20Computing%20Market%20size%20is,the%20quantum%20computing%20industry%20growth

Funding has driven new business formation which now extends far beyond the large, established players in the quantum computing space like Google, Microsoft, Honeywell, and IBM. Startups have raised significant funding, allowing a number of pure-play firms to go public.[38] As more firms advance beyond series A funding, the chances of failure tend to decrease, with a large drop between series A and B funding.[39]



There are also increases in government funding. The new CHIPS and Science Act passed in the US contains $153 million (most to be spent between 2023 and 2027) to support quantum computing efforts, including funding for a Next Generation Quantum Leaders Pilot program.[40] The European Quantum Flagship program is providing 1 billion Euros in support for quantum computing research over a ten year period beginning in 2018.[41] Back in 2017, China started

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[38] https://oxfordquantumcircuits.com/oqc-series-a-38-million
https://meetiqm.com/articles/press-releases/european-leader-in-quantum-computing-iqm-raises-128m-led-by-world-fund/
https://www.quantum-machines.co/blog/quantum-machines-raises-50-million/
https://atom-computing.com/atom-computing-raises-60m-series-b-to-build-second-generation-quantum-computing-systems/
https://psiquantum.com/news/psiquantum-closes-450-million-funding-round-to-build-the-worlds-first-commercially-viable-quantum-computer
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https://www.forbes.com/sites/moorinsights/2021/03/23/ionq-takes-quantum-computing-public-with-a-2-billion-deal/?sh=1aa314b75d06
https://www.prnewswire.com/news-releases/xanadu-closes-100m-usd-series-b-to-build-a-fault-tolerant-photonic-quantum-computer-301298647.html
Also: Russell, John 2021. "IonQ is First Startup to Go Public: Will It be the First to Deliver Profits?" *HPC*, Nov. 3. https://www.hpcwire.com/2021/11/03/ionq-is-first-quantum-startup-to-go-public-will-it-be-first-to-deliver-profits/

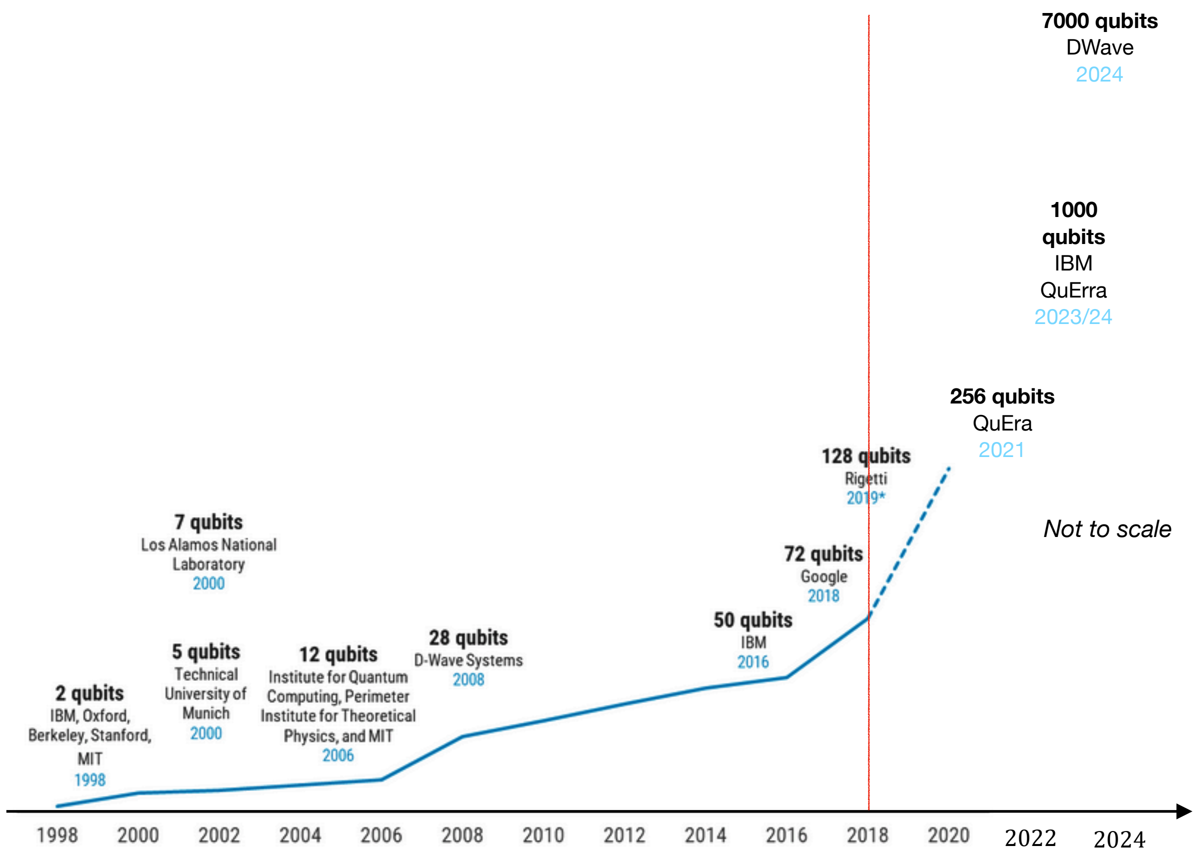
[39] Qunintero, S. 2017. "Dissecting Startup Failure Rates By Stage," *Journal of Empirical Entrepreneurship*, Nov. 7. https://medium.com/journal-of-empirical-entrepreneurship/dissecting-startup-failure-by-stage-34bb70354a36

[40] Quantum|Gov 2022. "Quantum in the CHIPS and Science Act of 2022," Posted on August 9. https://www.quantum.gov/quantum-in-the-chips-and-science-act-of-2022/

[41] Cartlidge, E. 2018. "Europe's Billion-Euro Quantum Flagship Hands Out First Grants," *Science*, October 29. https://www.science.org/content/article/europe-s-billion-euro-quantum-flagship-hands-out-first-grants

construction of a multi-node quantum science research laboratory.[42] Combined public and private sector activities are driving the demand for researchers and engineers in firms, government labs, and universities and demand could outstrip supply. The QED-C directory, which contains job listings in the field, now has almost 700 openings.[43]

In addition, the capabilities of the quantum computers have been rapidly increasing since around 2018, when a US National Academies report indicated that, "The field is now entering the era of noisy intermediate-scale quantum (NISQ) devices —the race to build quantum computers that are sufficiently large (tens to hundreds or a few thousand quits) that they cannot be efficiently simulated by a classical computer."[44] These advances in computational capacity (see figure) are important for further developing the technology, and for evaluating which problems may see nearer-term speed-ups on quantum hardware.



Finally, there has been a significant increase in the number of use cases where quantum computing is being applied to real-world problems with initial positive results. The emergence of near-term commercial use cases is critical in avoiding decreases in funding as the field advances. The 2018 National Academies study noted that, "…the most critical period for the development of quantum computing will begin around the early 2020s,…if commercially

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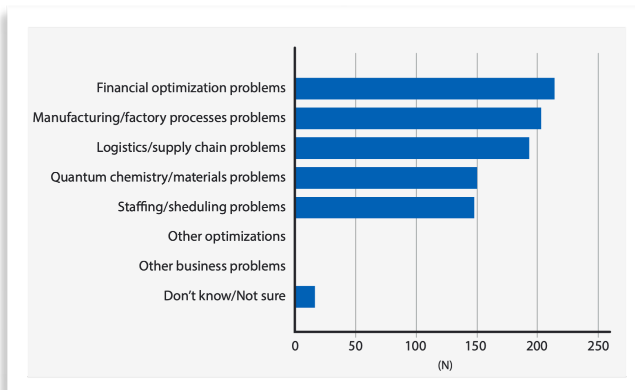
42 https://technode.com/2018/09/05/china-quantum-information-laboratory/

43 https://quantumconsortium.org/quantum-jobs/ Checked 8.16.2022.

44 NASEM, 2018. *Quantum Computing: Progress and Prospects*, Washington, DC: National Academies of Science, Engineering and Medicine.

attractive applications for these machines emerge." These proof-of-concepts are now multiplying and a few examples provide some sense of the breadth of applications being explored.

Recently, BMW used a quantum computer (from QCI) to solve an optimization problem with 3,854 variables and over 500 constraints to determine the best sensor placement in new vehicles.[45]. The Canadian grocery chain Save-On-Foods, in collaboration with quantum computing company D-Wave, is using quantum technology to improve the management of in-store logistics, reducing computation times from 25 hours to less than 2 minutes.[46] . Microsoft has already demonstrated how quantum computers can help manufacture fertilizers with better yields by improving the catalytic process used to produce ammonia-based fertilizers.[47] Volkswagen demonstrated the first real-time traffic-routing system to rely on quantum computing and tested the approach in Lisbon, Portugal. This system used both classical computing to analyze anonymized movement data combined with optimization using a quantum algorithm (running on a D-Wave quantum computer).[48]. Mercedes Benz is working with PsiQuantum to develop new electrolytes for lithium-Ion batteries for electric cars.[49] The goals are to improve battery energy density (efficiency), charging speed, life, range, cost, and safety. Other use cases are advancing with a focus on areas like financial services and computer security. There was a recent announcement by Master Card to explore quantum computing to help with consumer loyalty and rewards, cross-border settlement, and fraud management.[50]



A recent survey covering potential quantum computing applications involving 400 respondents found that respondents identified improving research capabilities and driving innovation and revenue generation as the largest opportunities offered by quantum computing. Possible business challenges addressable by quantum computing included logistics and supply chain problems ranking high by the aerospace, transport/mobility sectors, and energy; with biosciences and pharmaceuticals ranking computational chemistry and simulation at the top of the list. The report makes an important point that, "Most current and planned QC users, however, will be looking to QC suppliers to roll out a series of steady advances that can provide some

[45] https://www.quantumcomputinginc.com/press-releases/qci-bmw/

[46] https://tekdeeps.com/save-on-foods-quantum-computers-in-the-supermarket/ ; https://www.dwavesys.com/resources/application/save-on-foods-quantum-computing-in-grocery/

[47] https://cloudblogs.microsoft.com/quantum/2018/12/04/simulating-nature-with-the-new-microsoft-quantum-development-kit-chemistry-library/

[48] https://www.volkswagen-newsroom.com/en/press-releases/volkswagen-optimizes-traffic-flow-with-quantum-computers-5507

[49] Kim, I.H. et al. 2022. "Fault-tolerant resource estimate for quantum chemical simulations: Case study on Li-ion battery electrolyte molecules," *Phys. Rev. Research*, 4. https://journals.aps.org/prresearch/abstract/10.1103/PhysRevResearch.4.023019. Also: https://thequantuminsider.com/2022/04/13/psiquantum-mercedes-benz-study-how-quantum-computers-can-accelerate-ev-battery-design/

[50] https://www.hpcwire.com/off-the-wire/d-wave-and-mastercard-announce-quantum-computing-collaboration/

assurance that the QC sector is successfully moving to achieve stability and reducing the risk of an early adapter."[51]

Beside reducing risks for first movers, a wide range of proof-of-concept trials across different technology platforms, with different algorithms, and various end use cases creates a rich experimentation space that is key to long-term innovation, in part, because, "New technologies are most powerful when they are deployed to test what works and what doesn't work as early as possible."[52] The more experiments one can run, the more hypotheses one can test, the faster the rate of learning. It sounds paradoxical but in terms of learning and innovation, "Whoever makes the most mistakes wins."[53]

One word of caution is in order. In trying to estimate the possible timing of quantum computing breakthroughs and potential commercial applications, we need to keep in mind that we see only a portion of the research and related activities. Not only do companies themselves often obscure their achievements and setbacks, but because of the national security implications one needs to assume that quantum computing activities being undertaken by some government agencies and intelligence services are, and are likely to remain, classified, and not accessible to the general public.

A significant amount of quantum computing effort is not focused on developing planet-saving applications, but on providing protection against the possibility that quantum computers could render historical (and future) encryption systems ineffective. There is a race between the time required to develop practical quantum computing and deploying a quantum resistance cryptographic infrastructure that can ensure data security for industry, governments, and individuals. Recently the National Institute of Standards and Technology (NIST) announced the winners of a competition to develop so-called 'quantum resistant cryptographic algorithms' that can provide both general encryption, used to protect information exchanged across a public network; and digital signatures, used for identity authentication.[54]

We should also keep in mind that the large and well-funded classical computing ecosystem will not sit still while the quantum folks try to get their systems to work. One can expect improvements in the speed, capacity, and costs of supercomputing, as well as their underlying algorithms, which could challenge quantum advantage.[55] Recently, one of computing's grand challenges — the protein folding problem — was effectively solved using a supercomputer combined with deep neural networks trained on large amounts of data.[56] This puts a premium on identifying "..which problems can [be mapped] to quantum circuits that have solutions

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[51] Sorenson, B. 2021. *Broad Interest in Quantum Computing As A Driver of Commercial Success*, Hyperion Research. https://www.dwavesys.com/media/an1helvq/hyperion_report_v2.pdf

[52] Thomke, S, 2003. *Experimentation Matters: Unlocking the Potential of New Technologies for Innovation*, Boston, MA: Harvard Business School Press.

[53] Farson, R., & R. Keyes. 2002. *Whoever makes the most mistakes wins: The paradox of innovation*. New York, NY: Free Press.

[54] NIST, 2022. "NIST Announces First Four Quantum Resistant Cryptographic Algorithms," July 5. https://www.nist.gov/news-events/news/2022/07/nist-announces-first-four-quantum-resistant-cryptographic-algorithms

[55] Luntz, S. 2022. "Traditional Computers Can Beat Google's Quantum Computer Thanks to Smart Algorithm Design," *IFLScience*, August 4. https://iflscience.com/traditional-computers-can-beat-googles-quantum-computer-thanks-to-smart-algorithm-design-64748

[56] Editorial Board, 2022. "AI Gives Us an Astounding New View of Life's Basic Building Blocks, *Washington Post*, September 1. https://www.washingtonpost.com/opinions/2022/09/01/proteins-research-drugs-ai/

which are better than classical approaches?”[57] Or, more specifically: which environmental problems can [be mapped] to quantum circuits that have solutions which are better than classical approaches? And how soon?

Solutions Chasing a Problem

There may be a quantum computing ‘killer app’ destined to save the planet lurking on the horizon, but, for reasons already discussed, it may be difficult to identify that application at this point in time. That said, there are two classes of quantum computing applications that are highly relevant to environmental problem solving, especially in the nearer term. The first involves **simulation** of a quantum system to better understand the structure of a substance, elucidate the behavior of chemical reactions, and support the development of new materials. This could include, for example, new approaches to CO_2 fixation and transformation, hydrogen and oxygen production, as well as novel fertilizers, catalysts, and clean energy processes. This class of problems could provide early demonstrations of the utility of quantum computing to address environmental challenges as researchers have noted: “In looking for an early practical quantum advantage in [the] near-term…it is best to consider the simulation of quantum-mechanical systems…[in] describing the behavior of electrons in materials, or in large molecules. Analog quantum simulators are now moving from from providing qualitative demonstrations of physical phenomena to providing well calibrated, quantitative solutions for native problems.”[58]

The second class of environmentally relevant quantum applications focus on what is known as the **Quadratic Assignment Problem** and include a range of problems relevant to energy grid optimization, i.e., determining what energy sources are needed to satisfy loads under changing scenarios, and variations of the so-called ‘traveling salesman problem’ relevant to transportation and logistics routing (for instance, fleet vehicle routing with time windows for goods/package delivery, bus counting, and cellular network planning).

But thinking further into the future, near real-time optimization will be critical to modernizing our energy grids, especially as thousands to tens of thousands of intermittent sources and loads as attached, such as electric cars in vehicle-to-grid systems with bi-directional charging.[59] Quantum computing may be especially effective for, “…energy systems in the presence of uncertainty, [where] online adaption is required to ensure the system is always operated optimally.”[60] Grid modernization is a decadal and expensive undertaking where quantum computing could be part of the longer term solution. By 2030, “… the U.S. will need to invest as much as $125 billion in the grid to allow it to handle electric vehicles alone.”[61].

As noted in the previous section, real world use cases of quantum computing are still in the process of ramping up and largely involve small scale demonstration projects. As one recent article noted, quantum computing is “newsful, but maybe not yet useful,” stressing that,

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[57] IBM 2022. “With Fault Tolerance the Ultimate Goal, Error Mitigation is the Path That Gets Quantum Computing to Usefulness.” https://research.ibm.com/blog/gammabar-for-quantum-advantage

[58] Daley, A. et al. 2022. “Practical Quantum Advantage in Quantum Simulation,” *Nature,* Vol. 607 July 28. https://www.nature.com/articles/s41586-022-04940-6

[59] An example is operating in the Dutch city of Utrecht. See: Dumiak, M. 2022. “This Dutch City Is Road-Testing Vehicle-to-Grid Tech,” *IEEE Spectrum*, June 22. https://spectrum.ieee.org/vehicle-to-grid

[60] Ajagekar, A. & You, F. 2019. “Quantum computing for energy systems optimization: Challenges and opportunities,” *Energy*, Vol. 179, 15 July, pp. 76-89. https://www.sciencedirect.com/science/article/abs/pii/S0360544219308254

[61] Englund, Will 20021. “Plug-in Cars Are the Future: The Grid Isn’t Ready,” *Washington Post*, October 16. https://www.washingtonpost.com/business/2021/10/13/electric-vehicles-grid-upgrade/

"….there have been some public announcements of a special type of QC solving real-world optimization problems, such as bus routing and radio cell planning. Most of these appear to have been more proof-of-concept trials rather than large-scale or active deployments."[62] . But much is at stake: "The race to make qubits at scale is a winner-take-all competition…If you make a scalable quantum computer, your advantage is so great that you'll leave everyone else in the dust."[63]

Not There Yet: The Long March to Market

It has been jokingly said that computer scientists, looking at new markets, count "1, 2, 3, . . . a million."[64]

Let's assume that the quantum computing community will take 8-10 years to solve fundamental issues and engineering challenges needed to create more fault-tolerant implementations of useful quantum platforms and algorithms, which could rapidly accelerate the scientific discovery process and solve calculations that remain unreachable with supercomputers. This will involve addressing major, and non-trivial, barriers to scaling the computing technology itself, which involve: cooling power, control electronics, connectivity, and testing. Now we need to add in the time to commercialize and scale novel applications and products of the quantum computing enterprise that could address environmental problems — a scaling upon scaling challenge.

Quantum critics have already noted that, "There are proposals to use small-scale quantum computers for drug design, as a way to quickly calculate molecular structure, which is a baffling application given that quantum chemistry is a minuscule part of the whole process."[65] Sticking with the drug use case, one can add the rest of the process, and time needed for any medication to actually impact public health. The Biotechnology Innovation Organization (BIO) recently analyzed almost 10,000 drug development programs from 2011 to 2020 and found that, on average, it took **10.5 years** for a drug to get from Phase I clinical trials to regulatory approval and market entry — keep in mind that is market entry, not widespread use. This process is unfortunately becoming slower. In a 2018 study, the Tufts Center for the Study of Drug Development (CSDD) found that FDA-approved drugs and biologics spent 89.8 months on average in clinical trials between 2014 and 2018, compared to 83.1 months on average between 2008 and 2013.[66] Costs to navigate this process can go as high as $2.6 billion US.

Of course, from an environmental perspective many interesting quantum computing applications lay outside of the drug realm and include areas such as nitrogen fixation, catalysts for hydrogen and oxygen production, carbon dioxide fixation, battery and storage technologies, or photochemical processes. For example, developing biological approaches to

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[62] Stewart, D. et al, 2021. "Quantum Computing in 2022: Newsful, But How Useful?" *Deloitte Insights*, December 1. https://www2.deloitte.com/xe/en/insights/industry/technology/technology-media-and-telecom-predictions/2022/future-of-quantum-computing.html

[63] Combs, V. 2022. "Quantum Computing Ecosystem Expands in All Directions," *TechRepublic*, April 11. https://www.techrepublic.com/article/quantum-computing-ecosystem-expands-in-all-directions/

[64] Brown, John Seely & Duguid, Paul, 2000. *The Social Life of Information* (Cambridge, MA: Harvard Business School Press.

[65] Das Sarma, S. 2022. "Quantum Computing Has A Hype Problem," *MIT Technology Review*, March 28.

[66] https://www.centerwatch.com/articles/25033-trend-of-longer-trial-timelines-is-likely-to-continue. Only about 0.1 percent of drugs that begin clinical trials make it to blockbuster status, generating sales of over $1 billion annually. https://blogs.einsteinmed.edu/the-high-cost-of-and-uncertain-path-to-a-blockbuster-drug/

nitrogen fixation using enzymes like nitrogenase have been difficult though they could substantially reduce our dependence on energy intensive industrial process presently in use. Research in Switzerland has shown that with anticipated reductions in error rates that could be achieved in superconducting or trapped ion systems (and certainly achieved with topological quantum computers) along with parallelizing could provide new molecular solutions for next generation fertilizers.[67] There remains, however, the rocky road to market. For instance, novel fertilizers can take 3 to 10 years to wind their way through the regulatory approval process in the US, which involves both federal and state regulations and, even when approved, face market penetration hurdles dependent on their acceptance by retailers and, ultimately, farmers.[68] There will also be competition from other sectors and other technologies. For example, there are already companies using biotechnology to replace synthetic fertilizers with bio-based alternatives, by transferring the genes responsible for nitrogen fixation found in legumes (like beans) to other crops, such as corn.[69]

Outside of fertilizers, there are regulations which would impact the time-to-market of novel chemicals for catalysts or other manufactured product or process improvements. In the U.S., these would likely be regulated under EPA's Toxic Substances Control Act (TSCA). On average, it would take 1-2 years for EPA's Pre Manufacturing Notice (PMN) review to be completed and another 1-2 years for the final Significant New Use Rule (SNUR), which would allow full commercialization. For substances with very short supply chains (immediate customer of manufacturer does not further distribute the substance), the final SNUR would not be a barrier — so let's assume 1-4 years to get to market.[70] The process in the European Union is generally shorter than in the US, requiring a submission of test data with the registration package to the European Chemicals Agency (under the REACH regulation).[71]

New battery technologies are urgently needed that can reduce charging times for electric vehicles — going from hours to minutes — and quantum computing and quantum mechanics may provide solutions.[72] But any novel battery integrated into a commercial product like an automobile will have to past stringent tests involving a variety of national and international organizations such as Underwriters Lab (UL), the Society of Manufacturing Engineers (SME), and the International Standards Organization (ISO). Some regulatory frameworks may be in flux such as the new EU Battery Regulation designed to improve the safety and sustainability of new battery technologies (the regulations will require a carbon footprint declaration for

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[67] Reiher, M. et al. 2017. "Elucidating Reaction Mechanisms on Quantum Computers," *PNAS*, July 3, Vol. 114, No. 29. https://www.pnas.org/doi/10.1073/pnas.1619152114. In 2017 there was talk about breaking the 49 qubit barrier: https://www.ibm.com/blogs/research/2017/10/quantum-computing-barrier/; recently a 500 qubit computer hit the cloud: https://www.ibm.com/blogs/research/2017/10/quantum-computing-barrier/

[68] Fertilizers are regulated in the US at the federal level by the Toxic Substances Control Act (TSCA) and the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). State approvals are coordinated by the Association of American Plant Food Control Officials (AAPFCO) https://www.aapfco.org/index.html. Time estimates from The Fertilizer Institute (conversation on 7.6.2022).

[69] See, for instance Pivot Bio. https://www.pivotbio.com/

[70] Since 2016, the average time for a pre-manufacture notice to resolve (across all submissions, including invalid, withdrawn, those PMNs still under review) is 421 days. For PMNs that have been allowed to go to market (with or without restrictions) is 364 days (ranging from 24-1780 days). Data from Dr. Rich Engler (email 7.23.2022)

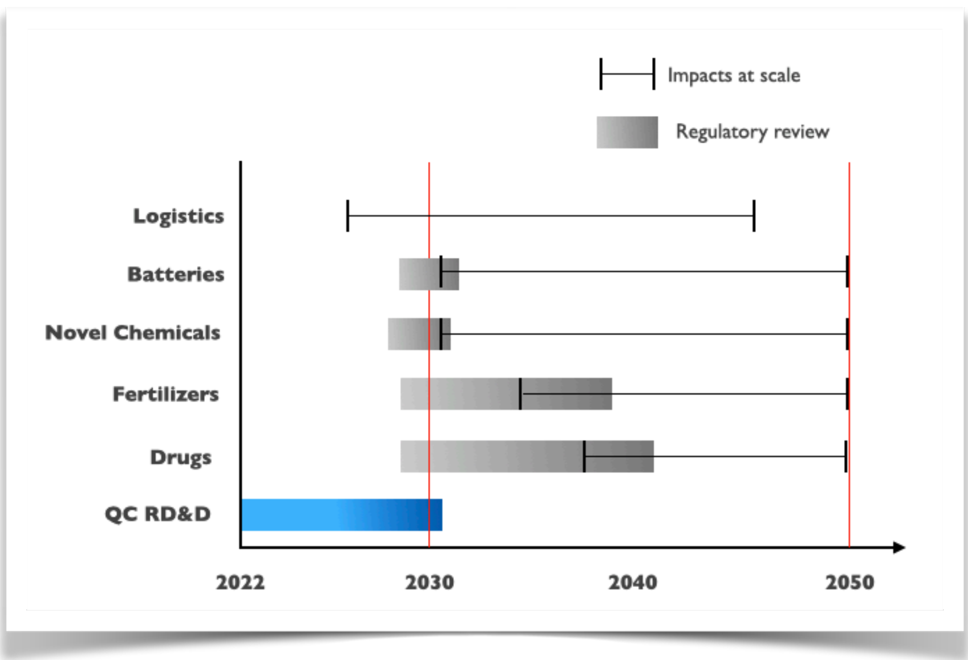
[71] https://echa.europa.eu/regulations/reach/understanding-reach

[72] See recent South Korean research on quantum batteries, which could dramatically reduce charging times. Cuthbertson, A. 2022. "Quantum battery can recharge electric car in 90 seconds, researchers reveal," *The Independent*, March 23. https://www.msn.com/en-us/news/technology/quantum-battery-can-recharge-electric-car-in-90-seconds-researchers-reveal/ar-AAVpT8q; Gyhm, J. et al. 2022. "Quantum Charging Advantage Cannot be Extensive Without Global Operations," Quantum Physics, April 11. https://arxiv.org/abs/2108.02491

batteries over 2 kWh).[73] Regulatory uncertainty and ambiguities can significantly increase business risks and time to market especially for emerging technologies, even impacting initial investments in new businesses and ultimately delaying market entry.[74]

The point here is to highlight the temporal gap between innovation and impact at scale and the stubborn inertia of the old technologies that continue to shape our lives and polices.[75] What is often being left out of the calculations of many techno optimists is the time and effort required to move from discovery to the actual delivery of commercial products that can penetrate markets at scale, a process often littered with multiple regulatory barriers, unanticipated costs, and consumer/end user resistance to adaption. Technologists have an unfortunate habit of underestimating scaling costs and time requirements, while overestimating consumer demand.

As a thought experiment, we can add in some rough estimates of the time required to scale new discoveries, attain regulatory approval (if needed), and achieve customer/end user acceptance needed to ensure significant market penetration. These come on top of the time required to scale quantum computing for commercial applications.



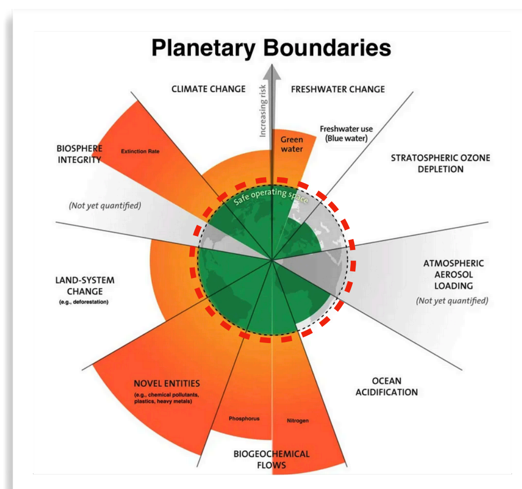
[73] Hogan & Lovells, 2022. "New EU Battery Regulation – Additional Challenges for Companies," May 24. https://www.engage.hoganlovells.com/knowledgeservices/news/new-eu-battery-regulation-additional-challenges-for-companies

[74] Hoerr, R. 2011. "Regulatory Uncertainty and the Associated Business Risk for Emerging Technologies," *Journal of Nanoparticle Research*, Vol. 13. https://link.springer.com/article/10.1007/s11051-011-0260-z. Hendricks, K. B. & Signal, V. R. 1997. "Delays in New Product Introductions and the Market Value of the Firm: The Consequences of Being Late to the Market," *Management Science*, Vol. 43, No. 4. https://pubsonline.informs.org/doi/epdf/10.1287/mnsc.43.4.422

[75] English historian David Edgerton suggests we focus on technologies in actual use than just the wiz-bang tech of the moment, noting that the U.S. strategic arsenal still relies on the B-52 bomber (in service since 1955), while machetes and small arms (like the AK-47) kill most people in conflicts (not high-tech armed drones). See: Edgerton, David 2007. *Shock of the Old: Technology and Global History Since 1900*, Oxford, England: Oxford University Press.

Regulatory approval processes can be accelerated in response to emergency needs, witness ‘Operation Warp Speed’ for the corona virus vaccines, but generally technological innovations run into headwinds exacerbated by the inability of our increasingly polarized government to act in a timely fashion, or act at all, as well as delays caused by switching costs, tied to economics, psychological inertia, and risk aversion. One implication of this type of analysis is that quantum computing applications that operate in sectors where regulatory barriers are low may have a greater chance of reaching the market and scaling, such as network optimization applied to logistics. But adding in the time from discovery to delivery of solutions at scale makes it unlikely that quantum computing will have significant impacts on our environmental problems *within the next decade*. Given these timelines, recently rosy estimates by McKinsey that quantum computing could achieve a 7 gigaton reduction in CO_2 equivalent by 2035 seem wildly optimistic (that is over 20 percent of the total 2050 reduction goal of 33 gigatons set by the International Energy Agency).[76] At this point in time, only a handful of countries are even on track to meet their Nationally Determined Contribution (NDC) targets specified the Paris Climate agreement for 2030. In many countries, emissions need to decrease by an average 80 percent above existing levels to meet the 2^0 C goal, with large emitters like the US and China having probabilities of 2% and 16% respectively of meeting their targets.[77]

The recent International Energy Agency report on *Reaching Net Zero by 2050* has emphasized that goal will require not only further rapid deployment of available technologies, but also the “widespread use of technologies that are not on the market yet,” emphasizing that, “in 2050, almost half the reductions come from technologies that are currently at the demonstration or prototype phase.”[78] Quantum computing is in this class of technologies under development that will probably have their full impact in the timespan of 2035-2050.



Quantum computing could help address global environmental challenges that go well beyond climate in areas where we have already exceed safe boundaries, which include nitrogen and phosphorus flows, fresh water availability, and environmental impacts from substances like plastics and heavy metals (so-called ‘forever chemicals’).[79] This provides a wider potential problem set for quantum computing efforts. One researcher commented that in order to live within the planet’s boundaries, “we would need a combination of very ambitious options . . . pushed to the edge of what

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[76] Cooper, P. et al. 2022. “Quantum Computing Just Might Save the Planet,” McKinsey Digital, May 19. https://www.mckinsey.com/business-functions/mckinsey-digital/our-insights/quantum-computing-just-might-save-the-planet

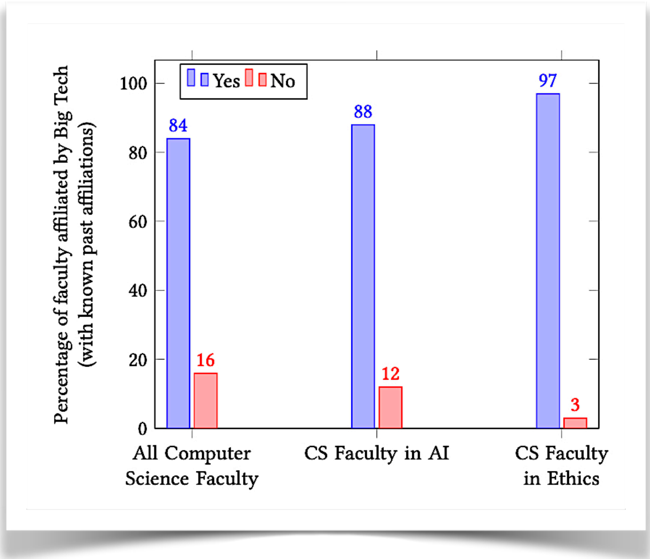
[77] Peiran, L.R. & Raftery. A.E. 2021. “Country-based Rate of Emissions Reductions Should Increase by 80% Beyond Nationally Determined Contributions to Meet the 2^0C Target,” *Communications Earth and Environment*, 2.29.

[78] IEA 2021. *Net Zero by 2050: A Roadmap for the Global Energy Sector*, Paris, France: International Energy Agency. iea.li/nzeroadmap

[79] https://www.ecomatcher.com/what-are-planetary-boundaries-and-why-are-they-significant/ . Also see: Masters, K. 2022. “Recklessness Defined: Breaking 6 of 9 Planetary Boundaries of Safety,” July 12, *Yale Climate Connections.* https://yaleclimateconnections.org/2022/07/recklessness-defined-breaking-6-of-9-planetary-boundaries-of-safety/

is possible."[80]

Finally, as quantum computing advances, there is a need to question what values are embedded, or becoming embedded, in the field and how these values could impact the direction of research, applications, media coverage, and public perceptions of quantum computing. As an example, a recent analysis of highly cited research papers in the area of machine learning found that only 15 percent of the papers made any connection to societal or environmental needs and a mere 1 percent made any references to possible negative impacts of the technology. The authors emphasized that, "it is important to challenge perceptions of neutrality and universal benefit, and document and understand the emergent values of the field: what specifically is the field prioritizing and working towards."[81] Discussions of negative effects of quantum computing often revolve about their threat to existing encryption systems weakening security systems for financial transactions for instance, but little else.[82]



The paper also highlighted another area relevant to quantum computing, the increasing corporate presence behind research funding — more than doubling in the past decade in the machine learning case. The bar chart (right) presents the percentage of computer science faculty members who have at any point in their career received direct funding/awards from Big Tech or have been employed by Big Tech stratified by areas of specialization.[83] A similar analysis is needed for quantum computing. Biases appear early in the research life cycle, as funders make decisions about awards. A recent analysis done by early career researchers of one million proposals submitted to the National Science Foundation between 1996 and 2019 found that White scientists are more likely to win a grant from NSF than Black, Asian, or Latino scientists, echoing similar racial disparities found in funding by the National Institutes of Health.[84]. As the quantum computing field advances a real challenge will be how to shape an ethical computing culture that encompasses funders (private and public), researchers, end users of the technology, and the affected 'publics'.[85] As some observers have emphasized, "Doing quantum ethics properly will require

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[80] Damian Carrington, "Huge Reduction in Meat-Eating 'Essential' to Avoid Climate Breakdown," The Guardian, October 10, 2018, https://www.theguardian.com/environment/2018/oct/10/huge-reduction-in-meat-eating-essential-to-avoid-climate-breakdown

[81] Birhane, A. et al. 2022. "The Values Encoded in Machine Learning Research," FAccT 22, June 21-22, Seoul, Korea.

[82] Szewczyk, C. 2022. "Something Has to be Done about the Quantum Computing Security Threat," *PCGamer*, April 25. https://www.pcgamer.com/something-has-to-be-done-about-the-quantum-computer-security-threat/

[83] Abdalla, M. & Abdalla, M. 2021. "The Grey Hoodie Project: Big Tobacco, Big Tech, and the Threat of Academic Integrity," *AIES '21*, May 19-21.

[84] Mervis, J. 2022. "NSF Grant Decisions Reflect Systemic Racism, Study Argues," *Science*, July 26. https://www.science.org/content/article/nsf-grant-decisions-reflect-systemic-racism-study-argues

[85] Shilton, K. et al. 2021. "Shaping Ethical Computing Cultures," *Communications of the ACM*, November, Vol 84, No. 11. https://dl.acm.org/doi/pdf/10.1145/3486639

detailed socio-political analysis of the technologies and the organizations trying to build them."[86] At this point in time, it is unclear who has the capacity and funding to undertake such analyses or, importantly, whether the quantum computing community would welcome insights from such studies.

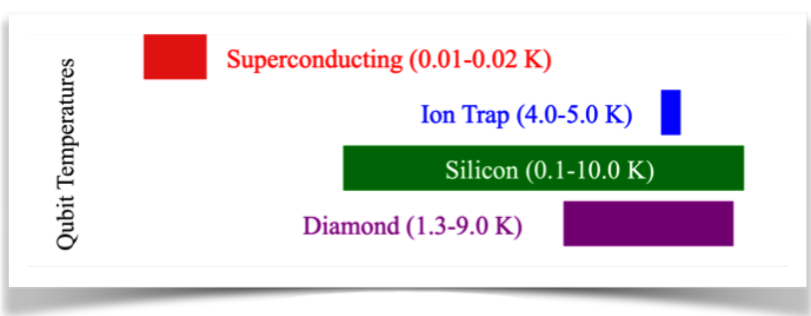
Quantum Computing and Energy Use

"Quantum computing could change the way the world uses energy"

The original headline for this piece was: "We'll run out of energy in 20 years if we don't switch to quantum computing," which the publisher later admitted, "overstated the threat to global energy production." The headline was updated to better reflect the article text.[87] The article's author was the CEO of a quantum computing company (surprise). Again, a caution against hype is needed but it raises an important question of whether quantum computing could help or hurt existing energy and resource use as well as associated environmental impacts.

This issue of the environmental impact of digital technologies has dogged the computer sector for over two decades with a large focus on the energy required by an ever growing network of large and hyper-scale data centers. Recent calculations have indicated that, despite rapid growth in demand for information services over the past decade, global data center energy use likely rose by only 6 percent between 2010 and 2018 and accounts for around 1 percent of world electricity use. The data now suggests that growth in energy use has largely decoupled from data center compute workloads but there remains an urgent need for better data and estimates going into the future to track and report progress.[88] This is important to remember since quantum computers are unlikely to exist as stand alone devices but will be integrated into existing high performance data centers — an approach called *hybrid quantum computing* — where quantum computers are used as accelerators, much like graphics processing units (GPUs) accelerate image processing in graphic-intensive applications like video games.

Because quantum computing is still at the R&D and demonstration stages, it is difficult to estimate its long term impact on our computational infrastructure but its energy impacts are likely to be related to the energy needed to achieve and maintain a quantum state, and the energy that may be 'avoided' if quantum computing reduces the need for more energy-intensive, classical computing resources. Remember that most existing quantum computing platforms require isolation from the environment to operate and that state is often achieved through very low temperatures, approaching absolute zero (zero degrees Kelvin, which equals minus 273 ^{0}C or 459 ^{0}F). The graphic shows quantum data center operating temperatures for the



[86] McKay, E. 2022. "Keep the Fight Unfair: Military Rhetoric in Quantum Technology," Preprint, February. https://www.researchgate.net/publication/358996977_Keep_the_fight_unfair_Military_rhetoric_in_quantum_technology

[87] Brownell, V. 2019. "Quantum Computing Could Change the Way the World Uses Energy," *Quartz*, March 11, Updated July 20 2022. https://qz.com/1566061/quantum-computing-will-change-the-way-the-world-uses-energy/

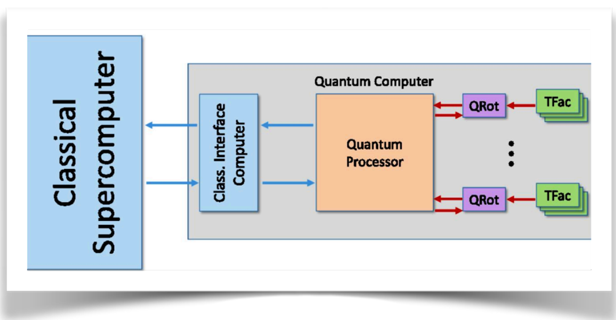
[88] Masanet, E. et al. 2020. "Recalibrating Global Data Center Energy-Use Estimates," *Science*, February 28, Vol. 367, Issue 6481.

most common quantum computing technology platforms.[89]

The energy required for cooling is significantly larger than that required for computation, a reversal from energy usage patterns seen in conventional computing. The energy use is also affected by the need to correct errors in today's noisy intermediate-scale quantum (NISQ) computers, which compared to conventional computers can be "more that a billion trillion times as likely to suffer a fault."[90] There are researchers and companies exploring alternatives that would dramatically reduce the error correction problem, and associated energy use, through an approach called topological quantum computing but "whether this is a viable approach to quantum computing — and whether it will win over competing approaches — is still anyone's guess."[91] The preponderance of competing technologies will make estimates of energy use difficult in the near to medium term but measurement techniques and metrics need to be explored, including the relevance and applicability of existing energy and environmental metrics, which cover areas like cooling, energy efficiency, and carbon footprint.[92]

The need for better measurement also applies to 'avoided' energy, i.e., energy saved by displacing classical computing time and effort with quantum computing. Some initial research compared the energy used to solve a problem (called the random quantum circuits problem) using supercomputers at NASA's Ames Research Center and the Summit Supercomputer at Oak Ridge National Lab to a NISQ computer at Google. The problem required 21 to 97 MWh to run on the supercomputers versus .00042 MWh on the quantum computer (the average household in the US uses around 11 MWh of electrical energy per year).[93] This is an impressive gain but provides one data point that was not run on a practical use case.

Also, pitting supercomputers against quantum computers is an unrealistic challenge, since the two systems are likely to be used together with the quantum computer serving as an accelerator to the classical components. The energy use of this hybrid, heterogenous architecture, where the quantum computers are potentially used in parallel and working with a supercomputer to solve a practical problem, would provide a better benchmark (see figure).[94]



This very early data provides some grounds for optimism regarding energy use, but at this point there are multiple, competing technologies with different energy profiles being applied to

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[89] Martin, Michel J. et al. 2021. "Energy Use in Quantum Data Centers: Scaling the Impact of Computer Architecture, Qubit Performance, Size, and Thermal Parameters," https://arxiv.org/abs/2103.16726v1

[90] Biercuk, M.J. & State, T.M. 2022. "Quantum Error Correction: Time to Make it Work," *IEEE Spectrum,* June 26.

[91] Ball, P. 2021. "Major Quantum Computing Strategy Suffers Serious Drawbacks," QuantaMagazine, Sept. 29. https://www.quantamagazine.org/major-quantum-computing-strategy-suffers-serious-setbacks-20210929/

[92] Vemula, D. et al. 2017. "Metrics for Sustainable Data Centers," *IEEE Transactions on Sustainable Computing*,

[93] Villalonga, B. Et al. 2020. "Establishing the Quantum Supremacy Frontier with a 281 Pflop/s Simulation," *Quantum Science and Technology*, April 27. https://iopscience.iop.org/article/10.1088/2058-9565/ab7eeb. Also: "Quantum Computers Vastly Outperform Supercomputers When It Comes to Energy Efficiency," *Physics World*, May 1, 2020. https://physicsworld.com/a/quantum-computers-vastly-outperform-supercomputers-when-it-comes-to-energy-efficiency/

[94] Reiher, M. et al. 2017. "Elucidating Reaction Mechanisms on Quantum Computers," *PNAS*, July 3, 114 (29), https://www.pnas.org/doi/10.1073/pnas.1619152114#

a shifting array of applications. Design strategies to reduce future energy use need to be developed now and could include: (1) reducing the energy for cooling, (2) designing quantum systems to achieve less energy use, and (3) improving error correction and noise allowing overall increases in computing efficiency.[95] It is not too early to begin thinking about how to measure energy impacts of the emerging quantum infrastructure, how to develop harmonized metrics, encourage data sharing, and heighten awareness within the field of the energy and broader sustainability impacts.

Initial Recommendations

Philanthropies and other stakeholders interested in quantum computing face their own set of decision points: if, when, and how to engage. Though the quantum computing ecosystem is in flux and the evolution of the technology is fraught with uncertainties, time still matters. Understanding the pace of change of the technologies and the actors in the innovation system will define strategies, for instance, shaping or adapting; and impact actions, such as placing big bets or creating options and no-regrets moves.[96] It will make the difference between getting in front of issues or falling behind. Falling too far behind has consequences, which are becoming clear with many digital technologies such as AI.[97] One can either speed up, which could lead to ill-considered actions or poorly conceived policies, or become irrelevant and incapable of impacting the dynamics of technological change.[98]

For those presently outside the quantum space it is worth considering a co-evolution strategy — to become part of the diverse, complex, and dynamic quantum computing innovation ecosystem, not isolated observers sitting on some external perch. The goal is to prevent risks, not just study them; to encourage innovation, not just write about it; and to accelerate the introduction of sustainable technologies into the marketplace; not to hinder it. The following are some initial ideas for engagement.

- ***Improve our understanding of quantum computing energy use and make quantum computing, including the development of harmonized metrics to measure overall energy impacts, part of the larger efforts to support sustainable computing.***

As noted, there is presently a dearth of data on the energy impacts of quantum computing. More research is needed to estimate both operational and ‘avoided’ energy. In addition, quantum researchers in both academia and industry could be integrated into on-going efforts to promote what is now termed ***sustainable computing,*** a subset of a larger, longer-term goal of addressing the “twin challenges of a green and digital transformation.”[99] For instance, the US National Science Foundation recently released a ‘Dear Colleague’ letter to “Encourage the

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[95] Martin, Michel J. et al. 2021. “Energy Use in Quantum Data Centers: Scaling the Impact of Computer Architecture, Qubit Performance, Size, and Thermal Parameters,” https://www.researchgate.net/publication/350542764

[96] See: Courtney, H.G. et al. 1997. “Strategy under Uncertainty,” *Harvard Business Review* 75 (6): 67–79, Nov./Dec.

[97] Roose, K. 2022. “We Need to Talk about How Good AI is Getting,” *New York Times*, August 24. https://www.nytimes.com/2022/08/24/technology/ai-technology-progress.html?referringSource=articleShare&smid=nytcore-ios-share

[98] Popper, S.W. 2003. “Technological change and the challenges for 21st century governance.” In: *AAAS Science and Technology Policy Yearbook*, In: Teich, A. & Nelson. S. (eds.), Washington, DC: American Association for the Advancement of Science.

[99] EC 2020. *Shaping Europe’s Digital Future*, European Commission. https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age/shaping-europe-digital-future_en

submission of novel and high impact proposals that advance sustainability in all aspects of computing."[100] Organizations like the Institute of Electrical and Electronics Engineers (IEEE) have established groups to bring together researchers in academia and industry who are interested in (1) promoting the design and implementation of sustainable computing, and (2) facilitating computing for sustainability.[101] The longer term development of metrics should be done, as much as possible, in coordination with standard setting bodies working to measure and quantify quantum computing impacts. For example, the IEEE Framework on Metrics and Benchmarks seeks, "…to outline a framework by which the continuing progress in quantum engineering can be monitored by the broader quantum computing community... to guide the decisions of policy makers and technology stakeholders as well to monitor the overall growth of the quantum research community."[102] Other models could be explored such as the one established by the OECD to evaluate and assess the impacts of artificial intelligence — the OECD AI Policy Observatory, possibly expanded to the Quantum Policy Observatory.[103]

- ***Create a portfolio of environmental problems where quantum computing could provide measurable improvements over other options and design ways to accelerate their deployment and commercial adaption.***

As noted earlier, "…the set of problems with efficient quantum solutions remains small, even as the latest research seeks to determine just what makes a problem a good fit for quantum computing."[104] So what pressing environmental problems could quantum computing help address? Answering that question will require much more effective and intensified collaboration between the quantum computing and environmental communities, including those involved in risk management and public policy. This gulf has existed for decades and little has been done to close it.[105] The support of research coordination networks, synthesis centers, convergence accelerators, or R&D sandboxes, that bring together researchers from both communities should be explored and evaluated. It is also important to engage the community downstream from the researchers because, "Most emerging technologies suffer from a disconnect between those who develop and deploy the technologies (upstream) and those responsible for assessing and managing any associated risks (downstream), including regulators and policy makers….Upstream scientists are less likely than downstream scientists to think that concerns about potential…risks are based on valid science and tend to consider a narrower range of uncertainties."[106] As noted, significant temporal barriers to technology commercialization can exist from oversight requirements (or lack thereof), so analyses of regulatory pathways should be incorporated into the upstream-downstream integration efforts.[107] A competition could also be designed and launched, similar to National Institute of Standards and Technology (NIST) competition to develop so-called 'quantum resistant

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[100] https://beta.nsf.gov/funding/opportunities/design-sustainability-computing

[101] http://stc-sustainable-computing.ieee.net/about

[102] IEEE, 2018. Framework on Metrics and Benchmarking, Draft Document version 0.2. Retrieved October 16. https://docs.google.com/document/d/liNETuK_X0A- HpwkCf4_H6xjVir7tWNVh1Y-jIEMfhWM

[103] https://oecd.ai/en/

[104] https://www.theregister.com/AMP/2022/07/21/quantum_computing/

[105] See for historical context: Brown, J.S. & Rejeski, D. 2001. "Ecological Computing," *The Industry Standard,* December 25.

[106] Powell, M. 2007. "New risk or old risk, high risk or no risk? How scientists' standpoints shape their nanotechnology risk frames," *Health, Risk & Society*, Vol. 9. https://www.tandfonline.com/doi/abs/10.1080/13698570701306872?journalCode=chrs20

[107] A cautionary tale about the impact of regulatory uncertainty is found with biotech food applications: Pollack, A. 2007. "Without U.S. Rules, Biotech Food Lacks Investors," *New York Times*, July 30.

cryptographic algorithms' mentioned earlier, but with a specific focus on quantum-solvable environmental and sustainability challenges.

- ***Create and update an inventory of quantum computing applications that focus on environmental and sustainability challenges, and share this information widely.***

Emerging attempts to apply quantum computing to environmental problems should be identified, evaluated, and where applicable, shared, to encourage learning and potential adaption. In-use applications can be identified as well as early stage proof-of-concepts, and research ideas, subdivided by sector (energy, agriculture, transportation, etc.) and made widely available on-line.[108] This baseline database can then be updated annually or bi-annually to better determine progress (by sector, computing platform, problem area, and country) and also map gaps in effort or potential pressures on the regulatory system from emerging applications. This inventory could inform broader efforts to understand the regulatory frameworks that could affect the impact and timing of products and applications of quantum computing and help craft better oversight frameworks (both formal and informal). This can be part of a broader and sustained effort at horizon scanning (with a hype filter) to determine realistic timelines and possible impacts for environmentally-related quantum computing applications. The inventory could also highlight industry efforts to bring quantum computing to bear on environmental issues or climate change challenges (see box on Qlimate). Results of these efforts, however, must be closely followed and evaluated (to avoid any issues around greenwashing).

Qlimate

Qlimate is a quantum computing net zero initiative that aims to support large-scale decarbonization. Qlimate is backed by PsiQuantum. PsiQuantum will dedicate a substantial share of initial quantum computing capacity to high-impact sustainability applications, and we are building partnerships with corporates, governments, and non-profits to develop and scale end-to-end the most promising decarbonization solutions that could take years off the path to net zero – and contribute towards the planet getting back on a 1.5°C pathway. https://www.qlimate.world/

- ***Assure equitable access to the environmental and energy benefits of quantum computing.***

Given the technological complexity of quantum computing and high expertise requirements for quantum researchers and practitioners, it is more than likely it could exacerbate the growing digital divide. Discussions about a quantum "digital divide" have focused largely on encryption, with people noting that, "The nation(s) possessing a large-scale commercially-relevant quantum computer will also have a massive espionage advantage."[109] But other positive benefits are also likely to be inequitably distributed. This outcome is highly probable, given the earlier mentioned under-representation of particular groups (by gender, race, or geography) in quantum computing workshops and publications, which undercut early and proactive considerations of equity and inclusion, particular groups in the global South. As one recent observer noted, "It is anybody's guess how quantum computing power will spread through society in the next few decades, but is is quite possible that it will not be widely accessible," which highlights one option that quantum computing, "is made accessible through

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[108] One example is the on-line inventory of future bioengineered products: https://futurebioengineeredproducts.org/ "This website allows you to search data originally assembled by the National Academies of Science, Engineering, and Medicine for their recent report on Future Biotechnology Products. "The database is being updated to support inquiries by the public, academic and industrial researchers, businesses, investors, and others interested in better understanding advances in bioengineered or biotechnology products."

[109] https://www.linkedin.com/pulse/quantum-effect-geographical-digital-divide-importance-paul-lucier/

the cloud by some organization for commercial or benevolent reasons (say by the Gates Foundation, or by a country like Norway)…to counter many of the risks of monopolization of access."[110] In the long term, there needs to be incentives for quantum computing researchers to perform ethical research that takes into account a wide range of social and environmental impacts, which will include involving the 'gatekeepers' of the research enterprise, such as funders, journal publishers, and conference organizers.[111]

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[110] de Wolf, R. 2017. "The Potential Impact of Quantum Computers on Society," *Ethics and Information Technology*, Vol. 19, September 15. https://link.springer.com/article/10.1007/s10676-017-9439-z

[111] This is slowly happening in AI research. See, Rivero, N. 2022. "AI Gatekeepers Are Taking Baby Steps Towards Raising Ethical Standards, *Quartz*, July 20. https://qz.com/1874134/computer-scientists-will-enforce-rules-for-ai-ethics/

Appendix

Technology platforms for quantum computing (examples):