ICT for peace foundation

POLICY PAPER

NAVIGATING THE QUANTUM WAVE

A Policy Maker's Guide for the Responsible Governance of Quantum Technologies

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FOREWORD

As we navigate an age rich with scientific breakthroughs and technological advancements, the "Navigating the Quantum Wave" report emerges as a vital resource for national and international policy-making of Quantum Technologies. Quantum Technologies have moved from a theoretical setting to real-world applications and are increasingly becoming more advanced. The potential for quantum advancements is becoming increasingly evident across multiple sectors, including defence, telecommunications, manufacturing, health care, information technology, pharmaceuticals, energy, finance, and navigation. Given the extensive implications, the impacts on our national and global societies and economies are profound. Consequently, effective governance of these technologies is essential to harness their benefits while mitigating potential risks.

Authored by Drífa Atladóttir and produced by the ICT4Peace Foundation, this policy paper provides a look into the potential and challenges of quantum technologies. It also addresses the governance needed to ensure outcomes that benefit society and the economy. This policy paper draws upon Drífa's research conducted during her Master's thesis at ETH Zürich to provide valuable insights. Her study delves into the contemporary landscape of quantum technologies and their ramifications on policy-making. By gathering perspectives from experts across various quantum domains, analyzing national quantum policy documents, and conducting focus groups with scholars specializing in governance, ethics, and societal impacts, Drífa Atladóttir offers a comprehensive understanding of the intersection between quantum advancements and governance considerations.

Supported by ICT4Peace, Drífa Atladóttir's contribution is not only educational but also a prompt for proactive policy-making. It underscores the need for informed and robust governance structures to ensure that quantum technologies bolster societal welfare without jeopardizing security or ethical norms.

Daniel Stauffacher
Founder, President and Member of the Board of the ICT4Peace Foundation

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EXECUTIVE SUMMARY

Quantum technologies hold transformative potential across societal, economic, and security landscapes. This paper serves as a guide for policymakers to understand the opportunities and threats posed by this field. It analyzes current national governance frameworks for quantum technology, comparing their strengths and similarities, and identifies gaps in security, ethics, and inclusivity based on expert interviews and focus groups.

Based on the findings, the paper proposes policy recommendations for national quantum technology governance strategies. It advocates for proactive policymaking to address the dual-use nature of these technologies, which can bring societal benefits but also pose risks.

Seven Key Pillars of Quantum Technology Include:

1. **Workforce Development**: Invest in educational and training programs to prepare scientists, engineers, and policymakers for the quantum era.

2. **Research Support**: Ensure sustained investment in public and private quantum research to prevent stagnation and advance the field.

3. **Innovation and Development**: Promote public-private partnerships to spur innovation while maintaining oversight to protect public interests.

4. **Security and Risk Management**: Consider potential risks in policy-making. Prioritize the development of quantum-resistant cryptographic standards and immediate preparation for cryptographic transitions to secure national infrastructure.

5. **Inclusivity and Diversity**: Set standards for accessibility and inclusivity in quantum technology governance. Learn from the lessons of past technological shortcomings resulting from a lack of diversity in development and innovation approaches.

6. **International Collaboration**: Form global partnerships to both develop and regulate quantum technologies, ensuring ethical and responsible use.

7. **Ethics and Responsible Innovation**: Consider the technology's potential social and environmental impacts. Support research into quantum technologies' responsible, ethical, and human rights aspects to ensure responsible development and maintain public trust.

Keywords: *Quantum Technologies, Quantum Computing, Quantum Sensing, Quantum Communications, Public Policy, National Security, Ethics*

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Acronyms

NISQ Noisy Intermediate-Scale Quantum. 9

NIST National Institute of Standards and Technology. 7

QKD Quantum Key Distribution. 8

QT Quantum Technology. 1, 3, 4, 13, 14, 15, 16, 17, 18, 19, 20, 22, 23, 24, 25, 26

QTs Quantum Technologies. 3, 4, 5, 8, 10, 11, 12, 13, 14, 16, 17, 20, 21, 23, 24, 25

U.K. United Kingdom. 16

U.S. United States of America. 16

Introduction

Quantum science is evolving from theoretical study to practical application and has now led to the emergence of Quantum Technologies (QTs). These technologies leverage the principles of quantum mechanics to drive innovation and application across various fields. QTs promise to revolutionize various sectors, such as national security, healthcare, and communications. This policy paper aims to demystify the realm of QTs, offering concrete examples of their implications accessible to policymakers and stakeholders, irrespective of their technical proficiency. It critically evaluates national strategies and frameworks adopted by pioneers in the field, aiming to identify the current trends in QT governance. Finally, this paper concludes with strategic recommendations for policy and research designed to guide future endeavours in quantum science and technology.

Relevance of Quantum Technologies for Policy

Quantum Technologies are poised to transform various fields, such as geolocation, optimization, cybersecurity, medical imaging, and communications (Acín et al., 2018; De Jong, 2022; Deutsch, 2020; Rosch-Grace and Straub, 2021). The properties that QTs possess offer remarkable opportunities for technological advancement, but they also expose nations to significant threats, including risks to national security, economic competitiveness, and societal welfare (Grobman, 2020; Johnson, 2019; Kop, 2022; Krishnamurthy, 2022). Consequently, effective governance of these technologies is crucial, not only to catalyze technological advancement but also to navigate legal challenges, adhere to ethical standards, and mitigate associated risks (Perrier, 2022).

Furthermore, the rapid advancement of QTs demands swift action. Given that these technologies are in their nascent stages, now is the time to act. As the Collingridge Dilemma highlights, once a technology is well-established, altering

its course becomes increasingly challenging, yet its early stages offer limited insight into its full potential and implications (Genus and Stirling, 2018). Moreover, researchers, tech leaders and politicians have observed that governance tends to lag or lack in regulating emerging technologies, such as with AI, which can lead to negative societal effects (Koniakou, 2023; McCabe, 2023). With quantum technology, there is an opportunity to learn from these past mistakes and implement more timely governance. Currently, QTs are at a nascent stage, providing a rare chance to shape their development to benefit the public interest, bolster national security, and drive economic growth. While it is crucial to avoid overregulation that might stifle innovation, it is equally important to consider strategies for responsible development. This paper advocates for the urgent creation of robust governance frameworks to steer the responsible advancement of QTs.

Foundation of the Research

The insights and recommendations presented in this policy paper are based on the research conducted for a Master's thesis authored by Drífa Atladóttir at ETH Zürich. This thesis provides a comprehensive exploration of quantum technologies and their implications for policymaking. Parts of this thesis will also be published in a scientific publication, which is currently under peer review; for access to the full study results and further inquiries, please contact the author via ICT4Peace.

Structure of this Paper

This policy paper begins with an introduction on QTs, what they are, application areas and their possible impacts. It then delves into an analysis of national QT frameworks, noting their similarities, strong points and where there might be gaps. Building on this foundation, the paper concludes with targeted policy rec-

ommendations designed to guide future governance efforts and research initiatives for responsible quantum governance.

Background on Quantum Technologies

QTs encompass a broad range of applications grounded in quantum mechanics. These technologies utilize phenomena like quantum entanglement and quantum superposition (see Figure 1). These phenomena enable QTs to potentially outperform classical technologies in accuracy, speed and efficiency. A common misconception is to equate quantum technologies with quantum computers. While quantum computing is a significant aspect of QTs and has gotten much attention due to its disruptive possibilities, it is part of a larger, diverse field that also includes fields such as quantum communications and quantum sensing. It is important to realize that each field and technology is at a different stage of readiness, and the application of quantum technologies in industry remains nascent. In the following sections, we will introduce three emerging subfields of quantum technologies. We will provide a brief overview of these technologies, discussing their functionalities, key aspects to understand, and potential application areas.

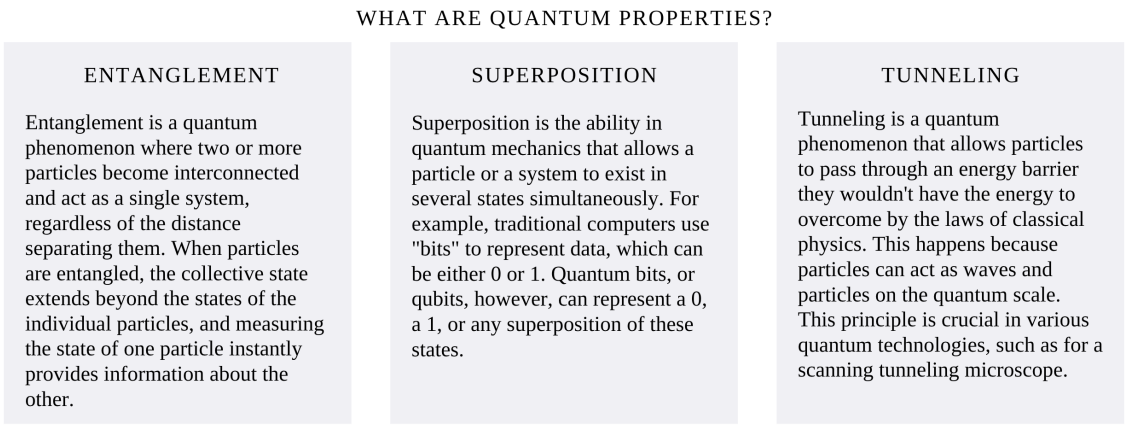

Figure 1: Short explanation of key quantum phenomena

Quantum Sensing

Quantum sensing employs quantum properties to achieve a high degree of precision and sensitivity in measurements, offering unprecedented precision over classical instruments (Degen et al., 2017). These sensors can be used for various applications, such as creating advanced atomic clocks for accurate timekeeping, detecting gravitational changes, precision imaging, and enhancing navigation systems immune to GPS blocking (Babcock-Chi et al., 2023; Coussens et al., 2021; Moreau et al., 2019; Potter, 2023). While promising, most quantum sensors remain experimental, with a few, such as quantum accelerometers and atomic clocks, commercially available (Inglesant et al., 2018).

Quantum Computing

Quantum computers are not universally superior to classical computers; unlike conventional devices such as laptops, they are specialized for certain applications with distinctive capabilities that offer a clear advantage. Employing qubits, quantum computers excel in specific areas such as factorization, optimization, and simulation. These capabilities have profound implications in various fields: drug discovery, material sciences, logistics, data analysis, and cryptography (Kung and Fance, 2021).

Perhaps the most well-known example of quantum computing's potential lies within Peter Shor's algorithm. This algorithm can theoretically compromise some public-key cryptography algorithms, including the RSA cryptosystem (Monz et al., 2016; Shor, 1994). RSA is notably one of the most widely used asymmetric encryption systems and is commonly used in data encryption of e-mail and other digital transactions over the Internet (Hasib and Haque, 2008). This raises significant concerns, as the potential to decrypt vast amounts of content is alarming. However, quantum computers of this nature, specifically large-scale fault-tolerant

quantum computers, are not a current reality. Many experts in the field speculate that the development of such advanced systems could take decades if not centuries, and some even predict that it is entirely impossible to achieve (Biswas et al., 2017; Lindsay, 2018). Achieving the full potential of quantum computing is contingent on overcoming challenges related to system fragility and error correction, which remains largely theoretical at this stage (Chen et al., 2022).

Currently, the principal concern is the security of data that requires long-term confidentiality, such as state secrets intended to remain classified indefinitely. There is a growing apprehension that adversaries may be collecting encrypted data with the intent to decrypt it in the future, a strategy known as 'store now, decrypt later.' While this is generally not a concern for the average user—most personal emails do not warrant preservation for decades—it does raise significant security issues. Consequently, there are ongoing efforts to update existing encryption methods to address these vulnerabilities, most well know is the National Institute of Standards and Technology (NIST) standardization efforts (Boutin, 2023). However, implementing these changes across all systems will be a lengthy process. Depending on the sensitivity of the information, some data may need to be transitioned to more secure systems more urgently than others.

Quantum Communication

Quantum communication utilizes the principles of entanglement and superposition in qubits (see Figure 1). Utilizing the ability of one particle to instantaneously reflect its entangled partner, irrespective of distance. Furthermore, qubits allow for the potential for highly secure communication channels, as their superposition properties mean they cannot be replicated without altering their state, thereby revealing any unauthorized interceptions. Some theorists favor the options that quantum communications bring, such as quantum cryptography, over classical

communications methods because it relies on provable physical principles to ensure security. This contrasts with traditional methods that depend on mathematical problems, which are currently assumed to be secure primarily because they are difficult to solve. Such security measures are fundamental to Quantum Key Distribution (QKD), a developing yet theoretical method to establish unbreakable encryption. However, current implementations, even successful ones, face the substantial challenge of transmitting qubits over long distances, restricting them to largely experimental settings (Cozzolino et al., 2019; Inglesant et al., 2018).

Current readiness of Quantum Technologies

QTs have implications far beyond academic research, impacting sectors crucial to national welfare and economic growth. Quantum sensing represents one of the most advanced technological fields, where applications are already emerging and others are rapidly developing. This sector is driving innovation in precision-oriented fields such as aerospace and defence, the automotive industry, and healthcare. Early-stage quantum sensing devices are currently in use, including gravimeters for geophysical research, laser-based quantum devices for metrology, and atomic clocks that provide unprecedented accuracy in timekeeping (Dargan, 2021). Looking ahead, quantum sensing devices are poised to enhance satellite navigation and missile guidance systems, improve the reliability of autonomous driving technologies, and make significant advancements in medical diagnostics.

Quantum computing, though still in the early stages of development, represents a highly promising industry with vast potential applications. The realization of sufficiently powerful quantum computers could have transformative implications across multiple sectors. It could enhance industries reliant on advanced scheduling and optimization, such as the financial sector, by optimizing investment portfolios, modelling market dynamics, and securing transactions, thereby

boosting efficiency and security. These technologies could also accelerate pharmaceutical development through precise molecular simulations, reducing time and costs.

At present, the quantum computing industry is focused on developing Noisy Intermediate-Scale Quantum (NISQ) devices. These devices offer opportunities to explore applications in quantum chemistry, materials science, and optimization. A handful of commercial applications utilizing quantum computing are currently available, with companies like D-Wave offering products that leverage quantum computing for optimization tasks (*DENSO: Optimizing Transportation with Quantum Computing: Using quantum to make the future of urban transportation faster, smoother, and more sustainable.* 2023). Near-term applications, such as quantum simulation, show promise in advancing drug design and material science. In the longer term, there is potential to utilize quantum computing to enhance fields such as optimization and artificial intelligence. However, as previously mentioned, the realization of large-scale, fault-tolerant quantum computing is still a considerable distance away (Biswas et al., 2017; De Jong, 2022).

Finally, quantum communications, while still theoretical and in the initial stages of development, hold the potential to greatly enhance cybersecurity. There have been notable breakthroughs in the field, including successful long-distance quantum communications (“Toshiba Announces Breakthrough in Long Distance Quantum Communication”, 2021). However, much progress remains to be made before these technologies can be practically implemented. In the future, quantum communications could potentially offer unbreakable encryption, thus providing robust protection against cyber threats. Given the broad implications of the whole spectrum of quantum technologies, continued investment and research are crucial to fully realize their transformative potential across various sectors.

Identifying Opportunities

QTs offer a broad spectrum of opportunities that can enhance national security, drive economic growth, and lead to groundbreaking scientific discoveries. These technologies are poised to transform numerous sectors through various applications:

- **Enhanced Optimization Processes**: These processes could revolutionize industries by enhancing efficiency and cutting costs, significantly impacting sectors like manufacturing and logistics.
- **Advancements in Simulation Technologies**: More advanced simulation technologies could allow for the accurate modeling of complex systems. This is crucial for advancing research in areas such as drug discovery and supply chain management.
- **Advancements in Sensing Technologies**: New sensing technologies provide precise geolocation capabilities, essential for applications in navigation and autonomous vehicles.
- **Advancements in Measuring Techniques**: Improved measuring techniques enable the detailed analysis of environmental data, supporting advancements in climate science and pollution control.
- **Advancements in Imaging Technologies**: High-precision imaging techniques are transforming medical diagnostics and materials science, enabling the detailed study of complex biological structures and new materials.
- **Strengthened Encryption Methods**: These methods enhance the security of digital communications. Although in early development stages and considered theoretical by some experts, they hold promise for future application.
- **National Defense Opportunities**: Quantum technology provides signifi-

cant tactical advantages, including advanced geolocation, surveillance and encryption-breaking capabilities. However, the reliance on exploiting vulnerabilities in encryption systems to enhance surveillance introduces a critical ethical dilemma, as it contrasts the very essence of promoting security.

These opportunities illustrate the transformative potential of QTs across various domains, emphasizing the need for strategic development and ethical considerations in their advancement.

Identifying Potential Threats, Challenges, and Concerns

While presenting a host of transformative opportunities, QTs, also introduce significant threats, challenges, and ethical considerations. These dual-use characteristics can enhance areas like national defence but also pose security risks.

- **Communications Security Concerns:** The primary threat is the potential of quantum computing to compromise existing cryptographic systems, a concern echoed by experts who stress the significant risk to asymmetric cryptographic protocols fundamental to digital security.
- **Dual-use potential:** There are also some longer-term concerns regarding the dual-use potential of quantum computing, particularly in its application to AI and big data analysis. The capabilities of quantum technologies could be exploited to develop surveillance tools reminiscent of 'Big Brother', raising significant privacy and security risks. This includes the possibility of unauthorized eavesdropping and misuse by large technology companies or governments. This could allow it to converge into a new weapons landscape, as highlighted by current research on the ethical and peaceful use of emerging technologies (Surber and Stauffacher, 2022).
- **Cryptographic System Agility:** The existing cryptographic infrastructure's

lack of agility poses a significant challenge. Both government and industry manage extensive, dispersed data across various software and formats. Transitioning to quantum-resistant cryptographic protocols will be a complex and time-consuming process necessary to secure data against potential quantum computing threats. Experts stress the importance of crypto-agility in enabling swift adaptation to new protocols without disrupting existing systems and effectively addressing vulnerabilities.

- **New Cryptographic Standards:** The development of new cryptographic standards is crucial yet brings risks. New protocols, such as those currently being developed, lack the extensive testing that established ones have undergone. This was highlighted by the breach of the SIKE algorithm (Castryck and Decru, 2023), illustrating the inherent risks and potential for undiscovered vulnerabilities in emerging cryptographic methods.
- **Workforce Development:** The rapid advancement of QTs necessitates a technically skilled workforce to support its development and secure implementation. Countries and universities must prioritize the education and retraining of technical professionals to ensure we have the necessary resources to facilitate this significant technological shift.
- **Knowledge Gap Among Decision-Makers:** The gap in understanding between policymakers and technical workers can lead to disproportionate actions, such as excessive regulation or insufficient oversight. This complexity necessitates informed decision-making to align policies with technological capabilities and requirements.
- **Regulatory Delays:** Experts frequently highlight the tendency for policy to lag technological advancements, leaving consumer rights and public safety vulnerable. With the advent of QTs, the need for agile policy frameworks to keep pace with rapid technological changes continues to be of key impor-

tance.

- **Access and Democratization:** The significant development costs associated with QTs may concentrate power among a few large tech firms and governments, potentially stifling innovation and exacerbating technological disparities. Given the high expenses, lengthy development times, and unknown returns, there is concern that this could widen the existing tech gap.
- **Ethical Implications:** Similar to challenges faced during AI development, the lack of diversity in QT development could result in biased outcomes. Ethical considerations are crucial to ensure inclusivity and prevent unethical practices in technology development.
- **Global impacts:** Given the potentially wide-ranging implications of these technologies and their varying effects depending on accessibility, there could be significant ramifications for both geopolitical and economic security. Moreover, any energy and resource-intensive activities associated with these technologies are likely to have environmental impacts.
- **Quantum Hype:** The overhyping of quantum capabilities can mislead the public and policymakers, potentially stunting long-term investment and technological advancement.

In conclusion, the development of QTs represents a transformative shift in our scientific and technological landscape. As these technologies continue to evolve, they will undoubtedly play a pivotal role in shaping the future of humanity. However, realizing their full potential while mitigating associated risks requires thoughtful governance, ethical considerations, and international collaboration, underscoring the importance of informed and proactive policy-making in the quantum era.

Current National QT Governance Approaches

As nations navigate the governance of QTs, their approaches reflect a mosaic of priorities, concerns, and aspirations. This chapter will outline the rationale behind these governance efforts, examine the approaches taken by different countries, identify common themes, and highlight any existing gaps. By analyzing national frameworks, we will gain insights into the global landscape of QT governance.

Rationale for National Frameworks

Governments worldwide recognize the transformative potential of QTs—not just as a scientific advancement but as a strategic asset. The push towards establishing comprehensive national frameworks for QT governance stems from a multifaceted motivation to harness QTs for economic competitiveness, national security, scientific leadership, and societal welfare.

The development of national QT frameworks is essential to support QT research and development, encourage public-private partnerships, enhance national security, develop a skilled workforce ready for the quantum era, and ensure responsible innovation and development. Given the expansive nature and high costs associated with this technology ecosystem, government support is justified. No single company, including the largest tech giants, can address all aspects alone. This chapter will explore how various countries have approached these challenges, examining their strategies as potential models for harnessing the quantum advantage while mitigating risks.

National Frameworks analyzed

This analysis encompasses government frameworks related to the governance of QTs, this includes cybersecurity governance documents that reference QTs. It

includes any official governmental documents available from late 2023 in English, such as quantum strategies, initiatives, roadmaps, and security documents that outline specific goals or strategic actions. In the following chapter, we will refer to this as "National QT Frameworks" or "frameworks" for short.

Documents focusing on the governance of QT subfields were excluded to maintain a holistic view of QT governance. For countries with multiple documents over time, only the most recent ones were considered to reflect current policies. The analysis was performed in Autumn 2023.

Ultimately, the analysis reviewed documents from 15 countries, ensuring a comprehensive dataset to reflect the global landscape of national QT governance. The following documents were examined:

1. Australia (*National Quantum Strategy: Building a thriving future with Australia's quantum advantage*, 2023),
2. Austria (Weitgruber, n.d.),
3. Canada (*Canada's national quantum strategy*, 2022; *National cyber security action plan 2019-2024*, 2019),
4. Denmark (*Strategy for Quantum Technology*, 2023),
5. Germany (*Cyber Security Strategy for Germany*, 2021; *Quantum technologies – from basic research to market*, 2018),
6. Ireland (*Positioning Ireland for the Quantum Opportunity*, 2019),
7. Italy (*National Cybersecurity Strategy 2022-2026*, 2022),
8. Japan ("Vision of Quantum Future Society", 2023),
9. Netherlands (*National Agenda for Quantum Technology*, 2019),
10. South Africa (*Framework for quantum technology driven research and innova-*

tion in South Africa, 2021),

11. South Korea (*In 2035, Korea Becoming the Global Hub for Quantum Economy!*, 2023),
12. Sweden (RISE et al., 2023),
13. Switzerland (*Strategic considerations for a new call for quantum research projects*, 2023),
14. The U.K. (*National Quantum Strategy*, 2023), and
15. The U.S. (*National Cybersecurity Strategy*, 2023; *National Strategic Overview for Quantum Information Science*, 2018).

Common Themes in National QT Frameworks

The frameworks varied, often reflecting country-specific priorities. Nations with comprehensive frameworks included Australia, Canada, Germany, the Netherlands, the U.S., and the U.K.. Smaller countries like Denmark, which published the first of several planned reports, focused on more localized concerns (*Strategy for Quantum Technology*, 2023). Differences in political and governance ideologies result in varying emphases among countries. Some prioritize innovation and commercialization, while others emphasize government and research collaboration. Despite these differences, many similarities emerged among countries' strategies.

This analysis synthesizes common themes and actions across national QT frameworks that aim to advance QTs. Typically, the actions within these frameworks align with one of four themes, illustrating the common priorities across different nations. Below, we detail these themes and the most frequent actions associated with each:

- **Innovation, Research, and Development**: Predominantly emphasized across all national frameworks, this category includes actions such as establishing

research hubs, innovation platforms, and entrepreneurial ventures. Common initiatives also involve allocating specific funding for external research projects and maintaining a dynamic awareness of the field to support the quantum industry continuously.

- **Infrastructure and Workforce Development**: Reflecting significant investment priorities, actions in this category often involve developing quantum infrastructure and hardware, leveraging existing assets for QT development, and integrating quantum physics into educational curricula. Additionally, frameworks often highlight the importance of re-educating and retaining technical workforces and attracting new talent.

- **Security and Public Safety**: The majority of frameworks include some actions to enhance security to mitigate risks associated with quantum advancements. However, overall, there are fewer actions within the frameworks that focus on security than actions that prioritize innovation, development, infrastructure, and workforce development. Within the security actions, the most common actions in frameworks included developing national and international standards for quantum-safe technologies and funding research into the security, privacy, and ethical implications of QTs.

- **Collaboration, Inclusion, and Diversity**: Within the frameworks, there is often a strong emphasis on international cooperation, particularly with allied nations. Actions also focus on enhancing public engagement and accessibility in the quantum realm. This often includes initiatives to raise public awareness and integrate diverse perspectives into the development of QTs.

The review of these national frameworks underscores that there is a global emphasis on strategic innovation, research and infrastructure development for QTs. The distribution and focus of these actions, detailed through figures and tables available at the request of the author, highlight how different countries

prioritize their QT initiatives. These insights not only reflect the current state of QT strategies but also guide future policy considerations.

Gaps in National Frameworks

Despite the comprehensive nature of many national QT frameworks, certain gaps persist, notably in the areas of ethical considerations, regulatory standards, and risk mitigation strategies. Few frameworks adequately address the long-term societal implications of QT, such as privacy concerns, ethical use guidelines, and the potential for technological disparities between nations. Additionally, the rapid pace of QT development outstrips existing regulatory mechanisms, underscoring the need for adaptive governance models that can evolve in tandem with technological advancements.

- **Cryptographic agility**: While most frameworks address security concerns, few discuss the imperative to update cryptographic systems and prepare for the potentially lengthy transition period. This topic is prominent in current cybersecurity and cryptography discussions but seems to be lacking in quantum-specific frameworks. The development of quantum technologies necessitates a corresponding emphasis on protecting against their potential threats. Surprisingly, only three countries explicitly acknowledge this critical need despite its widespread recognition among experts. This gap highlights a potential vulnerability in national strategies regarding the adaptability of security infrastructures to emerging quantum capabilities.
- **Ethical Considerations and Responsible Innovation**: Many frameworks lack thorough plans for preventing long-term unethical uses of QT, ensuring responsible development, and considering environmental and societal needs in governance. While some mention forming research groups for ethical usage, this approach is not widely adopted. There is a clear need for

more robust discussions on safeguarding public security and welfare in the context of QT.

- **Inclusion and Diversity**: Although 13 out of 15 frameworks mention initiatives related to inclusion and diversity, the focus predominantly lies on international collaboration. Few frameworks explicitly commit to fostering a diverse community within QT or discuss obligations to assist underdeveloped nations, missing an opportunity to benefit from a wider array of perspectives in QT development.

The analysis reveals that while national frameworks generally have comprehensive actions and goals when it comes to fostering industry, research, workforce and infrastructure development, they insufficiently address crucial areas such as potential threats, e.g. cryptographic agility, or ethical considerations, e.g. inclusiveness and energy impact. This misalignment suggests areas for improvement, particularly in enhancing the security protocols in QT frameworks, considering responsible innovation practices, and ensuring that the benefits of QT advancements are accessible to a broader demographic.

Overall, these findings highlight the need for ongoing evaluation and adaptation of national QT frameworks to address all areas of responsible technology development.

Discussion and Policy Recommendations

The analysis of national strategies highlights the need for a nuanced approach to QT governance that is anticipatory, inclusive, and adaptable. This chapter draws its recommendations from the practices of leading countries with advanced quantum frameworks and expert insights, aiming to address gaps in current approaches. The following subchapters will outline the seven key pillars for QT governance

frameworks, detail the initial steps for policymakers and nations embarking on QT development, and finally, provide common actionable points and recommendations found in current QT governance frameworks.

The Seven Pillars of Quantum Technology Governance

Effective governance must balance the dual objectives of fostering innovation and mitigating risks, ensuring that QTs serve as a force for good. Key considerations for QT governance frameworks include:

1. **Workforce Development**: Addressing the quantum skills shortage is essential. Policies should focus on education and training initiatives to cultivate a workforce ready to lead in quantum technology, encompassing both future talents and current technical staff.

2. **Research Support**: It is critical to implement concrete actions to support research in both public and private sectors, ensuring sustained progress and avoiding a potential "quantum winter." This must be supported across technical fields and within fields of ethics and governance.

3. **Innovation and Development**: National frameworks should actively promote funding and support for QT development and innovation, for example, through innovation hubs or public-private partnerships, creating an environment conducive to innovation.

4. **Security and Risk Management**: Given the potential of QTs to disrupt existing cryptographic standards and other dual-use risks, it is crucial for national policies to outline potential risks and mitigation efforts. This could include efforts such as the prioritization of the development and integration of quantum-resistant cryptographic standards [1]. These measures are

[1]Quantum-resistant cryptographic standards are protocols designed to secure data against attacks by quantum computers, which can potentially break many current encryption methods. These standards rely on math problems that are believed to be difficult for quantum computers

essential to safeguard national security and economic interests. Additionally, considering the extensive timeframe required for system updates, policies should facilitate early preparations, enabling rapid adaptation to new standards once established.

5. **Inclusivity and Diversity**: Governance of QTs must learn from past mistakes in fields like AI by setting standards that ensure technology accessibility across different demographics to spur innovation and development informed by diverse perspectives.

6. **International Collaboration**: Recognizing the global nature of quantum advancements and challenges, policies should promote international collaboration in research, standard-setting, and ethical governance of QTs.

7. **Ethics and Responsible Innovation**: National frameworks should actively promote substantial support and funding for research into the ethical, environmental, and human rights implications of quantum technologies. For instance, through dedicated ethical oversight committees and partnerships with academic institutions, these frameworks should aim to create an environment that fosters transparency, accountability, and public trust in developing and applying quantum technologies. Incorporating these principles into governance not only aids in preventing undesirable implications but also facilitates the identification of opportunities where technology can contribute to addressing such issues. For instance, by proactively considering climate implications, technology can potentially assist in mitigating environmental challenges. A human-centric approach to security, which prioritizes the protection and empowerment of individuals within the digital realm, must be embedded in policy-making. This approach will address the societal impacts of quantum technologies and ensure that technological

to solve, ensuring future data security.

advancements contribute positively to human security. Referencing frameworks such as those outlined by Barbara Weekes on digital human security can provide valuable insights into structuring these policies (Weekes, 2018).

First steps into Quantum Technology Governance

Based on the analysis presented in this paper, we propose the following recommendations to guide the first steps into the development of comprehensive and effective national QT governance frameworks:

- **Educate the Policymakers**: Close the knowledge gap between policymakers and the QT field. It is essential to have informed individuals who understand key QT concepts and can make educated decisions about regulation and oversight.
- **Establish a National Quantum Initiative**: Governments are advised to create centralized taskforces tasked with coordinating national QT efforts, recognizing the broad impact these technologies can have across multiple sectors. Such an approach is essential for enhancing collaboration between academia, industry, and governmental bodies, ensuring a unified and effective national strategy.
- **Tailor QT Governance Considerations**: Quantum initiatives should assess how QT can specifically benefit national interests. This might involve focusing on particular strengths such as research, software development, or sector-specific applications.
- **Develop a Quantum Governance Framework**: A governance framework should be developed to align with national needs and priorities, ranging from comprehensive strategic plans to short policy briefs.
- **Address The Seven Pillars of Quantum Technology Governance**: Any

governance strategy should consider all seven pillars of QT governance as outlined in this document.

Actions to include in Quantum Technology Governance Frameworks

Detailed below are actionable steps that were most common in current QT governance frameworks, along with additions based on expert recommendations. These include securing critical infrastructure, advancing QT capabilities, and promoting inclusivity within the QT workforce. This comprehensive approach ensures that each aspect of QT governance is addressed, creating a robust framework for future developments and challenges.

- **Security against Quantum Technologies**
  - **Objective**: Ensuring the security of critical infrastructure and public safety by recognizing and addressing the dual-use nature of QT.
  - **Actionable Steps**:
    * Develop national and international standards for quantum secure technologies.
    * Identify Key Data and Infrastructure.
    * Establish cryptographic agility to prepare IT infrastructure for transitions to new standards.
    * Assess and understand QT-related threats and vulnerabilities for informed decision-making.
    * Safeguard QT-related Intellectual Property.
    * Consider export regulation for dual-use QTs.

- **Advancement of Quantum Technologies**
  - **Objective**: Capitalize on the opportunities of QTs.
  - **Actionable Steps**:
    * Fund current QT entrepreneurial and innovation efforts.
    * Fund current QT research activities.
    * Establish new initiatives, collaborative platforms, research hubs, and entrepreneurial ventures.
    * Invest in QT infrastructure.
    * Leverage existing infrastructure as a foundation for development.
    * Attract and retain QT talent.
    * Prioritize investment in specific QTs that align with national strengths and goals.
    * Ensure consistent financial backing for QT development.
- **Responsible Development of Quantum Technologies**:

  d**Objective**: Ensure that governance promotes responsible innovation standards. **Actionable Steps**:

  - * Engage in international collaborative efforts.
    * Foster national collaboration across industry, government, and academia.
    * Promote public awareness and facilitate stakeholder dialogue to enhance QT accessibility.
    * Establish Ethical Research Committees.

Additionally, it's essential to integrate the following recommendations across all facets of when developing any QT governance framework:

- **Measured Urgency**:
  - **Objective**: Balance the need for prompt action with the establishment of realistic, informed goals.
  - **Actionable Steps**:
    * Consult QT experts to inform decision-making on QT development.
    * Educate policy and decision-makers on the possibilities and realities of QTs
    * Support research-informed policy making.
    * Act promptly to benefit from QT advancements.
    * Support agility in frameworks to help regulation keep up with QT development.

In summary, it is essential for decision-makers to act promptly and consult QT experts or seek educational resources to guide governance. Frameworks should encompass security, advancement, and inclusivity and be tailored to fit each context. A well-informed and adaptable approach is crucial for devising a national QT framework that is both effective and responsive.

Direction for Future Research

While this paper has laid the groundwork for understanding and navigating the governance of QTs, several areas require further investigation. It is essential for each country to examine what is necessary and how to approach QT governance and development, tailoring strategies to ensure both national gain and security. Future research should explore the socio-economic impacts of QTs, the ethical implications of quantum computing and artificial intelligence convergence, and the long-term global dynamics of quantum supremacy. Additionally, studies on the

effectiveness of international QT agreements and the development of QT ecosystems will provide valuable insights, helping policymakers to adapt and optimize governance frameworks to meet specific national needs.

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