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Quantum Technologies in the Context of Climate Change: Emphasizing Sustainability in a Responsible Innovation Approach to Quantum Innovation

Dakota Root 

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Abstract Using quantum technologies (QTs) to solve problems related to climate change is a key goal for many physicists at the research and development stage. Recent research anticipates numerous real-world applications for quantum technologies that will address climate change and further sustainable development goals. However, currently there is no guiding framework for implementing responsible, sustainable innovation, or criteria for evaluating the sustainability of QTs. The goal of this article is to augment previous responsible innovation (RI) analysis of, and recommendations for, quantum innovation by emphasizing sustainability as a key value. This article will also provide specific recommendations for developing sustainable QTs and criteria to assess the sustainability of QTs. With increases in funding for quantum innovation and the predicted operability of many QTs in the coming decades, this is a key moment to discuss values and shape the quantum innovation trajectory. By using an RI approach with an added emphasis on sustainability, this article offers tools for developing responsible, sustainable QTs that are sensitive to the climate change context.

Keywords Quantum technologies · Responsible innovation · Sustainability · Quantum computing · Climate change

Introduction

Quantum technologies (QTs) have numerous practical applications that may transform future society, which include encrypting and securing data [1], solving intractable chemistry problems [2], highly sensitive and precise sensing [3], energy storage [4], and smart city infrastructure [5]. Scholars predict that they will also help solve social problems and support economic and environmental resilience [6]. QTs are divided into three classes: 1) quantum communication for secure data transmission, 2) quantum computation, for faster and more efficient calculations, and 3) quantum sensing, for precise and accurate measurement [5, 7]. Quantum properties, superposition and entanglement, mean that QTs have unique capabilities that differentiate them from other emerging technologies. As examples, quantum computers are predicted to have a *quantum advantage*, meaning that they can complete tasks faster than classical computers [8], and quantum sensors can access and process data that isn't accessible to existing sensors [9]. Recent research in responsible innovation (RI) has analyzed challenges that could emerge related to the distinguishing features of QTs. RI is a particularly useful approach for discussing and evaluating emerging technologies like QTs

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because it has evolved to shape innovation, is sensitive to values, has industry relevance, and is applicable at a policy level.

Some problems that have been highlighted in the RI literature on QTs include social inequalities from a quantum divide [10], threats to personal data and national security [11], and a lack of regulation to guide a responsible quantum trajectory [12]. Yet the environmental impact of quantum innovation, and how QTs relate to sustainability, has not yet been the subject of scholarship. This is a significant gap because the scientific community has called for more research on sustainability and quantum innovation [8, 13, 14]. Initiatives in physics, like Quantum4Climate¹ and the Quantum Energy Initiative,² show that sustainability is a core value for quantum research in the sciences. In addition, recent reports from the Open Quantum Institute³ anticipate numerous real-world applications for quantum technologies that will address climate change and further sustainable development goals (SDGs). However, there is no guiding framework for implementing responsible, sustainable innovation, or criteria for evaluating the sustainability of QTs. The goals of this article are to, 1) augment RI analysis by emphasizing sustainability as a key value, 2) propose recommendations for sustainable quantum innovation, and, 3) provide criteria to assess sustainable quantum technologies.

This article begins with a thorough review of literature on quantum innovation within the RI field, highlighting the gap around sustainability. Section "Sustainability as a Key Value" will show why sustainability is a significant value in an environment of competing values. I argue that a RI approach should emphasize sustainable quantum innovation given the context of climate change. The general aims of RI, and specific reports on responsible research and innovation (RRI) from the European Commission, will be used to support this argument. Next, I will discuss how we can define the sustainability of technologies in Section "Sustainability Recommendations and Criteria", drawing on recent research on sustainability and emerging technologies like artificial intelligence (AI) systems and high-performance

computing. Finally, Section "Envisioning Responsible and Sustainable Quantum Innovation" addresses what responsible and sustainable design and deployment would look like for quantum innovation.

Useful and transformative technologies emerged from the first quantum revolution, including lasers and transistors [15]. The second quantum revolution is now underway, developing on breakthroughs that allow physicists to control quantum objects and exploit entanglement [16]. Although a fault-tolerant quantum computer is still in the research and development phase, quantum computing services exist, and quantum sensors like atom interferometers and atomic gravimeters are already in use [17, 18]. This is the moment to evaluate the social and environmental implications of these emerging QTs. This article contributes the first comprehensive review of quantum technologies and sustainability and develops an RI approach to assess the sustainability of QTs by evaluating technological development, usage, and objectives. As Auffèves [8] argues, we can shape quantum innovation in a responsible and sustainable way and make QTs "a model of virtuous deployment."

Responsible Innovation and Quantum Technologies

As Roberson [12] has argued, RI is a broad field featuring competing values and diverse perspectives, however in general it promotes ethical, inclusive, and value sensitive innovation. According to Stilgoe et al. [19], RI is defined by four features: anticipation, reflexivity, inclusivity, and responsiveness. *Anticipation* means an engaged, participatory assessment of the future to discover risks, but also develop a vision of what citizens would like the future to look like. *Reflexivity* encourages researchers, policymakers, and industry-actors to analyze their research, technologies, and beliefs, questioning prevailing assumptions. RI is *inclusive* in the sense that it engages with the public via polling, focus groups, citizen events, and discussion groups. This public dialogue is taken seriously to draw out needs, interests, and concerns, giving citizen voices weight from the earliest stages of deliberation. Even if research and innovation anticipate risks, are reflexive about practices, and have engaged, inclusive dialogue with the public, they are not responsible unless they are also *responsive*.

¹ <https://q4climate.github.io>

² <https://quantum-energy-initiative.org>

³ <https://oqi.gesda.global>

Responsiveness means adapting the trajectory of innovation with incoming knowledge. Change is encouraged when risks appear, or in reference to public values and concerns.

Key Recommendation for QTs

As a significant emerging technology, QTs have been the subject of recent research in the RI discipline. Four key recommendations appear across the literature: 1) stakeholder dialogue, 2) improved comprehensibility, 3) risk assessment, and 4) an emphasis on equality (including a dimension of global access). Here, I'll break down the core arguments regarding these criteria, evaluating why particular goals and challenges have been emphasized and how they relate to the RI approach.

The RI approach requires that quantum innovation has an inclusive dimension. This means that diverse stakeholders should actively participate in shaping technological trajectories, and their needs and concerns should be considered. As Vermaas [20] points out, this is the difference between simple "dissemination to lay persons" and a real, open debate where citizens are listened to by policymakers, industry-actors, and researchers (244). Coenen and Grunwald [21] argue for "public engagement activities" that bring citizens in the deliberation processes on quantum innovation (291). As an example, the authors suggest that representatives from implicated civil society groups would be invited to discuss QTs. Ten Holter, Inglesant, and Jirotko [22] argue for developing pathways for engagement between stakeholders and researchers, and researchers and policymakers. The authors point out that right now, few researchers are invited to speak at legislative hearings, panels, and committees, making it difficult to share insights and knowledge outside of the academic domain. Real stakeholder dialogue allows for reflecting on design, on how technologies align with values, and encourages the inclusion of a diversity of viewpoints.

To have this inclusive public dialogue and multi-stakeholder discourse pathways, it's necessary to demystify quantum innovation. Vermaas [20] discusses this issue, pointing out that "the knowledge gap between research and society may not be so easily overcome in the case of quantum technologies, hampering an open debate" (242). Vermaas suggests

that physicists themselves must make the discussion comprehensible to the public. Ten Holter, Inglesant, and Jirotko [22] suggest that a significant responsibility for researchers is exploring and explaining QTs and their implications. As Roberson [12] discusses in interviews with researchers, perceiving *quantum* as a "magical strange word" is a major barrier when discussing the social implications of quantum innovation. With more communication, more educational outreach, and straightforward explanations of complicated terms and processes, it will be easier to address issues of accessibility, equality, and public good. More public comprehension around QTs will enable more inclusive debate, by citizens who are better informed about QTs.

The RI approach anticipates how technological innovation will affect the future, evaluating both benefits and risks from emerging technologies. As Inglesant et al. [11] point out, once a technology exists, it's hard to change the deployment path. This means that we must think carefully about a technology's possible implications, otherwise it could be challenging to make changes further down the line. The authors argue that an RI approach allows us to analyze different visions of a quantum future and reflect on the benefits and risks, using these considerations to inform policy. Interviews by Roberson [12] with quantum researchers show that one of the strengths of the RI method is identifying quantum risks and addressing them directly with responsible actors. Kop et al. [10] discuss specific risks related to QTs: increases in inequality if some countries benefit from innovation more than others, a quantum arms race in which technological and military dominance take precedence over shared values and international cooperation, and malicious use of QTs that could have severe implications for data security. By anticipating possible problems and assessing these risks, the RI approach allows for responsibility, shaping a better technological trajectory in the future.

Ten Holter, Inglesant, and Jirotko [22] emphasize that QTs are disproportionately accessible to start-ups, big companies, and well-funded research institutions (particularly in the Global North). On a national level, the benefits of QTs may be available only to a select few. On the international level, a quantum advantage may encourage protectionism and global competition. Kop et al. [10] agree

that QTs may strengthen existing inequalities. The authors encourage accessibility to bridge the quantum divide, and global cooperation to prevent international rivalries. Being aware that innovation can negatively impact groups, particularly those that are already impacted by structural injustice, means reflexivity on the current social conditions. However, it also requires that we anticipate the direction of technological development, developing guidelines that encourage more fair and equal access to technologies and their benefits.

RI and the Public Good

RI literature often discusses societal impact, and in particular, technological risks that may harm citizens, damage the environment, or cause other unintended negative effects. The four features of RI are important because they allow for developing and deploying technologies that will solve problems, improve society, and not do active harm. In the RI literature reviewed in Section "[Key Recommendation for QTs](#)", the four key recommendations for QTs all fit within a vision of positive quantum innovation where benefits are shared, and risks are avoided. One way of thinking about RI is that it encourages technological innovation aligned with public good. Roberson [12] makes the link to public good explicit when she discusses the objectives of QTs with researchers. I think this is a valuable point to keep in mind: if RI is about shaping and guiding innovation [19], then it's clearly guiding technology towards outcomes that are good for the public. We may need anticipation, dialogue, and reflexivity to deliberate on what the common good looks like, but it is an overall aim.

A problem arises here, because RI directs innovation towards a beneficial trajectory for society, and yet RI scholarship on quantum innovation only minimally acknowledges the context of climate change, arguably the most pressing challenge facing human and nonhuman life. Sustainability, as an approach to mitigate climate change, is largely missing from the discussion. Kop et al. [10] do explicitly refer to sustainability in their eighth recommendation for quantum innovation, calling to, "Actively stimulate sustainable, cross-disciplinary innovation." This is a valuable contribution, but the authors don't explain why sustainability is important for emerging

technologies or what "sustainable cross-disciplinary innovation" means in practice. The World Economic Forum's 2022 report on responsible quantum computing governance lists sustainability as one of nine core values and provides more detail on possible policy recommendations [18]. First, they define opportunities, such as the quantum energy advantage and improved climate modeling. Second, they detail risks, such as the environmental costs of materials used in quantum hardware and energy costs of cooling quantum computers. Finally, they offer some possible actions, like prioritizing funding for applications that would target climate-related problems. This is another contribution to the literature on quantum innovation and sustainability, but the discussion lists sustainability as one among nine innovation values, doesn't provide context for sustainability as a value, and does not provide key criteria for assessing QTs. Given the context of climate change, I argue that sustainability is a non-negotiable value for public good and should be at the center of a responsible quantum innovation approach, with recommendations for development and criteria for assessing deployment.

It's true that exactly what constitutes responsible innovation is a "widely debated" topic [23, p. 672]. In any value sensitive approach with diverse stakeholders and multiple perspectives, "it is not always clear how to balance competing values" [24, pp. 17, 22]. In a complex environment of diverse stakeholders with competing goals, it's not easy to determine what principles should take center stage. But I aim to show that, given the significance of climate change and the negative impact humans continue to have on the environment, RI should emphasize sustainability for quantum innovation. In the next sections, I'll support my argument. First, I'll discuss the significance of sustainability in the context of climate change, and then I will use literature from the RI field and policy reports from the European Commission regarding innovation to support my claim.

Sustainability as a Key Value

Sustainability is of urgent importance because climate change is "the defining issue of our time" and we are living in the last years in which action is possible to prevent future catastrophe [25]. Humans already face

extreme weather patterns, raising sea levels, dramatic decreases in biodiversity, and the increased severity of droughts, wild-fires, and tropical cyclones [26, pp. 1, 5]. There are a million species under threat of extinction, whose scarcity and eventual disappearance will dramatically impact ecosystems around the world [27]. Research shows that human societies are also experiencing increases in insecurity around food and water, rises in mortality due to severe heat events, and more water and food-borne pathogens [26, p. 9].

Sustainability and Sustainable Development

Sustainability recognizes that humans have impacted and continue to impact the environment, and that the current social and economic developments are not sustainable for the planet [28]. Sustainability means maintaining human well-being and quality of life, but simultaneously preserving ecosystem integrity and assuring biodiversity [29]. Sustainable practices limit consumption to prevent waste and resource depletion. The objective is to meet needs in the present, while guaranteeing that future generations can also meet their needs.

At a policy level, guidelines for *sustainable development* have emerged to guide national action. Sustainable development emphasizes growth, but in a way that does not negatively impact the environment or deplete resources [30, p. 2]. Although the terms are sometimes used interchangeably, they are distinct. Sustainable development puts more emphasis on development, in comparison to sustainability, which puts more emphasis on limits.

The UN's Sustainable Development Goals (SDGs) represent a global effort to implement evidence-based solutions and reach key sustainable development targets [31, p. 342]. The 2015 SDGs provided 169 global targets, related to subjects like energy consumption, biodiversity loss, renewable energy, and land degradation [31, p. 339]. Specific policy targets to mitigate climate change include transitioning from fossil fuels to low-carbon energy sources and carbon capture and storage [32]. Currently, no country meets sustainability thresholds, meaning they cannot provide for "the basic needs of its population, while also using sustainable levels of resources" [33]. Unfortunately, reports also show that no country is on track to reach SDG targets by 2030 [31, p. 339]. Making sustainability a key feature of recommendations for

emerging technologies is just one part of a broader push to prioritize the mitigation of climate change.

Sustainability in the RI and RRI Literature

I argue that sustainability needs to be emphasized in the RI approach to quantum innovation and will use RI literature and EU policy reports to support my position. First, as I pointed out in Section "[RI and the Public Good](#)", if RI seeks to encourage positive innovation that is aligned with public good, then sustainability should be emphasized. Second, sustainability has been discussed by authors in the RI field as a significant value [34–37]. Third, sustainability is present at the governance level, in European Commission reports on a responsible research and innovation (RRI) approach.

Regarding the first point, in their review of the RI scholarship, Fisher et al. [34] point out core goals of RI, including alignment with public values, collective ethical reflection, and risk anticipation. Long and Blok [37] make a similar point when they describe the three key goals of an RI approach as "avoiding harm," "doing good," and developing global governance (249). I suggest that since climate change is a global risk touching every individual, sustainable practices and policies are essential for the public good.

Many authors in the broader field include sustainability as a key aspect of responsible innovation. Fisher et al. [34] reflect on the "responsibility of humankind at the planetary level" (19). The authors recommend that climate change and urgent planetary action be the subject of future RI analysis. Jakobsen et al. [36] argue that RI and RRI guide research to meet "social, ethical and environmental goals" (2331). Long and Blok [37] connect RI to positive social impact that supports sustainable development (249). Imaz and Eizagirre [35] go further, recognizing that responsible innovation can be a "driver" that enables implementing sustainable policies and reaching SDGs.

At the policy-level, the RRI approach has consistently discussed the significance of sustainability. RI and RRI are linked and often used interchangeably but have key differences [38, 39]. RRI has emerged out of the European Commission and is a policy-oriented, top-down approach to technological innovation that specifically addresses grand

societal challenges and seeks to make RRI values more practical through governance measures [38, 39]. RRI shares the four key RI features of anticipation, reflexivity, inclusivity, and responsivity, however it is distinguished by an emphasis on six key indicators for assessment: public engagement, gender equality, science education, open access knowledge, ethics, and governance [40, p. 10, 41, p. 754]. Reports from the European Commission actively call for research and innovation that will “preserve the environment” [42]. The European Commission also discusses their strategies for “smart, inclusive and sustainable growth” [40, p. 11]. At the policy level, sustainability is recognized as a goal for innovation in RRI reports, however I note that it was not selected as a key indicator for assessing innovation.

Sustainability is already present in discussions about RI and RRI, both in research scholarship and policy reports, even if more emphasis and detail is necessary. Yet to date, there is little mention of sustainability in relation to QTs. My argument is that these general suggestions should become explicit. With QTs at a research and development stage, making sustainability a key value could shape the technological trajectory in a positive way. My approach fits with research by Van de Poel et al. [43] on the importance of emphasizing select values in RI to “foreground what is considered important and desirable” (701). Focusing on climate change and making sustainability a main value shows that climate change is a defining issue, and that sustainability is taken seriously rather than given lip service.

Is Sustainability Enough?

Although I have argued that sustainability should be a key value for quantum innovation, it is important to address the criticism of sustainability, sustainable development, and SDGs. Sustainability, with its emphasis on providing for human needs with limits, and sustainable development, with its emphasis on growth without overconsumption, both maintain the political, social, and economic status quo. They are criticized for not providing adequate protection for nonhuman species, recognizing the rights of nature, or acknowledging the relationships between pollution, the destruction of natural environments, and inequality. In addition, sustainability

and sustainable development prioritize human interests; the earth is viewed through the lens of human needs.

Other approaches associated with environmental ethics take a different approach, calling for interspecies and intergenerational justice, meaning obligations to nonhuman species and future generations. Increasingly, voices from environmental ethics call for a radical shift towards reductions in production and consumption [30, p. 2]. The Deep Ecology movement rejects the prioritization of human interests over ecosystems, biodiversity, and nonhuman life [44, pp. 3-4]. Environmental justice focuses on “justice outcomes for both humans and non-humans” [45, p. 1622]. An earth system boundaries approach calls for maintaining strict thresholds for the “climate, the biosphere, fresh water, nutrients and air pollution at global and subglobal scales” [46, p. 103]. Some scholars, like Bihouix [47], call for a low-tech transition that would shift back towards simpler, less polluting, and low energy-consuming technologies. These are all alternatives to sustainability and sustainable development that view climate change as the most significant risk to both current and future life on earth. In this article, I argue for putting a focus on sustainability in an RI framework for QTs. However, I acknowledge that sustainability is the minimum approach, and more radical policies may be necessary.

Sustainability Recommendations and Criteria

In this article, I have argued for making sustainability a key value for the RI approach to quantum innovation. However, Kop et al. [10] also list sustainability as one of ten recommendations for QTs, and the World Economic Forum [18] report on quantum computing includes sustainability among nine key values. What is currently lacking in the scholarship is more definition: what does it mean for QTs to be sustainable? What actions would make it easier to develop sustainable QTs in the future? What criteria can be used to assess the sustainability of quantum innovation? Research on this topic has not been done, either by RI scholars or in the broader social sciences and humanities literature. Therefore, to clarify what sustainability means for quantum innovation, I’ll analyze existing literature on sustainability and emerging technologies. I will use research from frugal

innovation, green innovation, and specific research on artificial intelligence (AI) systems and high-performance computing to develop a concept of sustainable technologies that is applicable to QTs.

Sustainable Applications vs. Technologies that are Sustainably Developed and Deployed

Van Wynsberghe [48] argues that sustainability has two dimensions for AI systems. Technologies can have *sustainability applications*, meaning they tackle climate change challenges or support sustainable development. However, sustainable applications are not a sufficient condition for sustainability. To be sustainable, technologies must be developed and deployed *sustainably*. Sustainable technologies are those that minimize their environmental impact, for example through reduced energy consumption. Van Wynsberghe's approach means evaluating AI systems on more than what they do, considering "the sustainability of developing and using AI systems in and of themselves" (213). Even if a system is designed to reach positive goals, the environmental impact may be negative.

We can look at AI systems as a case study to consider this tension in practice. As Coeckelbergh [49] points out, AI systems have broad applications due to their data processing and pattern identifying capabilities, which allow for ecosystem monitoring, tracking carbon emissions, improving climate predictions, reducing waste, and increasing transportation efficiency. For example, they have been used to process image data and identify poachers in protected parks [50], monitor and process noises to prevent deforestation [51], and track pollution in specific environments [52].

But these applications *for* sustainability do not consider the environmental footprint of training and deploying AI systems. Coeckelbergh [49] emphasizes that AI systems involve intensive energy consumption and the extraction of materials. Training one deep learning, language processing model generated 600,000 pounds of carbon dioxide emissions [53]. Forty days of training Google's AlphaGo Zero against itself, for self-learning Go, produced 96 tons of carbon dioxide [54]. Training ChatGPT-3 involved the evaporation of 700,000 liters of water [55, 56]. From this discussion, we take our first point: we must consider the impact of development and usage.

Development: Process Transformations

The environmental footprint of developing a technology includes mining and manufacturing raw materials, assembling components into parts, and energy resources used in developing the final technology [55–58]. Guinot et al. [59] argue that *green innovation* requires process transformations that prioritize sustainability in design and production. This means incorporating sustainability goals at the research phase and developing products and services that respect the environment. Sustainable technologies minimize the use of scarce minerals, are conscious about the environmental impact of raw material extraction and usage, and limit energy consumption. Recent research on sustainability and AI and high-performance computing offers recommendations and criteria for improving a technology's environmental footprint.

Right now, we often see *red AI*, which means that large gains in accuracy are being prioritized over gains in efficiency [60]. For example, there has been significant progress in training neural networks, but these increases in accuracy stem from upswings in energy consumption [53]. Research at Stanford shows that although two algorithms might perform equally well, one may use significantly less energy [61]. Research by Dodge et al. [62] shows that time of day and regional variations are significant for carbon intensity. Training a large language model (LLM) in datacenters in France, drawing upon nuclear energy, and Norway, relying on hydroelectric power, was more efficient and less carbon-intensive than in countries with more carbon-intensive energy sources. Dodge et al. [62] also found that for short experiments, specific start times can lead to reductions of between 30 and 80% in emissions depending on the region. Implementing power caps is another sustainable policy. For example, a power cap on LLM training led to minimal training time increases, but significant emissions reductions, up to 15% for some models [63, 64]. In recent high performance computing research by Li et al. [55, 56], the authors highlight the importance of doing emissions analysis of the manufacturing process, from converting raw materials into electronic components, to assembly into the final technology. Such analysis offers valuable information about the carbon costs of a technology.

Deployment: Operationality and Technological Frugality

The environmental footprint of deploying a technology involves different dimensions, including the hardware choices that determine energy usage, the energy resources it takes for the technology to work, and the lifespan of the technology [57, 63, 64]. Here we'll consider proposals from the AI and high-performance computing literature to see what transformations are necessary for more sustainable technological deployment.

Li et al. [55, 56] suggest that sustainable deployment requires operational emissions analysis. They argue for four kinds of evaluation: 1) calculating operational carbon emissions, 2) comparing emissions for different components, 3) comparing carbon intensity by region and time, and 4) evaluating carbon costs of hardware upgrades. This analysis helps scientists and industry-actors make decisions. For example, a new solid-state thermal transistor allows for better heat control, which is critical when half the electricity used in US data centers is for cooling devices [65]. Bondage [57] points out that since equipment manufacturing is such a large component of a technology's digital footprint (from 30 to 76%), extending the lifespan of final technologies would reduce waste (31). In the previous section, we discussed energy sources and high and low-carbon regions and times. Ideally, AI training, high-performance computers, quantum computers, and data centers would all be concentrated in regions with low-carbon energy sources. However, it's not possible for researchers in high-carbon zones to avoid using energy. One solution could be power caps, which have been used to reduce electricity consumption during AI training [63, 64]. In the long term, sustainable technologies require institutional change via large-scale transitions to green energy sources.

Even if energy consumption is minimized and a technology uses the most efficient hardware, there are still problems related to how much the technology is used. A technology may be more efficient, but if it is used more, consumption will increase, particularly if researchers tackle larger problems

[64, 66]. We can apply the technological frugality approach, minimizing usage to minimize energy consumption. As Almrott [67] argues, this approach questions prevailing beliefs about how much energy we need to use. This frugality lens also encourages us to ask if all tasks are worth investing resources into. Thinking about the carbon footprint of AlphaGo, "one has to ask if the emissions from algorithms that can play games (or do other menial tasks) is really worth the cost" [48, p. 214]. Technological frugality means rejecting a techno-solutionist mindset, which assumes that technologies fix problems and should always be used to solve them. Instead, we assess the significance of tasks and evaluate which system can complete them with minimal impact.

Sustainable Technologies: Dimensions

The different aspects of sustainability discussed in Sections "[Sustainable Applications vs. Technologies that are Sustainably Developed and Deployed](#)", "[Development: Process Transformations](#)", and "[Deployment: Operationality and Technological Frugality](#)" all provide a clearer notion of what a sustainable technology looks like. Sustainable knowledge and processes are applied to processing, manufacturing, and distributing mineral resources, for example, to avoid the use of scarce minerals or integrate recycled materials, optimize metallurgy processes, reduce environmental damage, and improve circular material usage cycles [58, 68–70]. Carbon analysis takes place at different steps, including manufacturing components (like transistors) from raw materials, and assembling components into larger parts (such as chips) [55, 56]. The most efficient hardware is prioritized, taking advantage of recent research and development [65]. Researchers also need to apply an energy consumption metric to do comparative analysis on different technologies to find the most carbon efficient tool for a task [18, p. 29]. When possible, researchers should prioritize low-carbon intensity regions, select low-carbon intensity times for short tasks, and apply power caps where performance costs are low compared to efficiency gains [62–64]. Extending the lifespan of

technologies could also reduce the carbon costs of sourcing new materials and assembling new parts [57, p. 28]. In the next section, I will translate this analysis into recommendations for developing sustainable quantum innovation and some early criteria applicable to QTs.

Envisioning Responsible and Sustainable Quantum Innovation

This section will use the analysis of objectives, process transformations, and sustainable deployment from Section "[Sustainability Recommendations and Criteria](#)" to develop recommendations for sustainable QTs and criteria to assess the sustainability of QTs. It will focus on quantum computing as a case study as there is existing physics literature on the subject. Although articles and reports do discuss QTs and sustainability (e.g. [14, 71, 72]), the authors discuss either sustainable applications for quantum computers, or energy minimization. They do not engage with the broader landscape of sustainability literature or expand their analysis to encompass different stages in quantum innovation. To address this gap, I'll propose a list of recommendations for developing sustainable QTs, and criteria for deploying more sustainable quantum computers.

Currently, the literature is dominated by reports and articles on sustainable applications for QTs, rather than the sustainability of QTs [71, 72]. Some of these applications include energy storage, supply chain logistics, precision agriculture, power flow analysis in electric power systems, carbon capture, and data storage [73], Bashirpour [4, 5, 32, 74, 75]. Although sustainable applications are promising and positive, Section "[Sustainable Applications vs. Technologies that are Sustainably Developed and Deployed](#)" showed that sustainable technologies are about more than sustainable applications and objectives.

Quantum computers are also predicted to minimize energy consumption. In the beginning of this article, I mentioned a quantum computing advantage, meaning that a quantum computer can solve

problems more quickly than classical computers in some cases, and it can also solve problems that are intractable for classical computers [14]. Many researchers predict that the quantum computing advantage will also mean a *quantum energy advantage*, where quantum computers solve problems using less energy than classical computers [8, 14, 18]. According to research by Fellous-Asiani et al. [14], quantum computers have an energy advantage in two different cases. A quantum computer may consume less energy because it solves a problem more quickly than a classical computer. As an example, the authors point out that a classical supercomputer could crack the RSA-830 encryption in 8 to 9 days using, while a quantum computer could complete the task in just 16 min. However, a quantum computer may also use less energy in tasks where it takes longer to solve a problem than for the classical computer, depending on qubit quality, and hardware and software parameters.

Despite these promising predictions, right now we cannot assume that quantum computers will always provide an energy advantage. Jaschke and Montenegro [76] shows that the quantum energy advantage may be a threshold, where quantum hardware performs better on some tasks, but has a higher energy consumption for others. In other words, researchers need to consider which system is better suited, in terms of energy consumption, to the task. The authors recommend doing predictive analysis to determine when it is more efficient to use classical computers and when it is more efficient to use quantum computers.

Recommendations and Criteria

Below is an organized list of actions for improving sustainability outcomes and assessing QTs, divided between development recommendations for sustainable QTs in general, and specific criteria for assessing quantum computers during operation. However, it's necessary to acknowledge the limitations of a discussion about sustainable QTs. This is an emerging field of research, and the recommendations and criteria proposed here will need to adapt to the practical realities of future quantum innovation.

Stage	Recommendations and Criteria
Development	<p>Recommendations:</p> <ol style="list-style-type: none"> 1) <i>Expand access to educational workshops for physicists on the significance of sustainability. Teach key practices for sustainable research to increase understanding and knowledge in the research environment.</i> 2) <i>Academic institutions and industry-actors should commit to using components and parts from providers who respect key sustainability measures across the supply chain, for example materials certified by the CERA4in1^a standard, which is in development now. (Sustainable mining and manufacturing).</i> 3) <i>Fund a broad range of academic and industrial research on methods of minimizing the carbon footprint of QTs. This includes research to (i) improve the efficiency of individual hardware components (e.g. the cryogenics that cool the quantum computers), (ii) developments in quantum software (finding new software methods of solving a given problem with less quantum resources), and (iii) system level-analysis (how the interplay of hardware and software parameters can be used to minimize consumptions). (Hardware analysis)</i> 4) <i>Develop industrial standards for measuring and evaluating a technology's carbon footprint and encourage companies producing quantum technologies (and components used for quantum technologies) to include energy consumption in the list of specifications supplied to users. (Reducing carbon-footprint)</i> 5) <i>Academic institutions and industry-actors could support and encourage local transitions to green energy alternatives in regions with high-carbon intensive energy sources. (Reducing carbon-footprint).</i>
Deployment	<p>Criteria:</p> <ol style="list-style-type: none"> 1) <i>Is there a quantum computing advantage when using a quantum computer for this problem? (Reducing carbon-footprint)</i> 2) <i>Is this the best quantum computer for the task? (Hardware analysis)</i> 3) <i>Is the energy consumption for this task reasonable? (Reducing carbon footprint)</i> 4) <i>Are the quantum computer's parameters tuned to run in a frugal manner (i.e. run in a way that consumes less energy, even if that means running slower). (Reducing carbon footprint)</i>

^a<https://www.maditrace.eu/cera4in1>

At the development stage, a sustainable approach to QTs at this stage makes recommendations that would support future sustainable QTs. Recommendation 1 would help scientists understand the environmental impact of quantum research and technologies and encourage them to adopt more sustainable practices and policies. Recommendation 2 highlights the need for sustainability certifications and policies for mining and manufacturing. Recommendation 3 addresses the kinds of hardware and software research that could improve outcomes and minimize the carbon footprint of future QTs. Recommendation 4 shows that sustainable technologies require real energy transitions at the state level. Together, these recommendations address different aspects in quantum research and development.

At the deployment stage, the proposed criteria are a starting place for assessing the sustainability of quantum computers specifically. Criterion 1 analyzes the best way to solve a problem, by comparing energy consumption per calculation for quantum computers and classical computers. This kind of comparison requires the development of an “energy consumption metric” [18, p. 31]. Criterion 2 demands comparative analysis of different quantum computers, where the efficient hardware is prioritized. Criterion 3 acknowledges that there may be situations where the environmental costs are too high for QTs, the objectives are not worth the cost, or increases in usage are more substantial than quantum energy gains. Such assessment requires new practices of ethical review at the level of research teams and labs. This criterion is an excellent opportunity to develop public engagement activities around social impact, as discussed in Section “[Key Recommendation for QTs](#)”. Finally, criterion 4 asks if the technology runs in the most frugal way possible.

Future research is needed to consider how recommendations and policies may be implemented. Specific environmental regulations may be necessary to encourage more sustainable technological innovation [77]. However, it's possible that some industry and academic actors would be interested in sustainable practices to secure a competitive advantage, by providing ‘greener’ products and services. They may also be incentivized by efficiency gains, for example by cutting energy costs. What is clear at this point is that QTs will need to be assessed on a case-by-case basis, making industry and research actors responsible by

prioritizing sustainability at the development stage. In addition, new challenges may emerge, demanding creative policies. The RI approach emphasizing sustainability outlined here is a starting place for discussion.

Conclusions

In this article, I argued for emphasizing sustainability in the RI approach to quantum innovation. Climate change, and the challenges it poses, is considered the crucial issue of our time. Biodiversity losses, land degradation, and rising temperatures pose major risks to human and non-human life. Sustainability is an approach that seeks to respond to climate change with limits on resource consumption and protective measures for the environment. My claim is that sustainability should become explicit in any RI framework for quantum innovation. This argument is justified by RI's own emphasis on shaping technological trajectories in positive ways, as well as the place of sustainability in RRI policy reports at the governance level.

In Section "[Responsible Innovation and Quantum Technologies](#)", I reviewed existing scholarship on QTs from an RI perspective. Previous scholars have highlighted the importance of stakeholder dialogue, improved comprehensibility, risk assessment, and equality. Although these are all important aspects of responsible quantum innovation, sustainability is largely missing from the literature. I contributed a more detailed discussion of the significance of climate change among competing values and specific criteria for assessing QTs.

Section "[Sustainability as a Key Value](#)" gave context to sustainability as a value, discussing climate change risks and defining sustainability, sustainable development, and SDGs. I argued that sustainability should be emphasized in an RI approach. To support my argument, I pointed out that sustainability as a value is often referenced in RI literature and RRI policy reports. Sustainability is also an essential dimension of RI's objective to promote technological innovation for public good.

Since there is no existing research specifically on QTs and sustainability, I turned to recent research on sustainability and emerging technologies in Section

"[Sustainability recommendations and criteria](#)". My aim was to develop recommendations and criteria for sustainable QTs based on existing policies and suggestions for other technologies. I used Van Wynsberghe's approach for sustainable AI systems; regardless of a technology's sustainable applications, we need to assess the sustainability of developing and using a technology. I discussed process transformations in green innovation, which call for sustainable practices in the mining, manufacturing, and technological development process. I also introduced a frugality approach to encourage new perspectives on consumption. I emphasized key points for assessment, including manufacturing carbon analysis, energy-sourcing, hardware efficiency comparisons, and power caps.

In Section "[Envisioning responsible and sustainable quantum innovation](#)", I applied the concepts and criteria from Section "[Sustainability recommendations and criteria](#)" to quantum innovation, with a focus on quantum computers. My goal was to connect my evaluation of QTs and sustainability to recent research by physicists on a predicted quantum energy advantage. For example, many QTs have sustainable applications, however we also need to think about their environmental footprint. While quantum computers are predicted to have a quantum energy advantage, we still need to assess how they perform compared to classical computers on different tasks. In Section "[Recommendations and criteria](#)", I made key recommendations for sustainable quantum development and listed criteria for assessing the sustainability of quantum computers.

In this article, I treat sustainability as the minimum response to climate change, a crucial value that should shape the design and deployment of QTs. It is important to develop a path for responsible quantum innovation at this stage when the technological trajectory can still be guided. We don't know when a fault-tolerant quantum computer will be available for practical use [18, 78], and useful, accurate quantum computing is limited by problems related to decoherence, stability, and scalability [16, 79, 80]. However, second quantum revolution QTs already exist. In quantum computing, industry actors like IBM⁴ offer limited quantum computing services and recent error-correction breakthroughs have led to accuracy improvements [81]. In quantum sensing, quantum sensors are providing new avenues for global

⁴ <https://www.ibm.com/quantum>

positioning, measuring, and bio-sensing [82, 83]. Billions of dollars in investment funds have poured into national quantum initiatives, for example, in the EU, US, UK, and China, as well as for projects at tech companies [84]. Recent research and experimentation show early, promising applications, but sustainability analysis is a necessary part of QT evaluation. Such research already exists to address sustainability in reference to other technologies, such as AI systems [85–87]. This article therefore fits within the broader literature on shaping responsible technological innovation in general, while contributing a specific analysis of QTs and sustainability. At this stage, we can anticipate risks and benefits and reflect on the kind of future transformations that QTs will make. Although we cannot anticipate every negative outcome, we can still shape a trajectory for quantum innovation that puts sustainability at the heart of responsible innovation.

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Data availability No datasets were analyzed or generated because this work proceeds within a theoretical approach.

Declarations

Competing interests The author states that there is no conflict of interest.

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