Research Directions: Quantum Technologies

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How might quantum computing impact climate change and the wider environment?

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Question

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Context

Quantum computing's potential impact on climate and the environment is of great importance and taking steps to shape its trajectory towards sustainability and positive impact, at this stage, is vital for responsible development. In this question, we suggest areas for investigation to build shared understanding and advance sustainable development.

There are two dimensions to consider in understanding quantum computing's environmental and climate impact. First is the direct environmental impact of developing and using quantum computers throughout their life-cycle, including, for example, resource requirements and carbon footprint (Arora and Kumar, 2024). Second is the possibility of quantum computing use cases targeted towards climate solutions (Berger et al., 2021; Paudel et al., 2022; Ho et al., 2024).

Although there have been initial steps towards investigating the energy requirements of quantum computing (see Auffèves, 2022; Meier and Yamasaki, 2023), we need to understand better the environmental impact of the full life-cycle of developing, using and disposing of quantum computers. This includes factors such as energy and water consumption, carbon footprint, waste disposal and recycling, and mineral use.

This initial research suggests quantum computing may provide advantages, reducing environmental cost when compared to, for example, high-performance computing (HPC). Though the current expectation is that quantum computers may require significantly lower energy than their classical counterparts to solve certain classes of problems (Arute et al., 2019; Meier and Yamasaki, 2023), it is first necessary to define and agree upon metrics to quantify these resources to properly claim this advantage.

For example, there remains a lack of community consensus on a quantum computing analogue to the classical concept of floating point operations per second (see, e.g., Nayak; Campbell for alternative proposals). As a result, quantifying the energy efficiency of a quantum computer is a challenge. Defining community-accepted metrics for this and other environmentally relevant metrics remains an open question.

Additionally, the support requirements for quantum computing systems, for example, cryogenic cooling, are themselves currently resource intensive, and therefore when calculating overall resource requirements, must be accounted for. Another open question is how resources utilisation scales for a useful quantum computer.

The second dimension to consider is the potential of quantum computing to address climate and other environmental challenges. A few highlighted examples (by no means an exhaustive list) are:

- The management and adoption of renewable energy sources. Use cases might include the use of quantum chemistry simulation to discover novel materials and improve battery technologies (Arenas et al., 2019; Sánchez-Díez et al., 2021; Rice et al., 2021; Delgado et al., 2022), and quantum optimisation to more efficiently balance the energy grid (Ajagekar and You, 2019; Yang et al., 2020; Zhou et al., 2022).
- The development of carbon-capture technologies through, for example, helping with the study of metal–organic frameworks (Greene-Diniz et al., 2023).
- Mitigating potential negative effects of unpredictable weather. Using quantum algorithms to solve the Navier-Stokes equations (Gaitan, 2021) could lead to better predictions of mass-impact disasters due to fast-changing weather patterns.
- Reduction of fuel consumption and emissions, assisting with a range of optimisation problems, such as identifying more efficient delivery routes (Harwood et al., 2021; Bentley et al., 2022; Osaba et al., 2024) and cargo loading strategies (Pilon et al., 2021; Phillipson, 2024).

Despite quantum computing's promoted potential, it remains unclear what impact these applications may have, as well as the timeline on which they may be feasible. A fuller understanding is required as is benchmarking of these quantum computing applications against the performance of current classical capabilities, including HPC. This is crucial to enable decision-makers, such as policy makers and funders, to choose the most promising applications to focus efforts and resources on. Since climate interventions are pressing, in some cases a particular intervention may be needed on a timescale which is not compatible with current projections on quantum computing's development. Transparency on current capabilities and expectations will help to ensure that research efforts, funding and other resources are not inappropriately directed towards quantum computing when a classical approach may be more appropriate.

Better understanding of the applications, benefits and environmental impact of the life cycle of quantum computers would help identify and perform appropriate actions to address climate and broader environmental challenges at this crucial moment of development. Associated research questions therefore include:

- The identification and assessment of use cases targeted towards climate and wider environmental challenges, and investigation into the extent to which they may help and the timeframe for doing so.
- Relevant metrics for quantifying energy efficiency when performing quantum computation.
- Identification of other environmentally relevant metrics across the full life cycle of quantum computing systems
- Proposals for means of effectively communicating key information about applications of quantum computing for climate change and wider environmental issues, including impact, timeline, comparisons with classical methods, and relevance, particularly for decision-makers, including policy-makers and funders.

How to contribute to this Question

If you believe you can contribute to answering this Question with your research outputs find out how to submit in the Instructions for authors (https://www.cambridge.org/core/journals/research-directions-quantum-technologies/information/author-instructions/preparing-your-materials). This journal publishes Results, Analyses, Impact papers and additional content such as preprints and "grey literature." Questions will be closed when the editors agree that enough has been published to answer the Question so before submitting, check if this is still an active Question. If it is closed, another relevant Question may be currently open, so do review all the open Questions in your field. For any further queries check the information pages (https://www.cambridge.org/core/journals/research-directions-quantum-technologies/information/about-this-journal) or contact this email (quantumtechnologies@cambridge.org).

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