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Energy and physical resource impacts of quantum computing merit greater attention

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Quantum computing research and development is growing worldwide; yet the energy and physical resource demands of future quantum-accelerated data centres are unknown. Planning for sustainable quantum computing requires strong collaboration between research communities across engineering, physics, environmental sciences, economics, policy, and energy systems and scenario modelling.

Quantum computing is on a path towards commercial scale[1]. However, without collaboration and management, the resource and infrastructure challenges associated with current-generation artificial intelligence (AI) data centres[2] are poised to repeat themselves in some form once fault-tolerant quantum computing (FTQC) gains momentum. If projections that FTQC systems could be ready for large-scale deployment by the mid-to-late 2030s[3] are correct, then interdisciplinary collaborations are urgently needed to ensure a robust and sustainable development path for quantum computing.

Preliminary estimates for superconducting qubit technologies – one of today's most mature options for quantum computing – suggest energy consumption requirements in the range of 1–10 Watts per qubit for large-scale, learned-out FTQC systems[4]. Considering that a single FTQC system would need ~10^6 qubits or more to solve useful problems[5], several FTQC systems linked together could draw tens to hundreds of Megawatts (MW) of near continuous power at a single location, a load on the order of today's classical computing AI data centres. Cooling water consumption for thermal management of FTQC systems could also be substantial, although how those volumes compare with the water requirements of today's largest data centres[6] (10^8–10^9 litres per year) remains an open question.

Future FTQC systems could additionally require substantial quantities of liquid nitrogen, liquid helium and helium-3 to achieve near-absolute zero temperatures (cryogenics) for low-error operation[7]. Both helium (the abundant isotope, helium-4) and helium-3 (a rare isotope) are non-renewable resources in relatively limited supply worldwide. Helium-3 is so scarce that the US annual production capacity in 2025, traditionally among the world's largest[8], might only be able to cover a small number of large-scale superconducting qubit-based FTQC systems. The possibility of this helium-3 shortage is already motivating research into qubit technologies that can operate at temperatures above 1–2 K and therefore require little-to-no helium-3, as well as into alternative sources of helium-3, for which lunar mining is currently being discussed[9].

To become commercially viable, qubit implementation platforms are trending towards greater scale, reliability and efficiency. These technological advancements will have important implications for energy and physical resource consumption. It is not yet clear which of the various platforms currently under active development worldwide – superconducting transmon circuits, semiconductor spin, trapped ions, photonic, neutral atoms and topological, among others – will be deployed in commercial-scale FTQC systems. For those platforms requiring deep cryogenics, researchers are working to further reduce the electricity consumption needed to deliver near-absolute-zero heat rejection. Meanwhile, others are packing increasing numbers of qubits into quantum chips. Progress on both fronts will decrease the energy and physical space needed for a given amount of computing power. Step-changes in control electronics and error-correction techniques will simultaneously be required[10].

The questions of when FTQC will arrive at scale and what the demand for it will be when it does are potentially even more defining for energy and resource use than their technological development. Jevons paradox – that increased efficiency typically leads to increased demand – becomes salient in this context. While quantum technology could promise advancements in compute efficiency, those efficiency gains could simultaneously lead to increases in demands for new services, including heretofore unimagined computing possibilities[11]. Follow-on questions centre around whether and how new quantum-driven demands for electricity can be met with available supplies; which generation sources might be tapped (such as fossil fuels, renewables or nuclear); and what might be the implications for consumers and the environment (for example, affordability, national security, critical supply-chains and the resiliency of social and environmental systems). Few published studies have explored these questions for quantum computing at scale.

Some promising work is emerging within a small cross-section of the physics, engineering and computer science communities[12,13]. An example includes the Quantum Energy Initiative, an open community of researchers exploring the topic from a bottom-up, highly techno-granular perspective. As quantum computing progresses towards FTQC systems deployed at scale, it will become increasingly important to approach from the top-down, macro-systems direction as well. This will require incorporating research from the disciplines of economics, policy, behavioural studies, environmental sciences, scenario and uncertainty analysis, and energy and infrastructure systems modelling. A widening of collaboration networks will be critical for developing more holistic quantum benchmarking frameworks and metrics[14] that incorporate key energy and physical resource elements. Notably, such elements have not been an explicit focus of major international efforts such as the Quantum Benchmarking Initiative.

Realizing stronger entanglement between the top-down and bottom-up communities needs researchers from both sides to meet each other where they are. Ensuring the development of FTQC that avoids the energy, resource and infrastructure issues caused by current-generation AI data centres will require going beyond an exclusive focus on process-level computational performance of hardware, software and algorithms[5]. Moreover, rather than using idealized diagnostic tests to benchmark quantum computers, interdisciplinary research communities could jointly design experiments that gauge the performance of hybrid quantum-classical machines that more closely resemble those likely to be deployed for future, real-world use-cases. Systematic comparisons across metrics could then be made for the various qubit implementation platforms and the results scaled to aggregate levels under plausible future scenarios (assuming multiple FTQC systems spread over many locations). While a given technology might seem feasible when the system boundary remains at a process or single-machine level, scaling analyses can highlight where bottlenecks could arise with substantial deployment of many machines, representing the true value and cost of quantum computing to society.

Given the interest in AI data centres today, the potential of quantum computing tomorrow and the technological and socio-behavioural uncertainties that will be present throughout, a systematic, international and inter-disciplinary research agenda must begin in earnest as soon as possible. Delaying action to mitigate the energy, resource and infrastructure impacts of FTQC until after a subset of qubit platforms has achieved commercial dominance misses a critical window — one that could have long-term implications. The period between now and 2030 is poised to see billions of dollars of investment in quantum research, development and demonstration worldwide[15]. The projects and people seeded by these near-term investments will subsequently shape the field over the medium term of the 2030s; the innovations that result will then lay the foundation for the infrastructure and supply chains erected in the long term into the 2040s and beyond. Therefore, the time for research communities to entangle is now.

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